Manufacturing Continental Crust in THE SUBDUCTION FACTORY

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WERE CONTINENTS BORN IN THE OCEAN?

Subduction zones have been consuming oceanic lithosphere since the dawn of plate tectonics on this planet (Figure 1). Raw materials such as pelagic and terrigenous sediments, altered and fresh basaltic oceanic crust, and lithosphere are conveyed into this "factory" as the subducted plate sinks deeper into the mantle. Assuming steady-state subduction of the entire 7-km-thick oceanic crust for 3 billion years, the accumulated crustal materials occupy ~ 10 percent of the lower mantle. Aqueous fluids and/or silicate melts that are progressively extracted from these raw materials through dehydration reactions and/or partial melting during subduction dissolve particular elements and carry them into the overlying mantle wedge, leading to generation of chemically distinct arc magmas that differentiate, solidify, and produce juvenile arc crust; the site of these transformations is known as the "subduction factory." Collisional coalescence and magmatic thickening of juvenile arcs ultimately yield continental crust, an important subduction-factory product. The factory inevitably emits waste materials, such as chemically modified, residual oceanic crust and sediments and delaminated arc mafic (high in iron and magnesium) lower crust, which sink deeper into the mantle. These waste materials, because of their great mass and residual crustal composition, contribute greatly to the thermal and chemical evolution of the mantle and ultimately may return to Earth's surface as mantle plumes and related magmas (Figure 1).

Intra-oceanic subduction systems, which occupy ~ 40 percent of the global length of Earth's 55,000 km of convergent margins (Stern, 2002) (Figure 2), provide vital information on how the subduction factory works. They are situated on thinner and dominantly more mafic crust than systems at continental margins and hence significant contamination of magmas by easily fusible felsic (light-colored rocks high in feldspar and silica, for example, granite) crust may not occur. Along such margins, we can also better measure crustal growth rates, now estimated to be 30–95 km^3 km^{-1} Myr^{-1} (Dimalanta et al., 2002). Intra-oceanic arcs, however, are significantly less well studied than continental arcs. The main reason for the paucity of research is that except for the tops of the largest volcanoes, most of the arc is submerged below sea level. Ocean drilling at intra-oceanic arcs, therefore, should provide key observations for comprehending the solid-Earth cycle and evolution. Because of the importance of this problem, both the MARGINS Science Plans (2003) and Integrated Ocean

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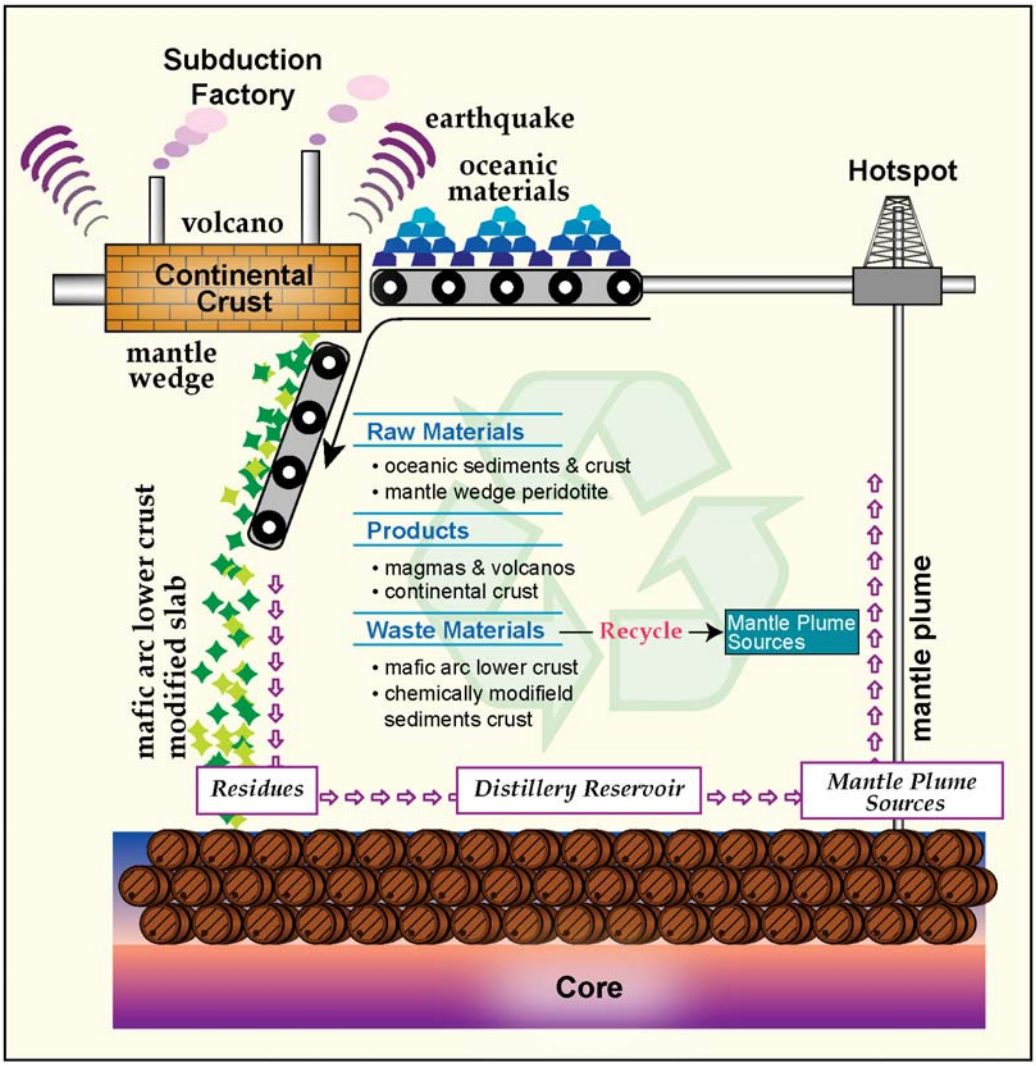

