Subduction initiation and evolution of oceanic island arc at its initial stage

Osamu Ishizuka
Institute of Geology and Geoinformation, Geological Survey of Japan/AIST, Central 7, 1-1-1, Higashi, Tsukuba, Ibaraki, 305-8567, Japan

Robert J. Stern
Geosciences Department, University of Texas at Dallas, 800 W. Campbell Road Richardson TX 75080-3021 U.S.A.

abstract

Subduction initiation and subsequent birth of a convergent margin and an arc are still one of the essential outstanding problems of plate tectonics. Fore-arcs with thin sediment cover – those of intra-oceanic arcs - are particularly valuable for understanding how subduction zones begin. For example, Stern and Bloomer (1992) and Bloomer et al. (1995) recognized that the fore-arc basement of the Izu-Bonin-Mariana (IBM) system formed in the initial phases of subduction zone development nearly synchronously over a zone up to 300km wide and thousands of kilometers long, at igneous production rates much higher than those of current arcs.

Our understanding of the magmatic rocks associated with subduction initiation and the birthplace of ophiolites has been retarded because intra-oceanic forearcs are deeply submerged and difficult to study. By extensive sampling and submersible observation of the Izu-Bonin forearc at two sites (near Guam and near Chichijima), we have been able to outlinethe crustal section exposed in inner trench walls. The members of forearc crustal section are from lower to upper: 1) lowermost gabbroic layer, 2) sheeted dyke complex overlying gabbros, 3) tholeiitic basaltic lava flows, 4) volcanic breccia and conglomerate with boninitic and basaltic clasts, 5) boninite and tholeiitic andesite lava flows and dykes.

These observations revealed similarity of the forearc crust section to oceanic crust apart from uppermost boninitic layer. This strongly implies that seafloor spreading occurred at the initial stage of subduction. At the same time overall section of the forearc show strong similarity to supra-subduction ophiolite.

Even though general idea of arc crust formed at the initiation of subduction has been obtained, retrieval of complete crustal section can be achieved only by drilling. Drilling through the entire forearc crust could test preexisting models for subduction initiation and evolution of early arc magmatism by providing a complete magmatic section.

Introduction

Subduction initiation and subsequent birth of an oceanic arc are still one of the essential outstanding problems of plate tectonics. Furthermore, such arcs could represent the building blocks of continental crust (Suyehiro et al., 1996; Takahashi et al., 1998, Stern and Scholl, 2009 in press). In order to understand the formation of arc and continental crust, it is necessary to estimate growth rates of arc crust coupled with petrological and chemical evolution. Oceanic arcs, where thickened crust has formed within oceanic lithosphere, provide a unique opportunity to investigate this problem. The Izu-Bonin-Mariana (IBM) arc is an outstanding example of such an arc system (Fig. 1).

Fore-arcs with thin sediment cover are particularly valuable for understanding how subduction zones begin. For example, Stern and Bloomer (1992) and Bloomer et al. (1995) recognized that the fore-arc basement of the IBM system formed in the initial phases of arc volcanism nearly synchronously over a zone up to 300km wide and thousands of kilometers long, at igneous production rates much higher than those of current arcs.

The Bonin Ridge (Fig. 1) is an unusually prominent forearc massif in the IBM arc that exposes early arc volcanic rocks on islands of Chichijima, Hahajima, and smaller islands (e.g., Umino, 1985). Submarine parts of the ridge, which could complement the record of volcanism preserved on the islands, had not been extensively investigated.

