IODP Proposal Cover Sheet

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Title:	**Testing Subduction Initiation and Ophiolite Models by Drilling the Bonin Forearc**
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Keywords: *(5 or less)*	Convergent margin, arc, forearc, oceanic crust, Moho — Area: W. Pacific

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Permission to post abstract on IODP-MI Web site:	x	Yes		No

Abstract: (*400 words or less*):

We propose to drill a section through the volcanic stratigraphy of the outer forearc of the IBM system in order to trace the processes of magmatism, tectonics and crustal accretion associated with subduction initiation. This in turn has implications for understanding the origin of the many ophiolites that are now believed to form in this setting and so is a good opportunity to test this supra-subduction zone ophiolite model and involve the land-based geological community in IODP. We propose two sites in the Bonin forearc (BON-1 and BON-2) which form an offset-drilling pair that together should penetrate the full c. 1.25 ± 0.25km lava section. The sites have been surveyed and surface-sampled by several diving and dredging cruises. Studies of the recovered samples have established a stratigraphy in which peridotites, gabbros and sheeted dykes are overlain by 'Forearc Basalts' (FAB) and then in turn by boninites. DSDP Site 459 in the Mariana Forearc provides a well-surveyed alternate site of similar age, stratigraphy and setting that will penetrate a similar lava sequence. Drilling BON-1 and BON-2 will contribute to our understanding of intra-oceanic convergent plate margins by providing 1) a high-fidelity record of magmatic evolution during subduction initiation; 2) a test of the hypothesis that “Fore-arc Basalts” (FAB) tholeiites lie beneath boninites; 3) a record of the chemical gradients within these units and across their transitions; 4) information on how mantle melting processes evolve during subduction initiation from early decompression melting of fertile asthenosphere to late flux melting of depleted mantle, providing key empirical constraints for realistic subduction initiation geodynamic models; and

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5) a test of the hypothesis that forearc lithosphere created during subduction initiation is the birthplace of supra-subduction zone ophiolites.

Scientific Objectives: (*250 words or less*)

Drilling the volcanic rocks of an intra-oceanic forearc has a number of related scientific objectives, all based on reconstructing the magmatic chemostratigraphy associated with subduction initiation (SI). Documenting how lava compositions change as SI proceeds will provide essential constraints for understanding how SI is accomplished and how mantle sources and processes evolve during SI, and for testing the idea that most supra-subduction zone ophiolites are fossil forearcs that formed during SI. This proposal cites five specific objectives:

Objective 1: To obtain a high-fidelity record of magmatic evolution during SI by coring volcanic rocks down to underlying intrusive rocks, including radiometric and biostratigraphic ages.

Objective 2: Use the results of Objective 1 to test the hypothesis that “Fore-arc Basalts” (FAB) tholeiites lie beneath boninites

Objective 3: To understand chemical gradients within these units and across their transitions and to understand their tectonic significance.

Objective 4: Use the results of Objective 1 to understand how mantle melting processes evolve during SI from early decompression melting of fertile asthenosphere to late flux melting of depleted mantle, providing key empirical constraints for realistic SI geodynamic models.

Objective 5: To test the hypothesis that forearc lithosphere created during subduction initiation is the birthplace of supra-subduction zone ophiolites.

Please describe below any non-standard measurements technology needed to achieve the proposed scientific objectives.

The technology required is that for drilling any 1km-deep hole in oceanic crust.