Figure 1. Role of the subduction factory in the evolution of the solid Earth. Raw materials, such as oceanic sediments, oceanic crust, mantle lithosphere, and wedge materials, are fed into the factory and are manufactured into arc magmas and continental crust. The waste materials or residues processed in this factory, such as chemically modified slab components (oceanic crust and sediments) and delaminated mafic lower arc crust, are transported and stored in the deep mantle, and recycled as raw materials for mantle-plume-related hot-spot magmatism.

Drilling Program (IODP) Initial Science Plan (ISP) (Coffin, McKenzie et al., 2001) have identified understanding the operation of Earth's subduction factory as a research priority.

PERSPECTIVES ON CONTINENTAL CRUST FORMATION

Continental crust occupies only 0.4 percent of the total mass of the solid Earth; however, it is by far the most important component because it is the storehouse of most natural resources and serves as substrate for agriculture and civilization. Chemically, the continental crust is a reservoir for "incompatible" elements that do not fit easily in mantle minerals, such as K, Rb, U, Th, and the light Rare Earth Elements. Continental crust thus possesses "differentiated" compositions, quite distinct from a chondritic (composition similar to that of asteroids) bulk Earth, primitive mantle, or even oceanic crust. The very distinctive composition of the continental crust indicates that understanding how this crust forms is essential for understanding solid Earth evolution. The IODP ISP includes continental-crust formation and growth as a priority drilling target (Coffin, McKenzie et al., 2001).

It is generally accepted that continental crust has an andesitic bulk composition (Rudnick and Fountain, 1995; Taylor and McLennan, 1995). Because andesitic magmatism typifies subduction zones, many researchers consider that continental crust has been created dominantly in arc-trench settings. However, modern-day, mantle-derived magmatism in such settings is dominated by basalt. This dilemma faces anyone interested in continental-crust formation.

To explain the characteristic andesitic composition of the average continental crust, several mechanisms have been proposed (e.g., Rudnick, 1995; Tatsumi, 2005). These hypotheses have been assessed petrologically, geochemically, and geophysically at various continental arcs. Reconstructing crustal-growth processes for continental arcs is, however, challenging. Low-density continental crust acts as a density filter, trapping mantle-derived mafic melts that then are likely to fractionate, assimilate, and melt the crust, strongly affecting the compositions of lavas and plutons. In contrast, intra-oceanic arcs are built on high-density, mafic oceanic crust. Oceanic crust is much less effective as a density filter and melts at a higher temperature, thus effects of pre-existing crust are minimized for intra-oceanic arcs. Nevertheless, intra-oceanic arc crust appears to differentiate to andesite and more felsic crustal compositions typical of continental crust. Seismic profiling of the Izu-Bonin-Mariana (IBM) (Figure 3) arc crust (Suyehiro et al., 1996; Takahashi et al., 2006) has further demonstrated the presence of middle crust that has a P-wave velocity of ~ 6 km s^{-1} (Figure 4a), interpreted to correspond broadly to intermediate-to-felsic "tonalitic" composition (Figure 4b). (A tonalite is an igneous intrusive rock of felsic composition.) Furthermore, tonalitic rocks are found as xenoliths included in lavas and as exposures along intra-oceanic arcs such as the IBM and

