Overview of the IBM Arc System: The Igneous Rocks

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The Izu-Bonin-Mariana (IBM) arc system extends 2800km from near Tokyo, Japan to Guam (Fig. 1) and is an outstanding example of an intra-oceanic convergent margin (IOCM). Study of this and other IOCM’s provide unique insights into the operation of the Subduction Factory because contamination of mantle-derived melts by pre-existing crust can be neglected and because the absence of continent-derived sediments makes it easy to examine arc infrastructure. Because the surface of the IBM IOCM is largely submerged and its Subduction Factory extends hundreds of kilometers to the base of the mantle, studying it will require a remarkable (and international) mix of marine technologists interacting with a diverse geoscientific community: field-oriented (marine and landlubber), laboratory-oriented, and computation-oriented geoscientists. Outputs from the IBM Subduction Factory can be sampled in four distinct settings: forearc vents, magmatic arc volcanoes, cross-chain volcanoes, and back-arc (extensional) volcanoes. The purpose of this presentation is to acquaint this talented and diverse audience with the magmatic products of this large and diverse system.

One of the most interesting and important aspects of IBM igneous activity are the boninites, named by Petersen (1890) after localities in the Bonin (Ogasawara) Islands. These testify to the hydrous melting of harzburgite at the beginning of large-scale lithospheric subsidence (not true subduction, but its precursor) associated with initiation of the IBM subduction zone, constrained to have begun about 45-50 Ma ago. Peridotites exposed in the trench wall and as xenoliths in forearc mud volcanoes are mostly highly-depleted harzburgites with Cr-rich spinels. These harzburgites are residues after this
intense, early melting episode. The IBM arc magmatic system subsequently has been in a steady state, in the sense that there are major progressive or systematic changes in magma composition are not observed. There are large variations in magma composition but these are controlled by location along or across the arc as well as by differences in tectonic style.

There are three active loci for magmatic outputs from the IBM arc system: magmatic front, cross-chains, and extensional. The latter includes igneous activity related to rifting as well as back-arc spreading. One of the major challenges facing the Subduction Factory research program is to better constrain the rates and volumes that magma is produced by the Subduction Factory. For the IBM system since inception, Taira et al. (1998 Is. Arc 7, 395-407) estimate an arc crust growth rate of 70-80 km$^3$/km-Ma, much greater than the estimate of 10-15 km$^3$/km-Ma for the magmatic front of southern IBM over the past 5 Ma (Bloomer et al., 1989 Bull. Volc. 51, 210-224). Part of this discrepancy reflects uncertainty about the proportion of magma that never erupts and the role of delamination, but much of it reflects rapid crustal growth associated with subduction initiation. There are no estimates of magma production rates for IBM cross-chains but these are likely to be an order of magnitude lower than those. Magma production in IBM rifts is probably on the order of 50 km$^3$/km-Ma, while seafloor spreading in the Mariana Trough south of 19°45’N produces crust at a rate of 200-250 km$^3$/km-Ma. Very high magma production rates may also characterize the southernmost Mariana Trough adjacent to the Challenger Deep.

IBM lavas from along the magmatic front are porphyritic and fractionated, with Mg# (=100Mg/Mg+Fe) typically in the forties and fifties. We don’t understand how or where this fractionation occurs, but we think it happens in crustal ‘magma chambers’, although none has been identified geophysically. Fractionation is probably accelerated by loss of magmatic volatiles. The lesson from the MELTS experiment may be that arc
magmas fractionate in thin, sill-like bodies. Scarcity of primitive lavas suggests multiple sites for fractionation. The cartoon in Fig. 2 presents some of the likely relationships and complications, and we very much need a better understanding of the magma plumbing and storage system beneath the magmatic front.

In spite of the generally fractionated nature of lavas erupted along the IBM magmatic front, significant differences appear on a plot of potassium vs. silica (Fig. 3A). Mariana arc volcanoes mostly erupt medium-K, calc-alkaline or tholeiitic lavas. Izu-Bonin arc volcanoes mostly erupt a bimodal suite of low-K tholeiites and rhyodacites. The IBM arc is the only IOCM where shoshonitic lavas erupt along the magmatic front. All IBM lavas from along the magmatic front show trace element patterns indicating involvement of the ‘subduction component’ (Fig. 4A), with elevated Rb, Ba, and U, strong depletions in Nb and Ta, and positive ‘spikes’ in K, Pb, and Sr. Shoshonites also show enrichments in Th and LREE, but the nature of the process or fluid that is capable of fractionating Th and Nb is enigmatic (Fig. 5).