Proposed Sites:

Site Name	Position	Water Depth (m)	Penetration (m)			Brief Site-specific Objectives
			Sed	Bsm	Total	
BON-1	28°27.0’N 142°45.5’E	4780	250	750	1000	Lower volcanic stratigraphy
BON-2	28°24.5’N 142°36.5’E	3100	250	750	1000	Upper volcanic stratigraphy.
Alternate						
DSDP Site 459	17°51.8'N 147°18.1'E	4100	500	1000	1500	Lower volcanic stratigraphy

An IODP Proposal

Testing Subduction Initiation and Ophiolite Models by Drilling the Bonin Forearc

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1. INTRODUCTION AND RELATIONSHIP TO IODP-ISP OBJECTIVES

This proposal describes the rationale and scientific objectives for non-riser drilling designed for decoding the earliest evolution of arc crust at the Izu-Bonin-Mariana (IBM) arc-trench system. It is based on achieving a full volcanic stratigraphy for the IBM forearc, which will then provide a basis for determining the petrogenetic evolution of the magmas that immediately post-date subduction initiation. This in turn will enable us to test hypotheses for the geodynamics of subduction initiation. This proposal is the product of discussion at four international workshops and incorporates feedback from two earlier SSEP reviews.

This proposal aims to study of the first products of the Subduction Factory, the crust produced when subduction begins. Crustal production rates at this time are much – perhaps an order of magnitude – greater than those estimated for mature arcs. The mode of crustal production during the initial stages of arc development appears to be the result of extension and seafloor spreading accompanying lithospheric collapse and asthenospheric upwelling (Stern 2004) and is quite different from focused magmatism that characterizes mature magmatic arcs. The early voluminous volcanism associated with subduction initiation is also responsible for many, perhaps most, ophiolites, themselves key indicators of Earth’s changing tectonics and ocean ridge magmatic, hydrothermal and tectonic processes. The IBM forearc is an excellent, probably the best, modern analogue for supra-subduction zone ophiolites and so is the ideal place to probe the structure of infant arc crust. It has already been studied by drilling, including at the highly successful DSDP Sites 458 and 459 in the Mariana forearc (e.g. Natland and Tarney 1981) and ODP Site 786 in the Izu-Bonin forearc (e.g. Pearce et al. 1992). However, these were drilled as relatively minor parts of drilling Legs: there has been no dedicated drilling Leg and hence there is no full lava stratigraphy of the detail needed to interpret subduction initiation and make the ophiolite link.

This proposal will mainly address the ISP theme of ‘Oceanic Crust and 21st Century Mohole’. It provides an opportunity to investigate oceanic crustal accretion following the initiation of subduction, the proposed setting of supra-subduction zone (SSZ) ophiolites, the most common ophiolite type (Pearce 2003). The origin of SSZ ophiolites is still debated, however. The original Miyashiro (1973) contention, that ophiolites orginated as the roots of island arc volcanoes, was contested in print but never tested. The subduction initiation/infant arc model provides a new site for seafloor spreading to produce a SSZ ophiolite, frozen in place to become forearc lithosphere, ready to be obducted when buoyant crust enters the trench. A complete ophiolite section is required to test the Miyashiro model. From the perspective of ridge crest processes, it provides the water-rich end-member not yet investigated by IODP. This is a particularly good place for IODP to realize the important ISP objective: "*the validity of the ophiolite model, will only be addressed by direct, in situ sampling of the lower oceanic crust and Moho by drilling. A high priority is to recover intact and tectonically undisrupted sections….*"

The IODP Initial Science Plan (ISP) identified the origin of continental crust as a primary target of the program: *'The creation and growth of continental crust remains one of the fundamental, unsolved problems in Earth science'*. It further emphasizes: *'Arc magmatism is thought to be a principal process in continental creation. Bulk continental crust is andesitic in composition, but the primary melt extracted from the upper mantle in subduction zones is basaltic. We still do not understand what causes this compositional change'.* As will be seen, the chosen sites provide a proven vertical observatory, where the early products of subduction-related crustal growth can be studied.