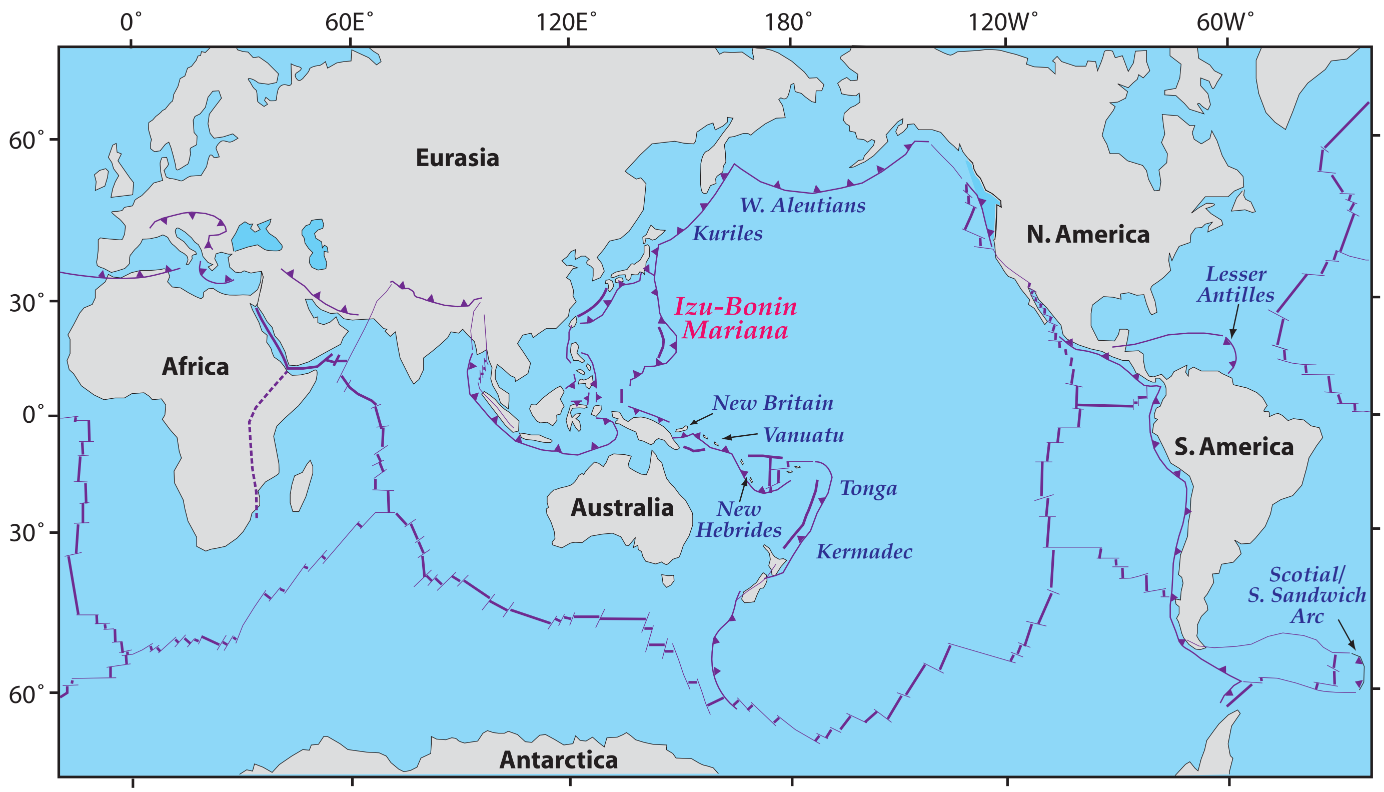

Figure 2. Locations of modern intra-oceanic arc-trench systems. Trenches associated with these systems are shown by barbed lines. Intra-oceanic arcs are sites where the effects of pre-existing continental crust can be neglected and represent relatively simple natural laboratories for the study of modern crustal growth.

