Introduction

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Geological models of subduction zones impact thinking about many of the central problems in the structure, dynamics, chemistry, and history of the solid earth. Should those models change, the effects will reach across the earth sciences. We are currently in the midst of such a change, brought on by several causes. First, the earth science community recently began an organized, multi-disciplinary study of subduction zones by way of the National Science Foundation's "Margins initiative." This has improved the quality of our descriptions of key focus areas and should continue to do so for the next several years. Less purposefully but of equal importance, several of the debates in subduction zone research have evolved in recent years, making us revisit both recent and old observations in a new light. This book consists of descriptions of these advances, written by the some of the leading participants. I describe the origin and organization of the book in the preface; here I review the context of previous thought regarding convergent margins, with particular focus on the link between tectonics and magmatism, and point out questions raised in the following chapters.

ANCIENT HISTORY

For much of geology's modern era, models of subduction zones have been inseparable from "the andesite problem"; that is, the question of the origin of andesitic rocks that are abundant in many magmatic arcs. This specialized petrologic problem is disproportionately important both because andesite makes up a large fraction of subduction zone products, and because andesites compositionally resemble average continental crust (e.g., *Rudnick and Fountain,* 1995). Moreover, the literature on the "andesite problem" has been a clearing-house for ideas about the geology of convergent margins generally.

It was recognized near the beginning of the 20th century that andesitic rocks are highly concentrated into young, geologically active belts surrounding the Pacific ocean basin. These belts were collectively referred to as the "the andesite line" and interpreted as evidence for a specialized kind of magmatism that occurs only at the boundary between continental land masses and ocean basins (*Marshall,* 1911). The earliest widely remembered explanation of andesite genesis was Bowen's hypothesis that they, like many other silicic magmas, are liquids residual to crystallization-differentiation of basalt (*Bowen,* 1928). By this interpretation, andesites are ultimately products of basaltic magmatism and, to project his ideas into the plate tectonic world-view, therefore are close relatives of volcanic rocks from mid-ocean-ridges and intraplate volcanic centers. More detailed and geological interpretations of andesites and associated rocks at this time called on geosynclinal theory and seem peculiar and non-physical when looked at with the benefit of hindsight. Figure 1a is the author's attempt to synthesize several of these ideas. A noteworthy weakness of such models is that they offered no clear explanation of why andesites are common in Pacific-rim magmatic arcs while rare elsewhere.

Inside the Subduction Factory
Geophysical Monograph 138

10.1029/138GM01

PRE-PLATE-TECTONIC HUNCHES

Several discoveries over the course of the 1950s and 1960s pointed out the special character of andesites from magmatic arcs and the link between tectonics, deep seismicity, and magmatism. First, it was recognized that seismicity associated with volcanic arcs is organized into Benioff zones, suggesting that oceanic crust founders into the mantle at what we now recognize as convergent margins (*Benioff,* 1954). Moreover, experimental and applied petrology provided controversial but growing evidence that mafic magmas are derived from partial melting of peridotite, that peridotite is the major constituent of the upper mantle, that water lowers the melting points of silicates, and that crystallization-differentiation of anhydrous basalt, as envisioned by Bowen's earliest work, produces typical andesites only under special circumstances (see *Ringwood,* 1975, for a review of these early experiments). The unique compositional character (i.e., high silica content and proportion of andesite) of lavas from magmatic arcs and similarities between andesite and the continents as a whole were recognized (*Polvedaart,* 1955). Finally, there were growing suspicions that partial melting of peridotites to low degrees and in the presence of water produces unusually siliceous melts. *Polvedaart* (1955) made among the earliest such suggestion, although he did so based on the outlandish contemporary belief that the primitive crusts of the moon and mars consist almost entirely of rhyolite pumice. *O'Hara* (1965) made a similar but more well-founded suggestion based on the phase equilibria of idealized systems.

The relationships among these discoveries and their overall significance were not widely recognized until the plate tectonic revolution was underway (for instance, a standard petrologic text of this era, *Turner and Verhoogen,* 1960, does not link Benioff zones and andesitic volcanism). However, speculative inklings appeared surprisingly early. For example, *Polvedaart* (1955) suggested that andesites are partial melts of rocks in the hanging walls of Benioff-zone faults (i.e., the mantle wedge), formed in the presence of water released from foundered (i.e., subducted) ocean crust, and silicic compared to basalts because of the effect of water on the melting behavior of peridotite. A charitable interpretation of his hypothesis is illustrated in Figure 1b; similar models with sounder petrologic basis and more explicit ties to the concept of subduction would crop up as plate tectonic theory took form (*McBirney,* 1969; *Wyllie,* 1971). Perhaps the greatest long-term impact of this hypothesis was to inspire experimental studies of peridotite-water systems (e.g., *Kushiro et al.,* 1968), which eventually became a centerpiece of modern thinking about arc magmatism. However, the idea that andesites are primary partial melts of hydrous mantle, while containing elements of the modern understanding of subduction zones, conflicted with evidence that andesites are complexly evolved rocks that interact extensively with the crust through which they erupt (see *Turner and Verhoogen,* 1960, and *Ringwood,* 1975, for contemporary summaries of these criticisms). Hence the "andesite problem": the secondary origin suggested by Bowen is unable to explain why andesites are common in magmatic arcs and rare elsewhere (and gets details of the petrology and chemistry wrong); a primary origin explains the association of andesites with Benioff zones, but gets the chemistry and petrology substantially wrong.