2. SETTING AND CHARACTERISTICS OF THE DRILL-SITE

The IBM system is the type locality for studying oceanic crustal accretion immediately following subduction initiation. It is sufficiently old that it carries a full record of the evolution of crustal accretion from the start of subduction to the start of normal arc volcanism – a c. 7Ma period – but sufficiently young that the key features have not been disturbed by subsequent erosion or deformation. Intra-oceanic arcs are built on oceanic crust and are sites of formation of juvenile continental crust (Rudnick, 1995; Tatsumi and Stern 2006). Most active intra-oceanic arcs are located in the Western Pacific. Among these, the Izu-Bonin-Mariana (IBM) system stands out as a natural scientific target. This predominantly submarine convergent plate boundary is the result of ~50 million years of subduction of the Pacific Plate beneath the eastern margin of the Philippine Sea Plate. Stretching for 2800 km from the Izu Peninsula, Japan, to Guam, USA (Fig. 1), the IBM system has been extensively surveyed and is a very suitable site for IODP expeditions to understand subduction initiation, arc evolution, and continental crust formation. A synopsis of our understanding of the IBM arc can be found in Stern et al. (2003). The scientific advantages of IBM were recognized by the US-NSF MARGINS-Subduction Factory experiment as the intra-oceanic arc focus site (the other focus site being the quasi-continental arc of Central America).

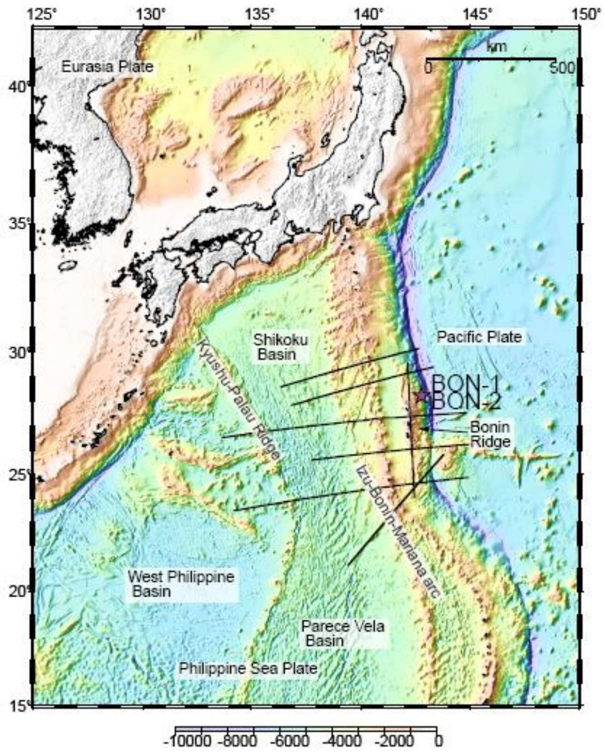


Fig. 1. Map of the Izu-Bonin-Mariana (IBM) system showing the locations of proposed drill sites BON-1 and BON-2 and of seismic lines relevant to the understanding of crustal structure at and around these sites. Crossing lines are planned for 2013.

Further rationale for the choice of the IBM system as an ideal location for studying crustal growth is discussed in related IBM proposals (#695, #697, #698). Most importantly for this proposal, the IBM forearc is likely the best site on the planet for studying the initial magmatic products of a subduction zone. We know when subduction and arc construction began (c. 51 Ma), even if the precise paleogeography is controversial, and there is a good time-space record of crustal accretion.

2.1 Petrologic evolution

The petrologic evolution of early stage magmatism in the IBM arc has been reconstructed mainly based on volcanic sections exposed on the forearc islands (Bonin Islands, Mariana Islands) and recovered from DSDP and ODP forearc drillsites. Recent dredging and submersible studies provide additional information (described in the Site Survey Section). In consequence, we can predict the sequence of magmas that characterize the drill site and its surrounding region and which developed prior to establishment of a stable magmatic arc ~150 km west of the trench by Oligocene time. This compositional evolution reflects the reorganization of mantle convective and slab-derived fluid flows in response to the changing behavior of the sinking Pacific plate, from sinking without down-dip motion to establishment of true subduction with down-dip motion (see the Tectonic Evolution Section). This evolution, from initial seafloor spreading and eruption of MORB-like tholeiites to eruption of boninites to fixing the magmatic arc ~150 km west of the trench, separated by a broad, dead forearc took ~7 million years. It is reflected in the succession of igneous rocks of the Bonin Ridge, which is described in greater detail below and depicted in the time-space diagram (Fig. 2).