Kyushu-Palau systems. This compelling evidence suggests that the ingredients for continental crust are indeed created today in intra-oceanic arcs. IODP drilling in intra-oceanic arcs will "be a tremendous step towards understanding the origin of the andesitic continental crust" (Coffin, McKenzie et al., 2001).

THE FLOOR PLAN OF THE SUBDUCTION FACTORY

Like all factories, the subduction factory follows specified procedures. To understand them, one must know where the various operations are carried out. We now understand that the subduction factory has two "floors." The lower level of the factory, the subducted slab and mantle wedge, extracts fluids and/or melts from subducted materials. These fluids and melts are enriched in the "continental component." This mixture is transferred upward, away from the slab, and mixes with normal asthenospheric mantle, enriching it and lowering its melting temperature. This hybrid mantle melts to form primitive (Mg-rich) arc basaltic magma that is enriched in continental-type incompatible elements. This primitive yet distinctive magma is then sent to the upper level of the subduction factory—the arc crust—where it is further processed by fractionation, partial melting, and delamination to generate tonalitic/andesitic continental crust.

We cannot visit (by drilling) the lower floor of the subduction factory, so our information about its operations must be indirect. One method to evaluate the processes in the lower floor of the factory is to analyze primitive, least-fractionated arc lavas, which are relatively rare, especially on large volcanic islands. It is easier to find primitive lavas by sampling small submarine arc volcanoes, which

