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Research Highlight

# Significance of a highly refractory source during subduction initiation to form the Izu-Bonin-Mariana Arc

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The ascendent theory that unifies the Earth Sciences is Plate Tectonics, a regime which is unique to Earth. Other convectively active, solid silicate bodies of our Solar System (Venus, Mars, and Io) are encased in a single deforming "lid"; on these, multiple plates and hence plate motions do not exist [1]. As Earth's tectonic plates are driven by the sinking of old and cold oceanic lithosphere at subduction zones, understanding how new subduction zones originate is vital for a complete plate tectonic theory. Proposed mechanisms of subduction initiation (SI) are controversial but can be either spontaneous, i.e., caused by forces originating at the SI site, or induced by ongoing plate motions [2].

In a review of circa 100 Ma SI-related Neotethyan ophiolites of the Mediterranean-Persian Gulf region (Mirdita, Albania; Pindos, Greece; Troodos, Cyprus; Semail, Oman), Whattam and Stern [3] identified a chemostratigraphic evolution from early mid-ocean ocean ridge (MORB)-like lavas to later more depleted volcanic arc basalt (VAB)-like lavas and sometimes youngest boninites, a progression they termed the "subduction initiation rule" (SIR). The SIR reflects formation of proto-forearc/forearc lithosphere as a result of mantle melting that is increasingly influenced by melt depletion of melt-mobile elements coupled with enrichment in water and fluid-mobile elements from the sinking slab. Earliest formed MORB-like basalts are the consequence of decompression melting of upwelling asthenosphere little affected by slab fluid contributions during early stages of SI; later "typical" suprasubduction-zone-like VAB and boninite lavas reflect fluid-flux partial melting of increasingly depleted mantle residue subsequently modified by slab contributions in the latter stages of SI. A similar chemotemporal progression has recently been documented for the earliest stages of forearc construction at the Central American Arc system [4].

The SIR is not always followed in detail. For example, the Troodos ophiolite is slightly different than Mirdita, Pindos and Semail as lower Troodos lavas are VAB-like rather than MORB-like; however, upper lavas are boninite. Similarly, at the Izu-Bonin-Mariana (IBM) forearc (Fig. 1), generation of earliest MORB-like basalts or "forearc basalts" (FAB) during SI was followed by eruption of boninites [6,7] and hence production of VAB-like lavas apparently did not occur. Nevertheless, in the case of both Troodos and the IBM forearc, a progression from less to more depleted and subduction slab-modified lavas occurred with time over the course of SI, consistent with the SIR.

The IBM forearc (Fig. 1a) sequence of SI magmatic products is "ophiolite-like", similar everywhere the forearc has been stratigraphically sampled, and shows depleted (harzburgitic) peridotite in the deepest part of the inner trench wall, overlain by minor gabbro, FAB and then boninite. Ages of FAB and boninite recovered by dredging, remotely operated vehicles and by drilling at International Ocean Discovery Program (IODP) Sites U1439 and U1442 (Fig. 1) during IODP Expedition 352 [6] range from 51.9 to 51.3 Ma and 51.3 to 46 Ma, respectively [8–10]. Boninites also erupted between 48–45 Ma and ~45–44 Ma along the Ogasawara Ridge and in the northern segment of the Chichijima Island group, respectively [9,11]. After boninite eruptions ended, magmatic activity stopped in what is now the forearc and retreated to the site of the mature arc magmatic front where normal arc activity commenced by 44 Ma [11] where typical arc tholeiites and calc-alkaline lavas erupted from arc volcanoes. This transformation of convergent margin magmatism reflects the reorganization of asthenospheric flow, from upwelling during SI to induced convection coupled to the downgoing slab during normal subduction.

For some Mediterranean-Persian Gulf ophiolites, forearc-continent collisions aborted subduction before normal arc activity could commence but in the case of the IBM system, there was no collision and subduction-related magmatism continues to this day. Crucially, a recent study [5] documents late-stage SI magmatism at 49 Ma [12], hundreds of kilometers to the west of IODP Sites U1439-1442 drilled during Expedition 352 [7] at the Bonin forearc. As a result, the study of Amami-Sankaku Basin (ASB) basalts from Expedition 351 Site U1438 in the IBM backarc (Fig. 1a) [5] documents a unique situation in which magmatic products produced in the interim between the final stages of SI and the initial stages of normal arc activity could be investigated.

Prior to establishing normal subduction following SI, magmatic outputs in emerging arcs allow the nature and temporal evolution of the mantle wedge to be estimated from the magmatic products it produces. On the basis of advancing studies of the IBM forearc and SI ophiolites, this evolution is coming into focus [6,7,13,14]. However, we still have limited knowledge of the nature of the

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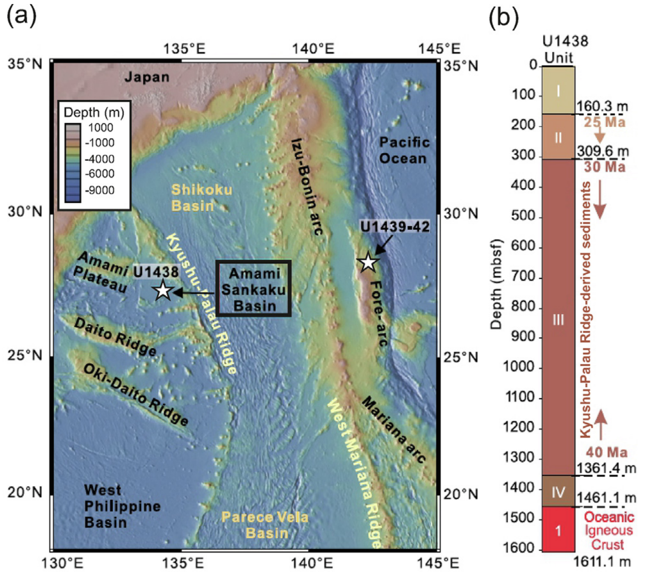