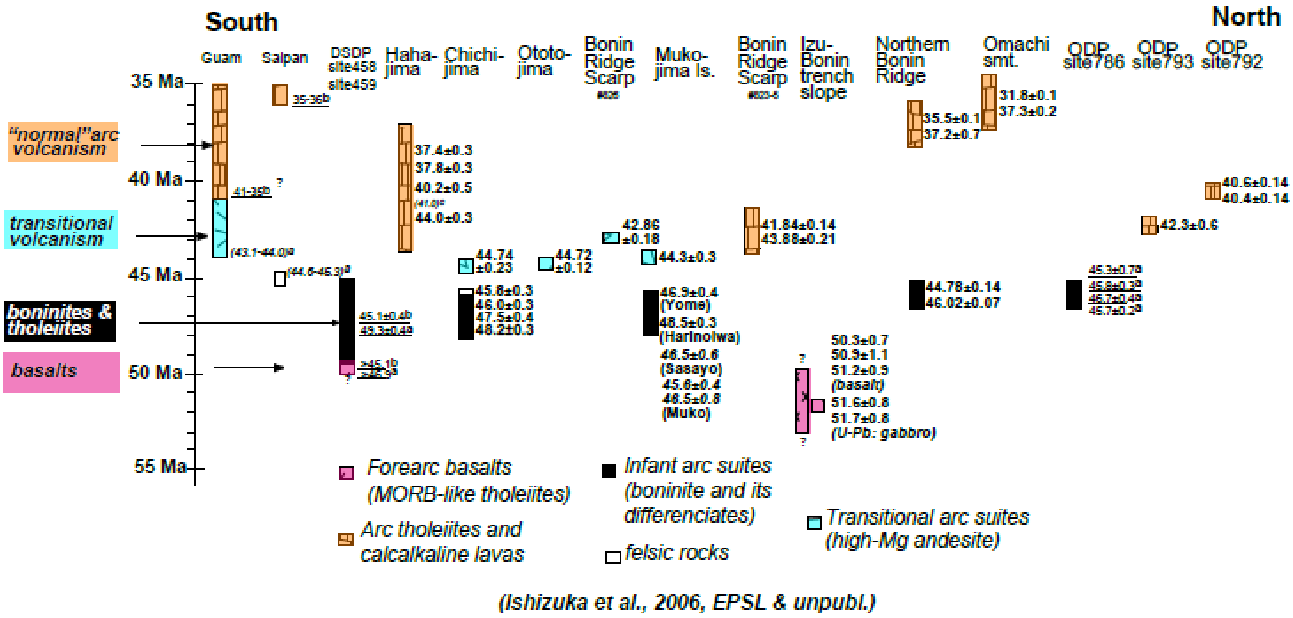


Fig. 2. Time-space variation in volcanic activity in the IBM system from subduction initiation at about 52Ma through to normal arc volcanism starting at about 45Ma. This proposed expedition focuses to the detailed stratigraphy of the 7Ma period between these events.

Subduction Initiation volcanism

Basaltic rocks have been recovered in the IBM forearc from stratigraphic levels below boninite as is described in the Site Survey section. These basalts have chemical compositions that are similar to N-MORB and the term "Fore-arc basalt" (FAB) has been coined by Reagan et al. (2010) to distinguish them from MORB. Most of the reliable $^{40}Ar/^{39}Ar$ ages of FAB from the submarine Bonin Ridge are identical within error and indicate that FAB magmatism occurred ~50- 52 Ma, preceeding boninite eruption by 2-3 m.y. (Ishizuka et al., 2009). U-Pb zircon ages from gabbros below the FAB indicate that these are contemporaneous (Ishizuka et al., 2011) and probably comagmatic. Lavas with compositions transitional between FAB and boninites from DSDP Site 458 were dated at 49 Ma (Cosca et al., 1998). FAB and related gabbro are the first magmas produced as the IBM subduction zone began to form.