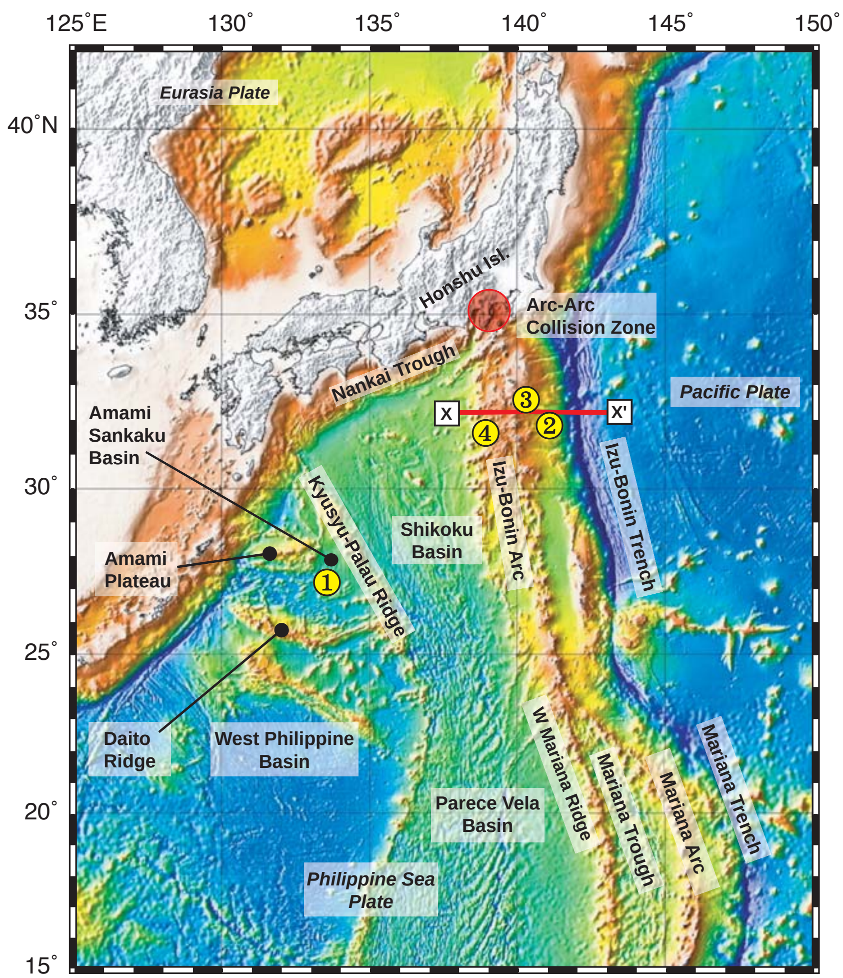

Figure 3. Location map of the Philippine Sea region. The Izu-Bonin-Mariana (IBM) arc-trench system forms the convergent margin between Pacific and Philippine Sea plates. Backarc basins such as Shikoku Basin, Parece Vela Basin, and Mariana Trough were created by seafloor spreading between the formerly contiguous remnant arc (Kyushu-Palau and West Mariana ridges) and the active IBM arc. At its northern tip, the IBM arc has collided with Honshu Island since 15 Ma. The X-X' red line locates the structural model cross section (Figure 4). Numbers show proposed drill sites.