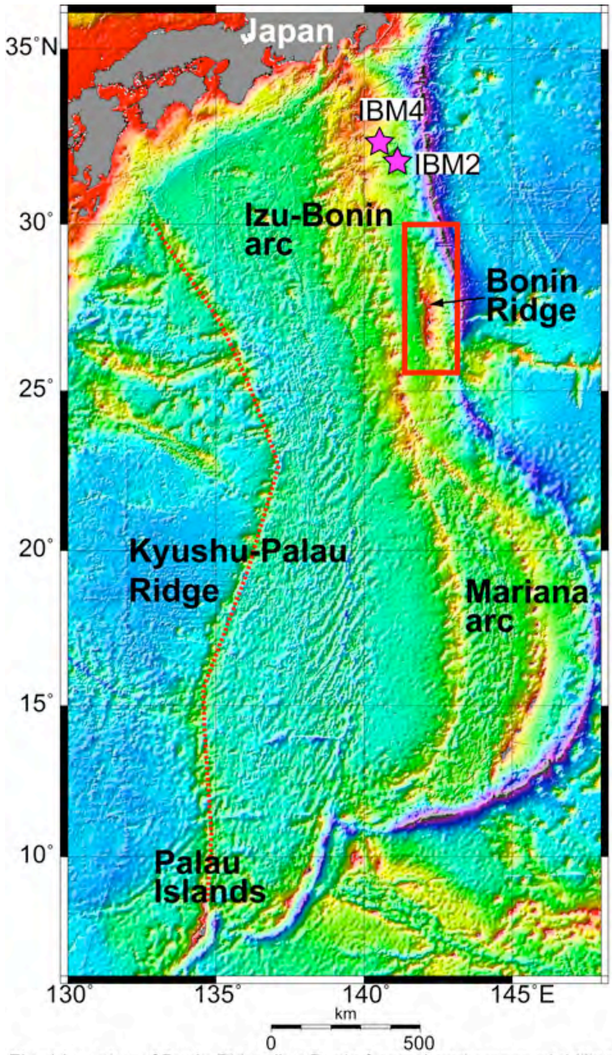

Fig. 1 Location of Bonin Ridge (Izu-Bonin forearc) and proposed drilling site in the forearc (pink-colored stars).

Recent findings in the Izu-Bonin forearc

By extensive dredge sampling of the Izu-Bonin forearc, we have found evidence of MORB-like volcanism at the very initiation of lithospheric collapse leading to establishment of a new subduction zone. We sampled along the entire length of the Bonin Ridge between the Bonin Islands and Izu-Bonin Trench to establish the nature and timing of the earliest stages of Izu-Bonin arc and to attempt to recover material from the deepest sections of the arc crust.

Shinkai 6500 submersible survey in 2009 enabled us to obtain general idea of the crustal section that formed when this oceanic arc began (Fig. 2). The members of forearc crustal section are from bottom to top: 1) lowermost gabbroic layer, 2) sheeted dyke complex overlying gabbros, 3) basaltic lava flows, 4) volcanic breccia and conglomerate with boninitic and basaltic clasts, 5) boninite and tholeiitic andesite lava flows and dykes (subaerially exposed on Bonin Islands).

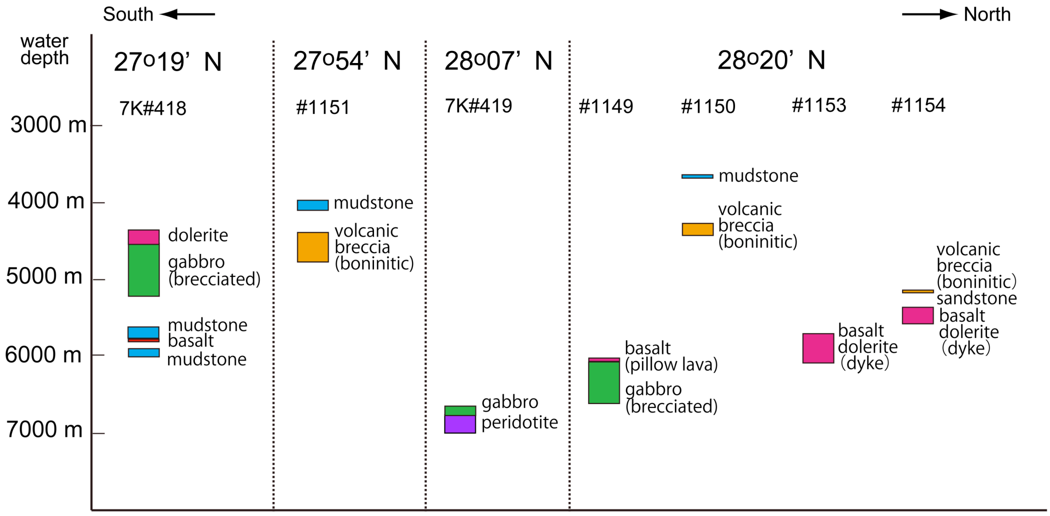

Fig. 2 Summary of forearc stratigraphy observed by submersible and ROV dives. These dives revealed the following forearc stratigraphy: 1) lowermost gabbroic layer, 2) sheeted dyke complex overlying gabbros, 3) basaltic lava flows, 4) volcanic breccia and conglomerate with boninitic and basaltic clasts, 5) boninite and tholeiitic andesite lava flows and dykes (subaerially exposed on Bonin Islands).