THE LAST BIG THING

Responses to this dilemma played out during the formulation of plate tectonic theory, and therefore both built on the preceding arguments and integrated them with new insights about earth's plates. The following geophysical, geochemical, and experimental observations were particularly important: Magmatic arcs were shown to be clearly associated with convergent margins and subduction of ocean lithosphere; active convergent-margin volcanism was found to consistently occur ca. 80 to 150 km above the top of the down-going slab, suggesting control by a single pressure and/or temperature-dependent reaction in the slab; partial melting of high-pressure mafic rocks (e.g., eclogites) were shown to have compositions broadly similar to those of convergent-margin andesites; and the new tools of isotope and trace-element geochemistry demonstrated that convergent-margin magmas sample the top of the subducting plate (see *Gill,* 1981, for review of these developments).

These new constraints (and a variety of abstruse petrologic arguments) were used to suggest that magmatism at convergent margins is ultimately driven by melting of basalt in the down-going plate. Simple versions of this hypothesis equated andesites with slab melts (*Hamilton,* 1969; *Oxburgh and Turcotte,* 1970); more sophisticated versions called upon reaction between slab-derived melts and the overlying mantle wedge, upwelling and decompression melting of that hybrid mantle to produce basaltic and andesitic melts, and complex processes of differentiation, mixing and crustal contamination prior to eruption (Figure 1c; *Ringwood,* 1975). These suggestions obviously require that the top of subducted lithosphere melts, placing lower limits on its conductive and frictional heating (e.g., *Oxburgh and Turcotte,* 1970), and makes predictions about the compositions of residues of melting in deeply subducted slabs, which stir

