The Izu-Bonin-Mariana Subduction Factory
Robert J. Stern, Geosciences Dept., U. Texas at Dallas, Box 830688, Richardson TX 75083-0688, rjstern@utdallas.edu

The IBM arc system lies in the Western Pacific and defines the eastern margin of the Philippine Sea Plate (Fig. 1). Because IBM is an endmember arc system in a number of ways, it is an outstanding natural laboratory for studying earth’s largest geodynamic system, the Subduction Factory. IBM is the largest intra-oceanic convergent margin, being constructed entirely within and upon oceanic lithosphere. Lithosphere produced during the ~48 million years that this Subduction Factory has operated makes up a region about the size of India, but the presently active part extends for about 300 km west of the IBM trench. IBM manifests subduction of Pacific lithosphere, with the Pacific moving NW relative to IBM, at rates that vary from about 20 mm/a south of Guam to almost 60mm/a near Japan [1]. The Philippine Sea Plate itself is moving rapidly northwestward. Subducted lithosphere varies in age from mid-Jurassic (~170 Ma) outboard of the Marianas to early Cretaceous (~130Ma) adjacent to Japan (Fig. 2). The combination of a retreating upper plate and an extremely old (hence dense) subducting plate results in a strongly extensional convergent plate boundary, particularly in the southern IBM where these effects are maximized.

Off-ridge volcanism was common during mid- and Late Cretaceous time on the Pacific Plate now outboard of southern IBM. As a result, there are significant differences in the bulk composition of subducted sedimentary columns in the north and south, although the thickness of sediments is relatively constant at about 500m [2]. This modest sediment thickness is well below the ~1km thickness required for development of an accretionary prism [3] and is completely subducted. Plate convergence is oblique over most of the IBM arc, approaching pure sinistral strike-slip motion in the northern Mariana arc (Fig. 3). The Wadati-Benioff zone is well-defined beneath IBM, dipping about 45° in the north and nearly vertically in the south (Fig. 4); some of the deepest seismic activity in earth – down to 700 km - is found beneath the central Mariana arc. These and other physical constraints need to be identified and incorporated in the construction of realistic, 4-D models of mantle and fluid flow, thermal evolution, and fluid/melt generation, migration, and storage.

Earth’s only T-T-T triple junction defines the northern end of IBM, where collision continues with southern Honshu at a rate of about 40mm/a. This provides an opportunity to study terrane accretion in action [4] as well as exhuming IBM arc middle crust [5]. These exposures of arc crust are correlatable with crustal structure inferred for in situ IBM crust (Fig. 5). Not only does northern IBM provide an unparalleled opportunity to examine the formation of juvenile continental crust, societal considerations compel it: continuing convergence between buoyant IBM crust and Honshu presents an imposing earthquake hazard to the greater Tokyo metropolitan area, with far-reaching implications for the global economy. An analogous opportunity to study deeper arc crust and upper mantle lies on the wall of the 11km-deep Challenger Deep at the south end of the IBM arc system.

Three combined forces – retreat of the Philippine Sea Plate, subduction of unusually dense lithosphere, and oblique convergence – combine to make IBM the most strongly extended convergent margin on the planet. This evisceration provides unique opportunities to monitor the Subduction Factory. Extension in the southern IBM is oriented trench-parallel in the forearc and trench-normal in the back-arc [6]. This strongly extensional regime provides three opportunities - forearc, active arc, and back-arc basin - to sample Subduction Factory fluids and melts, more than any other convergent margin on the planet. The Mariana forearc contains the only known occurrences of subduction-related serpentinite mud volcanoes (SMV) [7] on this planet. Flows from Mariana SMV contain fragments of blueschist from the subducted slab [8] as
well as abundant mantle fragments [9]; several SMV are actively venting slab-derived fluids, some of which support active chemosynthetic communities.