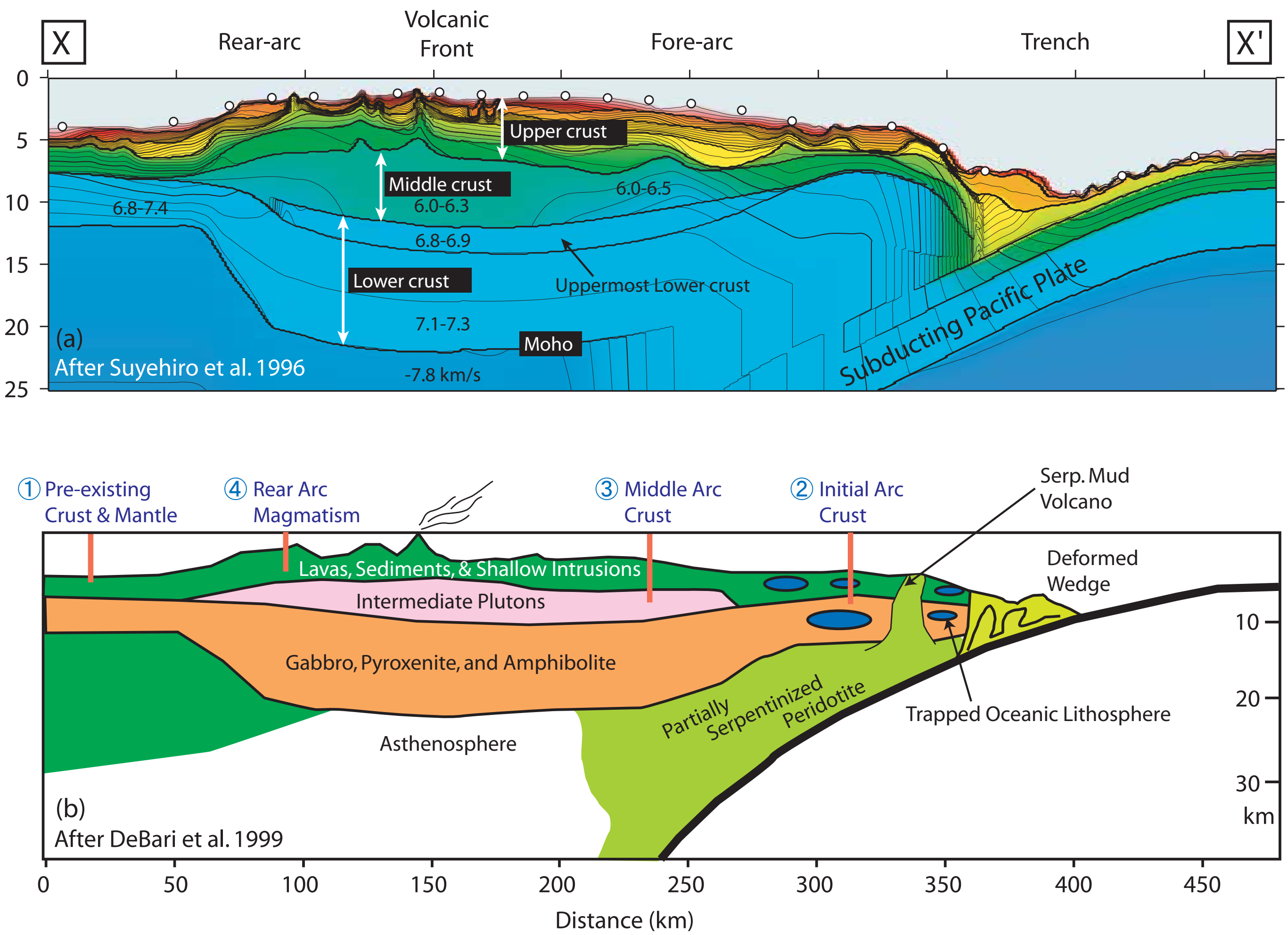

Figure 4. (a) Seismic structure of the crust and upper mantle based on seismic refraction and wide-angle reflection data along a X-X' cross-arc section within the IBM system (Figure 3). The arc crust seismic structure is explained by the distribution of upper, middle, and lower crustal layers as schematically shown in (b). IBM is the only juvenile intra-oceanic arc known to have a well-developed, low-velocity middle crust with V_p=6.0-6.3 km/s, possibly of similar composition to the average continental crust and provides key constraints on the process of continental crust formation. Numbers in (b) show schematic representation of proposed drill sites.

are too young to have developed effective magma chambers where magmatic fractionation occurs, or by drilling the oldest, most primitive parts of the forearc. The composition of primitive lavas is used to constrain models for arc magma genesis, which must be integrated with our understanding of the composition of the downgoing slab and sediments, models of how fluids and melts migrate from the slab up into the mantle wedge, models for thermal structure of the mantle wedge, and models for how melts rise from the mantle wedge into the crust.

To understand how continental crust is generated from primitive arc magma, we must visit the upper floor of the subduction factory, the arc crust. Physically, the upper floor is much smaller in size than the lower floor, but intra-oceanic arc systems—the simplest example of the subduction factory upper floor—are nevertheless immense. Intra-oceanic arc systems have the dimensions of gigantic flat noodles, much longer than they are wide and much wider than they are thick. For example, the IBM arc system is ~ 3000-km long, ~ 200-km wide, and ~ 25-km thick (Figures 3 and 4). The physical dimensions of intra-oceanic arcs are thus subcontinental in scale; our ability to understand these processes is challenged not only by the tremendous size of intra-oceanic arc systems but also because even the roof of the subduction factory is submerged, with only a few chimneys (volcano summits) reaching sea level. These dimensions and the submarine nature of the subduction factory second floor are very suitable for marine geophysical surveys (e.g., seismic reflection and refraction; electromagnetic and gravity surveys), which routinely extend for several hundred kilometers and can image tens of kilometers into the crust. Interpretation of the geophysical sections that are generated, however, requires calibrating the seismic profiles with drill core, which at present is impossible. The deepest drillhole to date on Earth (Kola Superdeep Borehole in Russia) only penetrates ~ 12 km into the continental crust and the deepest scientific drillhole at sea only penetrates ~ 2 km below the seafloor. The new IODP drillship *Chikyu* can drill with a riser (to remove rock bits from the drilled hole and stabilize the hole) to depths of ~ 7 km below the seafloor, which is still less than half way to the bottom of arc crust. But, depth of seafloor and total depth below the seafloor are not the only limitations on scientific drilling of intra-oceanic arc systems; we are also not able to drill into very hot (> 200°C) rocks. Drilling deeply into arc crust thus requires that we avoid the volcanic arc itself and focus on forearc and perhaps backarc settings, where lower geothermal gradients can be found.

In the following sections we discuss how to take advantage of the *Chikyu*'s new drilling capabilities to better understand the subduction factory. To get the most information and to more tightly constrain models of the subduction factory, IODP scientists must integrate data from many sources, such as multichannel seismic reflection and wide-angle seismic profiles imaging the crust and upper mantle, heat-flow measurements, and petrological/chronological examination of seafloor and on-land samples.

ARC EVOLUTION AND CONTINENTAL CRUST FORMATION

Understanding how continental crust forms at intra-oceanic arcs requires that we first know how intra-oceanic arcs form and mature. Key questions for comprehending arc crust formation are: (1) What is the nature of the crust and mantle in the region prior to the beginning of subduction? (2) How does subduction initiate and initial arc crust form? (3) How do the middle and arc crusts evolve? (4) What are the spatial changes of arc magma and crust compositions of the entire arc? Possible strategies for answering these questions include drilling by IODP at the IBM arc-system, which is one of the best-surveyed intra-oceanic island arcs. Figure 4a shows the across-arc seismic structure of the IBM (line X-X' in Figure 3), which is representative for the entire IBM arc (Suyehiro et al., 1996). IODP has proposals to drill at the IBM, including three non-riser holes (1, 2, and 4 in Figures 3 and 4b) and one riser, ultra-deep hole (3 in Figures 3 and 4).