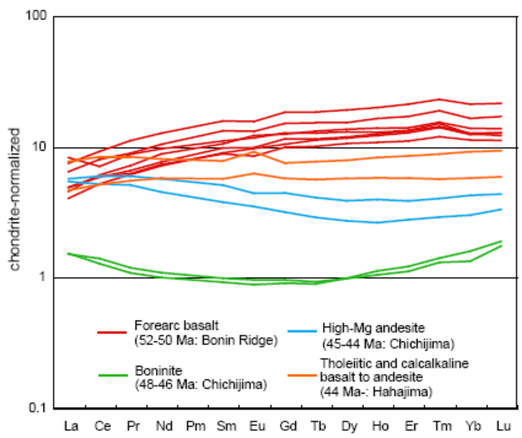


Fig. 3. Variations in rare earth element patterns in the Bonin forearc following subduction initiation. Note the recently-discovered MORB-like patterns of the first volcanic products, the Fore-arc Basalts (FAB), and the contrast with the later U-shaped boninite patterns. The proposed expedition will obtain the full information on gradations within and between these units. Ddata sources as in Fig. 2.

Geochemical data show the similarity of these basalts to MORB, with no or minor slab signature. FAB have LREE-depleted REE patterns, indicating derivation from a moderately-depleted lherzolitic upper mantle, similar to that responsible for generating MORB (Fig. 3). FAB have lower Ti/V (14-16), which distinguishes them from subducting Pacific MORB (26-32) and Philippine Sea MORB (17-25) (Fig. 4). Chemically and petrographically, Bonin Ridge FAB are indistinguishable from Mariana FAB, which are also considered to be related to subduction initiation and also predate boninitic volcanism in that region (Reagan et al., 2010; Ishizuka et al., 2011). This strongly implies that FAB tholeiitic magmatism was associated with fore-arc spreading along the length of the Izu-Bonin-Mariana arc. Like the overlying boninites, the likely source of Mariana FAB was an Indian Ocean-type mantle. Low concentrations of incompatible elements and low trace element ratios such as Nb/Yb imply that FAB magmas were derived from depleted mantle and/or were larger degree mantle melts compared to typical Philippine Sea MORB.

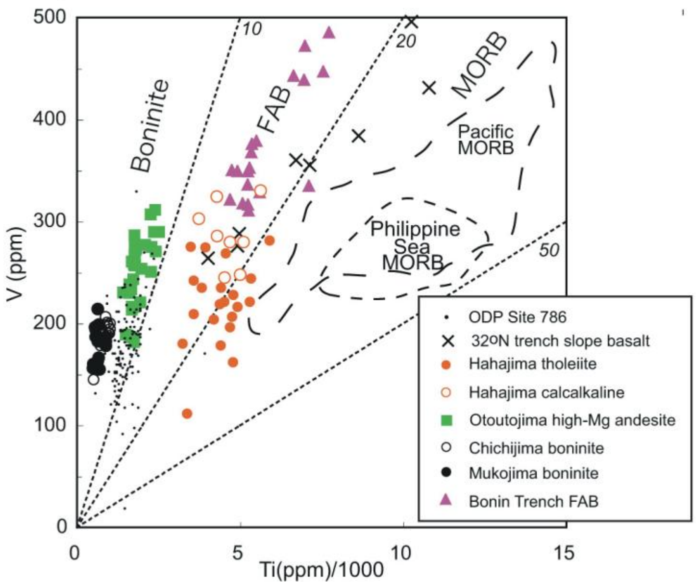


Fig. 4. V-Ti systematics (Shervais, 1982) for the lavas erupted following subduction initiation. Note that the earliest lavas to erupt following subduction initiation (the FAB) are distinct from MORB and from later boninites. These are, however, isolated outcrops: the expedition will provide the full stratigraphy.. Data sources as in Fig. 2.