**Fig. 1.** (a) Location of the study of Li et al. [5] at Hole U1438 from Expedition 351. Also shown is the location of Holes U1439-1442 from Expedition 352 (Reagan et al. [6]). (b) Unit thicknesses and ages at Site U1438 are from Li et al. [5].

mantle and magmatic products generated between SI cessation and subduction establishment. This is why the study of Li et al. [5] is so exciting: it documents the nature of the mantle and magmatic products at the ~49 Ma "watershed" between the end of SI-related FAB and boninite magmatism and the beginning of normal subduction and arc development by 44 Ma.

Interestingly, at this time (49 Ma), magmatism at Sites U1439-1442 in the Bonin forearc changed from FAB to boninitic but at Site U1438, magmatism was broadly similar to that of 52–51 Ma FAB recovered from Sites U1440-1441; i.e., magmatism at backarc Site U1438 was more similar to MORB than to boninite at 49 Ma. Based on studies of Mariana FAB and from Sites U1440-1441 in the Bonin forearc, although FAB have whole rock trace element patterns similar to MORB [7], they exhibit lower ratios of highly incompatible to less incompatible fluid-immobile elements (Ti/V, Yb/V, Zr/Y, Ce/Yb, and Zr/Sm) relative to MORB [7,13], indicating derivation from depleted lherzolitic mantle. Similarly, compared to MORB, ASB Unit 1 basalts have high Mg/Fe and Sc, but low Ti, Zr, Ti/V, and Zr/Y [15]. Collectively, these features have been interpreted to represent a mantle source during SI beneath what is now the IBM forearc that underwent more melt extraction than that of typical MORB [10,13].

The study of Li et al. [5] provides the first constraints of FAB petrogenesis based on trace element chemistry of Unit 1 ASB (Fig. 1b) clinopyroxene and in so doing, documents the nature of the rapidly changing mantle at 49 Ma during SI to form the nascent IBM arc system. Similar to the whole rock studies referenced above, petrography and mineral chemistry show some features similar to MORB, and others distinct from MORB. For example, although the inferred crystallization sequence of Unit 1 ASB basalts of spinel followed by olivine, plagioclase, and clinopyroxene is similar to MORB, the high Mg# and strongly aluminous nature of ASB basalt clinopyroxene is distinct from MORB [5]. Moreover, the persistence of phenocrystic clinopyroxene in ASB basalts is different from MORB where clinopyroxene is typically absent. Trace element patterns of clinopyroxene of ASB basalts are also consistent with a MORB-like crystallization order of plagioclase preceding clinopyroxene. For example, even the most primitive clinopyroxenes (with the highest Mg#) exhibit negative chondrite-normalized Eu-anomalies (i.e., Eu/Eu* where $\text{Eu}^* = \sqrt{\text{Sm} \times \text{Gd}}$) which range down to 0.6. This is inferred to reflect crystallization of plagioclase before clinopyroxene [5].

Comparison of ASB basalt REE patterns with those of MORB and IBM FAB also yields important information on the nature of the mantle source at 49 Ma [5]. Compared to MORB and other global ocean basalts, the extremely low REE abundance of ASB basalt confirms derivation from melt-depleted spinel peridotite that was more refractory than most MORB sources. Moreover, although IBM FAB has similar REE depletion to ASB basalt, the REE patterns also show differences, as the FAB exhibit less LREE depletion than ASB.

Clinopyroxene thermometry of FAB from forearc Holes U1440-1441 yields crystallization temperatures of 1142–1190 °C [14], which fall within the range of MORB. Clinopyroxene thermometry of ASB basalts ranges to lower temperatures (1090–1165 °C) [5] than FAB but the higher range falls within that of MORB. In terms of basalt generation temperatures, the range of temperatures calculated for FAB of Holes U1440-1441 of 1400–1480 °C [13] are higher than that of MORB and only slightly higher than those for ASB Unit 1 basalts (1350–1400 °C) [5]. It was suggested that the high mantle equilibration temperatures of FAB may reflect influence of the Manus plume during SI [13].

In summary, studies on the source and magmatic products of the IBM forearc during SI over the past decade show that FAB, although similar to MORB in some aspects, are unique as FAB were derived from a hotter, more depleted source than that of typical MORB. This may reflect a hotter, more depleted mantle source associated with plume emplacement or a previous melting episode. The study of Li et al. [5] confirms conclusions of other studies of ASB basalts (e.g., [15]) that SI magmatism persisted for at least 3 Ma prior to development of stravolcanoes associated with the onset of normal arc magmatism. To account for the source depletion, it was suggested that the mantle source became increasingly more refractory over this time [5], resulting in basalts generated in the ASB at 49 Ma some 250 km to the west of the site of SI FAB production at 52 Ma that are similar to FAB but different from MORB. This speaks to pre-SI events in the evolution of the Philippine Sea Plate, most likely related to Neo-Tethys, which existed in this region in Mesozoic time.

## Conflict of interest

The authors declare that they have no conflict of interest.

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