In addition to this crustal section, dredge sampling and ROV Kaiko dives recovered mantle peridotite below the gabbro. These observations strongly indicate that almost all of the forearc crust down to Moho has been preserved.

Preliminary data indicate that basaltic rocks (including dolerite) made of sheeted dykes and lava flows and lower gabbros are generally comagmatic. These basalts show chemical characteristics similar to MORB (i.e., with no slab signature). These lavas have lower Ti/V (14-16), which distinguishes them from subducting Pacific MORB (26-32) and Philippine Sea MORB (17-25), indicating this is not oceanic crust that was trapped when subduction began. Pb isotopes of the fore-arc MORB show that like other Izu-Bonin arc magmas they are derived from a mantle source with Indian Ocean characteristics. Chemically and petrographically they are similar to tholeiites from the Mariana fore-arc that predate boninitic volcanism in that region but that are nevertheless considered to be related to subduction but (Reagan et al., in prep). This strongly implies that MORB-like tholeiitic magmatism was associated with fore-arc spreading along the length of the Izu-Bonin-Mariana arc. Like the slightly younger boninitic rocks, the likely source of these MORB-like basalts can be linked to an Indian Ocean-type mantle. Low concentrations of incompatible elements and low ratios of diagnostic trace

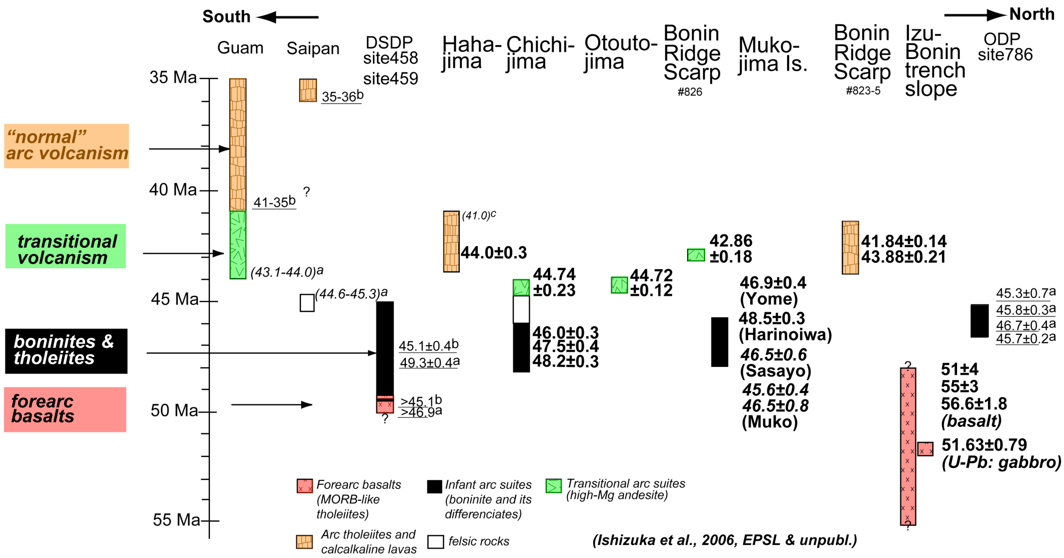

Fig. 3 Compilation of 40Ar/39Ar dating results on IBM forearc volcanics. Boninite volcanism appears to have started ~49 Ma and ceased before 46 Ma and characteristics of volcanism in the Izu-Bonin forearc seems to have changed at 45-46 Ma. Note early episode of MORB-like tholeiite at 56-51 Ma. Date sources; a:Cosca et al. (1998); b: Reagan et al. (2008), c: Kaneoka et al. (1970). 40Ar/39Ar age of Cosca et al. (1998) is calculated using an age of 520.4 Ma for MMHB-1; ages in bold letters are from Ishizuka (2006 and unpublished). 40Ar/39Ar age of Reagan et al. (2008) is calculated using an age of 27.84 Ma for FC-2 Fish Canyon Tuff. U-Pb data: Tani et al. (unpubl. data).

elements such as Nb/Yb imply that tholeiitic melts were from depleted mantle and/or were larger degree mantle melts compared to typical Philippine Sea MORB.