Magmatic activity is expressed differently within and along the IBM arc. A true back-arc basin (BAB), with seafloor spreading, is developed only in the Mariana Trough [10], although well-developed inter-arc basins are developed in the Bonin Arc Rifted Zone farther north (Fig. 6) [11, 12]. The active magmatic arc is largely submarine but with abundant subaerial volcanoes [13, 14]; strong variations in magmatic compositions affect both submarine and subaerial edifices. BAB lavas are often aphyric or have pillow rim glass that can readily be separated, and a substantial proportion are primitive basalts; these characteristics suit BAB lavas for analysis using approaches perfected for MORB. Arc lavas are predominantly porphyritic so that bulk compositions generally do not correspond to magmatic liquids, and should not be studied using the techniques appropriate for studying aphyric or glassy samples. Accumulation of plagioclase phenocrysts in particular has led to a misperception that mafic members are dominantly high-Al basalts when in fact aphyric samples or glass inclusions in phenocrysts are tholeiites. Primitive compositions (Mg# > 65) are uncommon among IBM arc lavas, so fractionation conditions and history need to be resolved. Old techniques for studying petrography should be revived and new techniques will have to be perfected if we are to understand the magmatic evolution of porphyritic arc lavas. In future studies, petrographic descriptions should be reported with major and trace element data. The need to find new ways to study evolved, porphyritic samples promises to revive traditional petrography as well as stimulate developments in quantitative petrography/image analysis and microbeam analytical techniques. These techniques will also aid investigations of abundant cumulate xenoliths, found in the lavas of several IBM volcanoes. One issue that awaits resolution is the abundance of felsic material in the IBM arc. IBM has traditionally been thought to have a basaltic bulk composition, but recent evidence from geophysics [15], exposures in the collision zone [5], glass inclusions in phenocrysts [16], and the abundance of felsic tephra in DSDP cores [17] indicates that felsic rocks comprise an important part of the IBM arc.

In spite of the different eruptive styles and extent of fractionation for arc and BAB, there are strong compositional affinities between arc and BAB suites, which provide different perspectives on important controversies and enigmas. The trace element signatures of these lavas strongly manifest the ‘subduction component’: enrichments in large-ion lithophile elements and depletion in high-field strength elements, both compatible and incompatible (Fig. 7). All arc and most BAB lavas have elevated water contents [12, 18] such that it is controversial the extent to which melts are generated by decompression [19] or fluxing by hydrous fluids [20]. One abiding mystery concerns how water gets into the source of Mariana BAB magmas when the subducted slab does not lie beneath the spreading ridge? In contrast to widespread recognition that water in IBM melts is recycled from subducted materials, the source of other elements in IBM melts is less clear. In particular, controversy continues regarding the extent to which the IBM ‘subduction component’ manifests fractionations imposed when elements are transferred from the subducted plate to the overlying mantle wedge as opposed to being developed during re-equilibration of hydrous fluids and melts with convecting mantle. U-Th disequilibria studies indicate that strong fractionation of radionuclides occurred within the last 30 kyr [21], providing timescales for fluid-mediated fractionation but where and how this occurs are unresolved. There is abundant evidence that some subducted components are recycled and can be found in young lavas, especially elevated water contents, $\delta$Li [22], B/Be, $\delta$B [23], $\delta^3$S [24], and $^{207}$Pb/$^{204}$Pb [25]. These studies differently emphasize roles of subducted sediments and altered oceanic crust. Rare gas data is lacking for arc lavas but BAB lavas contain recycled atmospheric Ar in spite of mantle-like $^{3}$He/$^{4}$He [26]; similar datasets for arc lavas promise to provide important constraints. The $^10$Be signal is muted probably because subducted sediment are much older than the half-life of this isotope [27]. Other isotopic and trace element data sets do
not readily allow recycled components to be identified: O, Sr, Nd, and Pb isotopic compositions as well as K/Rb and K/Ba are remarkably constant in arc lavas despite being extremely heterogeneous in subducted components. This homogeneity requires efficient mixing of subducted components or effective re-equilibration of ascending fluids with convecting mantle. It is critical to resolve the nature of the mantle source beneath IBM; there are strong indications from Nd, Hf, Pb, and Os data that this mantle has affinities to that beneath the Indian Ocean [28-30].

Disparate geochemical and isotopic data sets and controversial conclusions provide important constraints for understanding how the IBM Subduction Factory operates. It will be an exciting challenge for scientists with different talents and perspectives to synthesize these observations and use these to develop and test hypotheses to better understand the operation and budget of this outstanding example of the Subduction Factory. A critical aspect will be to collect and distribute representative samples to analysts and to communicate these results to modelers, and for modelers to tell analysts what kinds of information they need. Another critical effort will be the seismic imaging of the IBM Subduction Factory, with as high a resolution as possible.