Three cross chains have been studied, from north to south: Izu cross chain, four cross-chains near 32°N, and the Kasuga cross-chain (Fig. 1). There is a remarkable variability in the composition of cross-chain lavas. They are bimodal, erupting abundant primitive basalts with Mg# >65 as well as dacites and rhyodacites. Cross-chain lavas are usually more enriched in K and other LIL elements relative to lavas erupted from the associated magmatic front, mostly falling in the medium-K field, but both subalkaline and alkaline varieties are erupted. Small, unsampled submarine cones behind the shoshonitic volcanic complex are tantalizing in this regard. Cross-chain shoshonites are only common from the Kasuga cross-chain in the northern Mariana arc, although rare, high-K lavas have been recovered from the Izu cross-chains near 32°N (Fig. 3B).

Lavas related to extension are erupted from interarc rifts in the north (Izu rifts; Fig. 1) and the Mariana Trough back-arc basin. These lavas straddle the low-K/medium-
K divide (Fig. 3C). Lavas associated with IBM rifts – where true seafloor spreading is not yet underway - such as the Sumisu rift and other Izu rifts, as well as the Volcano-Tectonic Zone of the northern Mariana Trough are bimodal, with abundant felsic as well as mafic lava. Lavas erupted from the Mariana Trough south of 19°45’N, which is undergoing seafloor spreading, are all basalt or basaltic andesite (Fig. 3C). Most extension-related lavas show trace element patterns expected for subduction-related lavas and are not easily distinguished from the arc lavas on this basis (Fig. 4B); however a few back-arc basin basalts have MORB-like trace element patterns. The only known exposure of mantle peridotite in an active back-arc basin occurs in the southern VTZ of the Mariana Trough, near 21°N (Fig. 1). These are indistinguishable from those beneath mid-ocean ridges and are distinctly less depleted than those associated with forearcs (Ohara et al., 2002 CMP 143, 1-18).
Figure 1: Locality map for IBM arc system magmatic components. Bathymetry is from the Smith and Sandwell (1997) 2-arc-minute predicted and shipboard digital bathymetry grid, using GMT software and courtesy of Fernando Martinez, SOEST.
Figure 2: Idealized section through the magmatic axis of an intra-oceanic arc. Note that the asthenosphere is shown extending up to the base of the crust; delamination or negative diapirism is shown, with blocks of the lower crust sinking into and being abraded by convecting mantle. Regions where degassing of CO$_2$ and H$_2$O is expected are also shown. Note that orientation and even presence of crustal magma chambers is speculative; if these exist, they could be flattened or cylindrical.
Fig. 3: Potassium-silica diagrams for IBM arc lavas. A) Lavas from along the IBM volcanic front, showing mean compositions for each of 62 volcanoes. Names are indicated for calc-alkaline and tholeiitic series below the double arrows, above the double arrows for the shoshonitic series. Yellow field shows region covered by lower panel. B) IBM Cross-chains: Izu (red), Kan’ei-Manzi-Enpo-Genroku (blue), Kasugas (Green). C) IBM rift-related igneous rocks, including Sumisu and Myojinsho rifts (66 samples) and Mariana Trough Volcano-Tectonic Zone (VTZ: 41 samples), and Mariana Trough spreading segment (MTB, 167 samples). Note the bimodal nature of lavas erupted in rifts and strictly mafic nature of lavas erupted in the region undergoing spreading.
Figure 4: Incompatibility plot for IBM arc lavas. A) Incompatibility plot for lavas from along the volcanic front. Typical compositions for the Mariana arc (GUG-9 of Elliott et al., 1997; 51% SiO$_2$) and Shoshonitic province (54H of Peate and Pearce, 1998; 47.8% SiO$_2$) are plotted, along with a mean calculated for Izu arc mafic lavas (51.6% SiO$_2$; Taylor and Nesbitt, 1998). B) Incompatibility plot for extension-related IBM lavas. Sumisu Rift partial data is mean from data set of Hochstaedter et al. (1990). Mariana Trough data are for glasses analyzed by Pearce (unpublished ICP-MS data). VTZ sample is T7-54:1-1 (1.69% H$_2$O). Two representative samples are given for the Mariana Trough spreading segment: ‘arc-like’ sample GTVA75:1-1 (2.21% H$_2$O) and ‘MORB-like’ sample DS84:2-1 (0.21% H$_2$O; Gribble et al., 1996).
Fig. 5: Incompatible element ratios for lavas from along the IBM volcanic. Data for the Izu Arc are from Taylor and Nesbitt (1998 EPSL 164, 79-98); Mariana Central Island Province (CIP) and sediment (B=bulk sediment; V=volcaniclastics) data are from Elliot et al. (1997; JGR 102 14991-15019), and Shoshonitic Province data are from Sun et al. (1998 Is. Arc 7 432-442; 2001 JGR 106 589-608; filled diamonds) and Peate & Pearce (1998 Is. Arc 7 479-495).