Diving observation showed that these basalts are likely to underly boninitic volcaniclastics and lavas. Recent dating efforts appear to confirm this stratigraphic relationship. Ar/Ar ages for these basalts (even though with large error due to extremely low K concentrations) and U-Pb age of comagmatic tholeiitic gabbro are consistently older than IBM boninites (Fig. 3).

Boninite from the Bonin Islands are characterized by low high-field-strength element contents, U-shaped chondrite-normalized REE pattern, high Δ7/4Pb and low $^{143}Nd/^{144}Nd$ relative to local MORB sources and the MORB-like forearc basalt. These boninites are also distinct from the 44 Ma volcanics from the Hahajima Islands and the Bonin Ridge escarpment (Ishizuka et al., 2006). So potentially, the geochemical and isotopic characteristics of the arc may have evolved by 1) initial decompression melting without significant slab flux to producr MORB-like basalt at when fore-arc spreading began, 2) increasing involvement of fluids from subducted pelagic sediment and extremely depleted mantle to yield boninite during a limited period (48-45 Ma), and 3) involvement of convecting asthenosphere with more extensive hydrous fluid input to generate increasingly arc-like tholeiitic and calcalkaline magmas after 44 Ma (Ishizuka et al., in prep).

Drilling targets

IODP drilling is needed to test and refine these linked models for subduction initiation and evolution of early arc magmatism (e.g., Fig. 4) by providing complete magmatic section.

Major issue to be addressed by drilling target will be:

1)Stratigraphic relationships between MORB-like forearc basalt and boninitic rocks (e.g., do MORB-like basalts predate boninitic magmatism or are they contemporaneous?)

2)Duration of each type of early arc magmatism, temporal variation of chemistry, volume etc.

3)Across-arc variation of early arc magmatism

4)Relation between effusive rocks and plutonic rocks: Genetic relation, volume ratio, temporal relationship etc.

5)Volumetric (i.e., number and thickness) ratio between lava sequence and dykes to estimate rate of eruption and/or spreading rate at the initial stage of subduction