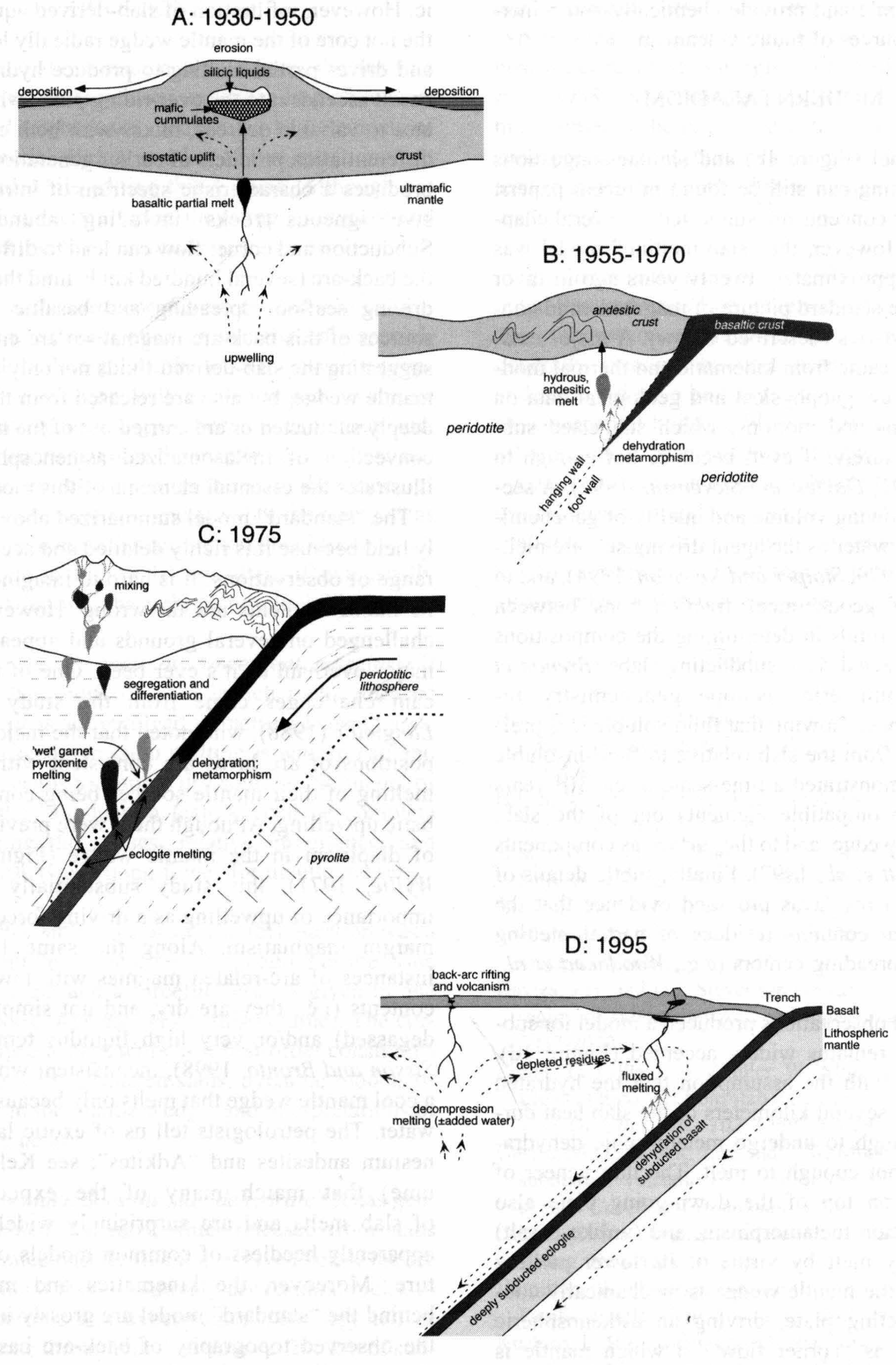

Figure 1. Schematic illustrations of conceptual models for the origin of igneous rocks at convergent margins. Panels A and B are the author's attempts to summarize ideas expressed in *Bowen* (1928), *Polvedaart* (1955), and their contemporaries. Panel C is after *Ringwood*, 1975. Panel D is the author's synthesis of ideas expressed in numerous recent studies of subduction zone magmatism and kinematics.

into the deeper mantle and provide chemically and mineralogically exotic sources of future volcanism.

THE MODERN PARADIGM

Ringwood's model (Figure 1c) and similar suggestions involving slab melting can still be found in recent papers, and broadly similar concepts are suggested in several chapters of this book. However, the "slab melting" model was widely discarded approximately twenty years ago in favor of what remains the standard picture of magmatism in convergent plate boundaries (described below). A major catalyst for this change came from kinematic and thermal models, supported by new geophysical and geological data on plate ages, positions and motions, which suggested subducted lithosphere rarely, if ever, becomes hot enough to melt (*Peacock,* 1991; *Davies and Stevenson,* 1992). A second key was the growing volume and quality of geochemical data pointing to water as the agent driving sub-arc melting (*Garcia et al.,* 1979; *Stolper and Newman,* 1994), and to the importance of geochemical fractionations between solids and aqueous fluids in determining the compositions of components extracted from subducting slabs (*Brenan et al.,* 1995). Uranium-series isotope geochemistry re-enforced this evidence, showing that fluid-soluble U is preferentially removed from the slab relative to fluid-insoluble Th, and further demonstrated a time-scale of ca. 10^4 years for transport of incompatible elements out of the slab, through the mantle wedge, and to the surface as components of lavas (e.g., *Elliott et al.,* 1997). Finally, subtle details of the geochemistry of arc lavas provided evidence that the mantle wedge often contains residues of partial melting beneath back-arc spreading centers (e.g., *Woodhead et al.,* 1993).

These and related observations produced a model for subduction zones that remains widely accepted (Figure 1d). This model begins with the assumption that the hydrated basalts in the upper several kilometers of the slab heat during subduction enough to undergo metamorphic dehydration reactions but not enough to melt. The thin veneer of pelagic sediments on top of the down-going plate also undergoes dehydration metamorphism, and (unlike basalt) might also partially melt by virtue of its lower melting point. The base of the mantle wedge is mechanically coupled to the subducting plate, driving an asthenospheric motion referred to as "corner flow" in which mantle is drawn horizontally into the wedge, dragged down along the top of the descending slab, compressed and cooled. At no point does the mantle heat or upwell beneath the arc, and thus we should expect convergent margins to be a-magmatic. However, infiltration of slab-derived aqueous fluids into the hot core of the mantle wedge radically lowers its solidus and drives partial melting to produce hydrous basalt. This basalt ascends into the over-riding plate, where it differentiates to variable degrees, mixes with both crustal melts and differentiation products of earlier generations of basalt, and produces a characteristic spectrum of intrusive and extrusive igneous rocks including abundant andesites. Subduction and corner flow can lead to diffuse upwelling in the back-arc (several hundred km behind the magmatic arc), driving seafloor spreading and basaltic volcanism. The sources of this back-arc magmatism are enriched in water, suggesting the slab-derived fluids not only pass through the mantle wedge, but also are released from the slab after it is deeply subducted or are carried out of the mantle wedge by convection of metasomatized asthenosphere. Figure 1d illustrates the essential elements of this model.