Nature of the Original Crust and Mantle

Pre-existing, non-arc oceanic crustal components should contribute to arc magma chemistry through assimilation and partial melting triggered during passage of arc magmas; oceanic crustal remnants could also make up an important part of the lower-arc crust. Typically, the presence of such relict oceanic crust is assumed, because recovery of samples from sub-arc depths of 15–20 km is impossible. At the IBM, pre-existing oceanic crust is present west of the arc, under 1–1.5 km of sediments in the Amami Sankaku Basin adjacent to the Kyushu-Palau Ridge remnant arc (Figure 3) (Taylor and Goodliffe, 2004) and may crop out on the lower fore-arc slope of the Bonin Trench (DeBari et al., 1999).

The backarc basins of the eastern Philippine Sea Plate are underlain by asthenosphere of Indian Ocean character, geochemically distinct from mantle sources beneath the Pacific Plate to the east (Hickey-Vargas, 1998). IBM subduction-zone inception may have therefore occurred along a major mantle domain boundary of the type presently exposed at the Australian-Antarctic Discordance. But, it is also clear that the initial construction of the IBM arc system, rather than developing solely upon oceanic crust, transected a series of Cretaceous-Paleocene ridges (e.g., Amami Plateau and Daito and Oki-Daito ridges) and intervening basins that formed, at least in part, an arc-backarc system (Figure 3) (Taylor and Goodliffe, 2004; Hickey-Vargas et al., 2005). Alternatively, these proto-continental ridges and plateaus may have rifted away from Asia. Decoding the nature of the magma source in the upper mantle that existed immediately before IBM subduction inception is key to understanding the cause of initiation of subduction zones and intra-oceanic arc formation. This decoding can be accomplished only by examining pre-arc oceanic crust, such as that of the Amami Sankaku Basin in the Northeast Philippine Sea Plate (1 in Figure 3), or by examining crust that might be encountered in deep drilling of the fore-arc.

Initial Arc Crust Formation and Subduction Initiation

The nature of arc magmatism, and hence the nature of the arc crust, at the very initial stage of IBM subduction is distinct from that of later stages. To better constrain the initial arc crust formation at the IBM, deepening of the previous Ocean Drilling Program (ODP) hole (Hole 786B; shown as 2 in Figures 3 and 4b) is proposed.

ODP Leg 125 drilled a series of holes in the IBM fore-arc (Arculus, Pearce et al., 1992) to recover samples of initial arc crust. The last of these (Hole 786B) cored 666 m of Eocene volcanic basement. The recovered rocks were a complex series of pyroclastics (fragmented bits of rock) and lavas, followed by dikes, exhibiting compositions distinct from the later stage magmas. The recovered extrusive rocks likely were pillow lavas that formed the flanks of a volcano, which was intruded by dikes and sills—similar stratigraphy to normal oceanic crust. These observations, including the structural and compositional similarity between the IBM fore-arc crust and ophiolites (oceanic crust that has been thrust onto land), led Pearce et al. (1992), Stern and Bloomer (1992), and Ishiwatari et al. (2006) to conclude that the IBM fore-arc formed by seafloor spreading.

The abundant dikes drilled at the bottom of ODP Hole 786B (Arculus, Pearce et al., 1992) suggest that much (~ 1 km) of the additional proposed drilling there by the IODP will be spent passing through a significant thickness of sheeted dikes. Whether or not a significant section (about 1000-m thick) of sheeted dikes exists at the IBM for-arc is an important test of the hypothesis that the IBM fore-arc formed by seafloor spreading. Existing geophysical data provide no constraints on this question. Attempting to penetrate a sheeted dike complex also comprises an important test of the hypothesis that most ophiolites form by seafloor spreading during the initial stages of subduction. We should be able to determine the strike of dikes and thus the local direction of spreading, which may provide critical constraints on tectonic regime at the very initial stage of arc evolution.