Pb isotopic compositions of FAB show that, like other IBM magmas they are derived from a mantle with Indian Ocean characteristics, as shown by high Δ8/4 compared to Pacific MORB. Isotopic characteristics indicate some differences between the mantle sources of Philippine Sea MORB and FAB, including distinctly higher $^{87}Sr/^{86}Sr$ and $^{206}Pb/^{204}Pb$ (Fig. 5), which may imply the presence of lithospheric mantle with ancient enrichment (Parkinson et al., 1998). Most significantly, there is no evidence that subducted sediments (with elevated $^{207}Pb/^{204}Pb$) affected the source region of these basalts. Different isotopic as well as trace element characteristics between IBM FAB and Philippine Sea MORB strongly implies that the FAB do not represent the pre-existing ocean crust of West Philippine Basin, trapped prior to subduction initiation, as originally concluded by DeBari et al. (1999) for MORB-like tholeiites recovered from the Izu inner trench wall.

Lavas with compositions transitional between FAB and boninite were recovered at DSDP Leg 60 sites 458 and 459 (the alternate site). The oldest of these lavas have REE patterns like MORB, but are more enriched in silica, and have higher concentrations of “fluid-soluble” elements such as K, Rb, U and Pb than FAB. These lavas also have Pb isotopic compositions more like lavas from the Pacific than Indian plate, supporting the contention that subducted fluids were involved in their genesis. The youngest lavas at DSDP site 458 are strongly depleted in REE like boninites, but are less magnesian and more calcic.

Boninitic and High-Mg Andesitic volcanism

Boninite volcanism follows FAB volcanism as an integral part of the evolution of the nascent subduction zone. The type locality of boninite is in the Bonin Islands, an uplifted segment of the IBM forearc. Exposures of boninite and other early arc lavas are better exposed on the Bonin islands than anywhere else in the world, and this is the most important reason that these islands became a UNESCO World Heritage Site in 2011 < http://whc.unesco.org/en/list/1362 >. ^{40}Ar/^{39}Ar dating indicates that boninitic volcanism on Chichijima Island took place briefly during Eocene time, between 46-48 Ma (Ishizuka et al., 2011). A slightly younger volcanic succession is identified along the Bonin Ridge, including 44.74±0.23 Ma high-Mg andesite from the Mikazukiyama Formation, the youngest volcanic sequence on Chichijima, and 44.0±0.3 Ma tholeiitic to calc-alkaline andesite from Hahajima Island. Four submersible Shinkai 6500 dives on the Bonin Ridge Escarpment mapped an elongate constructional volcanic ridge atop the escarpment and recovered fresh andesitic clasts from debris flows along the northern segment of the ridge, and high-Mg andesite lava blocks from the escarpment northwest of Chichijima. Three samples of andesite collected from the Bonin Ridge Escarpment range in age from 41.84±0.14 to 43.88±0.21 Ma (Ishizuka et al., 2006).

Boninites from the Bonin Islands are characterized by high MgO at given SiO_2, low HFSE, low Sm/Zr, low REE and U-shaped REE pattern (Fig. 3). These are “low-Ca boninites” (Crawford et al. 1989) and can be explained by low pressure melting of a depleted harzburgite that was massively affected by a slab flux. These boninites are isotopically characterized by high Δ7/4Pb, ^{87}Sr/^{86}Sr, and low ^{143}Nd/^{144}Nd relative to local MORB and FAB sources (Fig. 5). In contrast to the FAB mantle source, which was not affected by subduction-related fluids or melts, the boninite magma source manifests a major contribution from subducted pelagic sediment. The boninites are also distinct from ~44 Ma lavas exposed on Hahajima Island and recovered by Shinkai 6500 diving on the Bonin Ridge Escarpment (Ishizuka et al., 2006). High-Mg andesites (HMA) from Chichijima and the Bonin Ridge Escarpment are similar to relatively enriched boninitic lavas from ODP site 786 and Guam, including having higher Sm/Zr at given Zr content, and higher REE and Ti concentrations compared to Chichijima boninites (cf. Taylor et al., 1994). The HMA are isotopically distinct from the boninites (Fig, 2) and were derived from a source mantle that was less affected by fluids or melts derived from subducted sediments.