Figure Captions:

Figure 1: IBM arc system, showing extent of crust generated over the 48 Ma life of the arc (fossil plus active) as well as those components which comprise the presently active IBM Subduction Factory. Also shown is the location of the deepest place on the face of the earth, the Challenger Deep (~11km deep) and the IBM collision zone.

Fig. 2: Seafloor feeding into the IBM Subduction Factory, modified after [31]. Arrows are relative velocities of the Pacific Plate with respect to the Philippine Sea Plate, in mm/a, after [1]. DSDP and ODP sites sampling units being subducted beneath IBM are shown as well. Note that the sedimentary section being subducted beneath northern IBM has fewer volcanics and volcaniclastics than that being subducted beneath the southern IBM.

Fig. 3: Obliquity of convergence between the Pacific and Philippine Sea plates, as inferred from earthquake slip vectors and modified after [32]. Note that convergence is highly oblique over much of the IBM arc system.

Fig. 4: Generalized topology of IBM Wadati-Benioff Zone, modified after [33]. Two perspectives are shown, with contours colored at every 100 km depth.

Figure 5: Structure of IBM arc crust at 32°15’N, modified after [15]. Vertical exaggeration is about 10x. Note the crustal thickness of 22km is nearly four times that of oceanic crust but only about half that of normal continental crust.

Figure 6: Along-strike profiles of the IBM arc system, from Japan (left) to Guam (right). The thick solid line shows the bathymetry and topography along the volcanic axis of the active arc, with the thin dashed horizontal line marking sea level. The approximate locations of the principal island groups (Izu, Bonin-Volcano, and Mariana) are shown. Submarine volcanoes (and the Sofugan Tectonic Line, STL) are given as italicized abbreviations: Ku, Kurose; Ms, Myojin-sho; Do, Doyo; Kk, Kaikata; Kt, Kaitoku; F, Fukutoku-oka-no-ba; HC, Hiyoshi Volcanic Complex, Nk, Nikko; Fj, Fukujin, Ch, Chamorro, D, Diamante; R, Ruby, E, Esmeralda; T; Tracy. Subaerial volcanoes are given as normal abbreviations: O, Oshima; My, Miyakejima; Mi, Mikurajima; H, Hachijo-jima; A, Aogashima; Su, Sumisuujima, T, Torishima; Sg, Sofugan; Nishinoshima; KI, Kita Iwo Jima; II, Iwo Jima; MI, Minami Iwo Jima; U, Uracas; M, Maug; As, Asuncion; Ag, Agrigan; P, Pagan; Al, Alamagan; G; Guguan; S, Sarigan; An, Anatahan. Dominant compositions of arc segments are also indicated. Locations of important zones of intra-arc and back-arc extension in the north (Bonin Arc Rifted Zone) and south (Mariana Trough Back-Arc Basin) are marked. The thick dashed line shows the maximum depth in the trench along its strike. Frontal arc elements are not shown, but consist of the Bonin or Ogasawara Islands between 26° and 28°N and the Mariana frontal arc islands between 13° and 16°N. ICZ = IBM collision zone.

Fig. 7: ‘Spider’ diagram for Mariana arc lavas. Elements are listed in order of increasing compatibility in mantle minerals; data for typical Mariana arc lavas is from [34]. Notice strong enrichments in LIL and depletions in HFSC, including Nb and Ta.
Plate convergence obliquity (from earthquake slip vectors)

Izu Bonin Mariana

Orthogonal convergence

Sinistral strike-slip

Plate convergence obliquity (from earthquake slip vectors)

Arc-parallel fore-arc slip rate

North South

Izu  Bonin  Mariana

0  1000  2000  3000 km

34.1°  25.2°  16.9°N

60  30  0

-30 -60 -90

Orthogonal convergence

0

-60

60

Obliquity (°) or rate (mm/y)
Perspective Views of the IBM Subduction Zone
(Colored depth contours every 100 km)
Sample/MORB

Mariana Shoshonites

Mariana Trough

Mariana Islands

Element Abundances:
- Cs
- Ba
- U
- Ta
- La
- Pb
- Sr
- Nd
- Hf
- Eu
- Ti
- HREE

Sample/MORB