Evolution of Middle Crust

Extensive seismic refraction studies reveal that IBM crustal structure is not only much thicker (25 km vs. 7 km) than typical oceanic crust, it also has a thick layer of low-velocity (V_p=6.0–6.3 km s^{-1}) middle crust (Figure 4a). Yet, intra-oceanic island arcs are thought to be constructed of basalt, similar to oceanic crust formed at mid-ocean ridges (~ 50 percent SiO_2). A basaltic bulk composition for intra-oceanic arcs is also expected because the mantle partially melts to produce basalt. As noted previously, subduction is also thought to ultimately be responsible for generating continental crust, which is andesitic in bulk composition (~ 60 percent SiO_2). The paradox posed by the basaltic composition of mantle melts and the andesitic composition of continental crust may partially be resolved if a low-velocity, mid-crustal felsic layer is generated in intra-oceanic arcs, coupled with a loss of pyroxene-rich lower crustal residues (Jull and Kelemen, 2001); this process may represent an early stage in the production of continental crust. Establishing the composition of IBM arc middle crust, correlating this composition to profiles of crustal seismic velocities, and inferring genetic relationships between *in situ* intra-oceanic arcs and upper crustal volcanic rocks and mid-crustal sequences exposed on land, can only be accomplished by scientific ocean drilling. We propose returning to the region of ODP Site 792 (3 in Figures 3 and 4) to drill through the Eocene-Oligocene upper crust down to middle crust. The mid-crustal layer in this area is shallow enough to be reached by drilling, and heat flow is low enough for drilling to proceed at mid-crustal temperatures.

Rear-Arc Magma and Arc Crust Compositions

Previous drilling efforts in IBM during the Deep Sea Drilling Project (DSDP)-ODP focused mainly on the forearc (the area between the trench and the volcanic arc) and documented the temporal variation of magmatism (e.g., increasing K_20 with time) along the volcanic front (the trenchward boundary of a volcanic arc) preserved in tephra and turbidites (Gill et al., 1994; Arculus et al., 1995; Bryant et al., 2003; Straub, 2003). However, the magmatic history of the rear-side of the IBM arc has not been similarly well studied, partly because rear-arc volcanoes are submarine so this tephra is not dispersed as far as that from subaerial volcanoes of the magmatic front.

Analysis of dredged rocks suggests that there is a consistent difference in chemistry between the IBM volcanic front and rear-arc magmas throughout the Neogene (Tatsumi et al., 1992; Hochstaedter et al., 2000, 2001; Ishizuka et al., 2003; Machida and Ishii, 2003); this difference has long been recognized for arc systems globally (Dickinson, 1975; Tatsumi and Eggins, 1995). The record for the IBM, however, is based on a small number of rocks dredged and dated from rear-arc cross chains (including results from Marianas as well as Izu: Stern et al., 1993; Stern et al., 2006). The only thing known about rear-arc volcanism between the Neogene cross chains is that the 7 Ma basalt and andesite dredged from one such site are similar to volcanic front rocks (Hochstaedter et al., 2001). Therefore, it may be that the apparent difference between volcanic front and rear-arc magmatism is restricted to the cross chains. The temporal variation in rear-arc magma chemistry also has not been well documented. This variation can be addressed only by examining the tephra and turbidite record stored in the basins located between the rear-arc volcanic chains. In the northern IBM, these basins should be largely free of ash from the IBM volcanic front because prevailing winds blow east. Finally, nothing at all is known about Oligocene rear-arc volcanism. Such information affects how crust formed and evolved across the arc, and can be learned only by drilling. We thus propose a drilling expedition at the rear-arc side of the Izu arc (4 in Figures 3 and 4b) along an across-arc section that passes other proposed drill sites (Figures 3 and 4).

SUMMARY

We are confident that ocean drilling at intra-oceanic arcs, such as the IBM, is the way to answer the fundamental question of how continental crust is created; to test the hypothesis of whether continents themselves are first born in the ocean; and to understand the role of subduction-factory processes in solid Earth evolution. The key objective of this drilling effort is to sample rocks that form the deeper part of the arc crust, which is feasible only by riser drilling with *Chikyu*. To implement these IODP expeditions, pre-expedition, non-drilling efforts will be required, including acquisition of multichannel seismic reflection and wide-angle seismic data for better imaging of the crust and upper mantle, heat flow measurements for confirming the deep drilling, and petrological/chronological examination of seafloor and on-land samples.

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