6) Use of arc basement to calibrate seismic velocities with depth

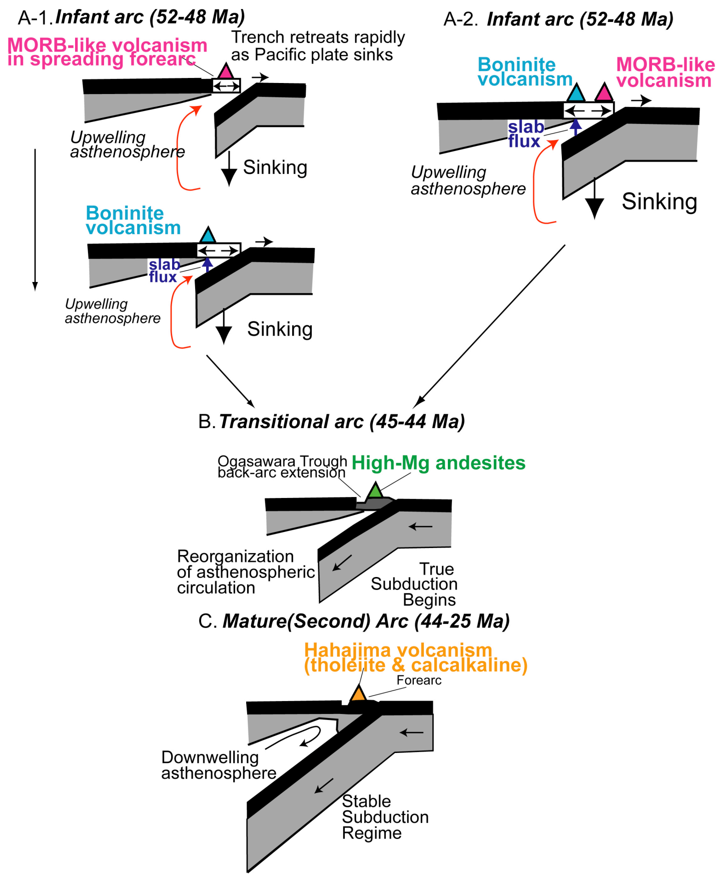

Fig. 4 Model of subduction initiation and evolution of infant arc (modified from Ishizuka et al. 2006)

After tackling these issues at a specific arc, next step will be to work with geodynamic and petrogeneitc modellers to use these results to constrain how subduction begins and how this controls early arc magmatism within a single arc. Modes of subduction initiation may vary from arc to arc, so development of a global model will require similar studies for other forearcs, designed to identify common features as well as differencess among different arcs. Such comparative studies, in tandem with geodynamic and petrogenetic modeling are indispensable to test and refine subduction initiation models and critical controlling factors for early arc magmatism. Possible critical factors may include 1) characteristics of the foundering lithosphere, 2) mode of convection and temperature variation in asthenospheric mantle, 3) structure and composition of what will become the overriding plate, 4)how quickly true subduction begins.

Forearc drilling will also allow thorough comparison between forearc stratigraphy and typical supra-subduction zone ophiolites. The outcome of IODP forearc drilling thus could finally resolve the long debate on the origin of these ophiolites.

References

S.H. Bloomer, B. Taylor, C.J. MacLeod, R.J. Stern, P. Fryer, J.W. Hawkins, L. Johnson, Early Arc volcanism and the Ophiolite problem: A perspective from drilling in the Western Pacific, in: B. Taylor, J. Natland, (Eds), Active Margins and Marginal Basins of the Western Pacific, American Geophysical Union, Washington D.C., (1995), pp. 67-96.

M.A. Cosca, R.J. Arculus, J.A. Pearce, J.G. Mitchell, $^{40}Ar/^{39}Ar$ and K-Ar geochronological age constraints for the inception and early evolution of the Izu-Bonin- Mariana arc system, The Island Arc 7(1998) 579-595.

O. Ishizuka, J.I. Kimura, Y.-B. Li, R.J. Stern, M.K. Reagan, R.N. Taylor, Y. Ohara, S.H. Bloomer, T. Ishii, U.S. Hargrove III, S. Haraguchi, Early stages in the volcanism: new age, chemical and isotopic constraints, Earth and Planetary Science Letters, 250, (2006) 385-401.

I. Kaneoka, N. Isshiki, S. Zashu, K-Ar ages of the Izu-Bonin Islands, Geochem. J. 4(1970) 53-60.

M.K. Reagan, B.B. Hanan, M.T. Heizler, B.S. Hartman, R. Hickey-Vargas, Petrogenesis of Volcanic Rocks from Saipan and Rota, Mariana Islands, and Implications for the Evolution of Nascent Island Arcs. J. Petrol. 49 (2008) 441-464.

R.J. Stern, S.H. Bloomer, Subduction zone infancy : Examples from the Eocene Izu-Bonin-Mariana and Jurassic California, Geol. Soc. Am. Bull. 104 (1992) 1621-1636.

R.J. Stern, D.H. Scholl. Yin and Yang of Continental Crust Creation and Destruction by Plate Tectonics. International Geology Review (2009 in press)

K. Suyehiro, N. Takahashi, Y. Ariie, Y. Yokoi, R. Hino, M. Shinohara, T. Kanazawa, N. Hirata, H. Tokuyama, A. Taira, Continental crust, crustal underplating, and low-q upper mantle beneath an oceanic island arc, Science 272(1996) 390-392.

N. Takahashi, K. Suyehiro, M. Shinohara, Implications from the seismic crustal structure of the northern Izu-Bonin arc, The Island Arc 7(1998) 383-394.

S. Umino, Volcanic geology of Chichijima, the Bonin Islands (Ogasawara Islands), J. Geol. Soc., Jap. 91(1985) 505-523.