The "standard" model summarized above remains widely held because it is richly detailed and accounts for a wide range of observations. It is hard to imagine at present that its major elements are far wrong. However, it has been challenged on several grounds and appears as close to a major overhaul as it's ever been. One of the first significant challenges came from the study of *Plank and Langmuir* (1988), who noted that the major element compositions of arc lavas are consistent with the extents of melting of their mantle sources being controlled by adiabatic upwelling. Although there were previous suggestions of diapirism in the mantle wedge (Figure 1c; see also *Wyllie,* 1971), this study substantially broadened the importance of upwelling as a driving force for convergent margin magmatism. Along the same lines, there are instances of arc-related magmas with low primary water contents (i.e., they are dry, and not simply because they degassed) and/or very high liquidus temperatures (e.g., *Sisson and Bronto,* 1998), inconsistent with the picture of a cool mantle wedge that melts only because it is fluxed by water. The petrologists tell us of exotic lavas (high-magnesium andesites and "Adkites"; see Kelemen, this volume) that match many of the expected properties of slab melts and are surprisingly widely distributed—apparently heedless of common models of slab temperature. Moreover, the kinematics and mantle rheology behind the "standard" model are grossly inconsistent with the observed topography of back-arc basins (*Billen and Gurnis,* 2001). Finally, the occurrence of earthquakes at great depth and the distribution of seismic activity into "double" seismic zones have opened new possibilities for where and when slabs devolatilize (e.g., *Peacock,* 2001).

QUESTIONS

The points listed above raise new questions, the answers to which will certainly enrich our understanding of convergent margins and might make us overhaul key elements of the "standard" model. Below is a list of five questions that I've kept in mind while editing this volume. Although not all are discussed in every chapter, they crop up in most and I suggest them as themes to consider as you read:

How does the asthenosphere deform in response to subduction? This is a technical question because only specialists in dynamical modeling have the tools to answer it properly. However, its solution will deeply impact everyone working on convergent margins because asthenospheric motions control where and how the mantle melts, where fluids go once they are released from the slab, the velocities and topographies of the plates, and how hot the slab gets as it descends into the mantle. There is enough evidence to tell us mantle motions in Figure 1d are often, if not usually wrong in detail; what will the right picture look like?

Why does the mantle melt at convergent margins? It seems obvious that fluids or volatile-rich melts released from subducted slabs are involved in melting beneath arcs, yet evidence for decompression melting is widespread and in some cases it seems to sample dry sources. No model of magmatism in the "subduction factory" can be complete without explaining the causes, relative importance, and interaction of these two driving forces for mantle melting.

Do "slabs" often melt? The answer to this question was a firm and confident "no" just a few years ago, but the issue has been raised again and a forceful "yes" is given in one chapter of this book (*Kelemen et al.,* this volume). The correct answer to this question will place first-order constraints on thermal models of subducted slabs, dynamic models of convection deep in the mantle wedge, and interpretations of the origins of arc lavas.

Where and how much does the slab dehydrate? It has generally been assumed that most water released from slabs comes from hydrated basalts, that it is evolved below the arc volcanoes, and that it leaves relatively dry residual rocks. In contrast, metamorphic and experimental petrology tell us that slabs dehydrate throughout their first ca. 200 km of subduction (*Schmidt and Poli,* 1998), seismicity suggests dehydration reactions might occur deep within the ultramafic portions of the slab (*Peacock,* 2001), dynamic models permit fluids to move large horizontal distances before reaching a zone of partial melting in the mantle wedge (*Davies and Stevenson,* 1992; M. Spiegelman, pers. com.), and experimentalists have produced exotic phases that might host water retained in deeply subducted slabs (*Schmidt and Poli,* 1998 and references therein). These new arguments must somehow be integrated with our model for subduction zone processes; in particular, it must be shown how they lead to relatively simple distributions of volcanoes in magmatic arcs.

Are ocean arcs the seeds of the continents? It is often noted that andesites from magmatic arcs resemble the average composition of the continents. However, oceanic arcs generally contain abundant basalts in addition to these andesites and have bulk compositions that are not appropriate continental building blocks. Several resolutions to this dilemma have been suggested; a final answer is likely to come from more complete and detailed understanding of the crustal structure and geological evolution of a few representative magmatic arcs and their derived sediments. This volume's chapters on focus regions provide examples of the cutting edge of that understanding.

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