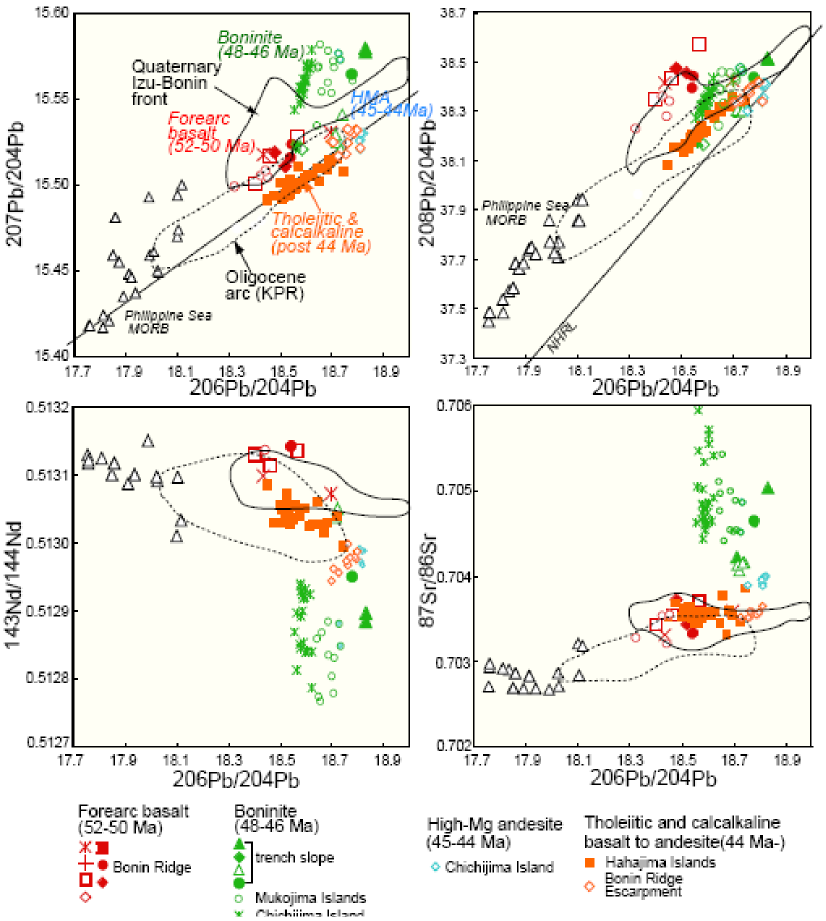


Fig. 5. Existing isotopic variations highlighting the complex variations in lava chemistry following subduction initiation. A complete stratigraphy will enable a better interpretation of these data in terms of variations in mantle sources and subduction components following subduction initiation. Data sources as in Fig. 2.

Post-45Ma, tholeiitic to calc-alkaline andesites from the Bonin Ridge and the c. 45Ma tholeiites from Saipan (Reagan et al., 2008) show strong characteristics of arc magmas: they are relatively depleted in Nb and enriched in fluid-mobile elements such as Sr, Ba, U, and Pb. These characteristics indicate that, by 45 Ma, near-normal configurations of mantle flow and melting, as well as subduction-related fluid formation and metasomatism, were established for this part of the IBM arc system. Bonin Ridge Escarpment - Mikazukiyama Formation–Hahajima andesites thus represent a transitional stage from the waning stages of forearc spreading (represented by forearc basalt and perhaps boninites) and the stable, mature arc that developed in late Eocene to early Oligocene time. These orthopyroxene-bearing high-Mg tholeiitic to calc-alkaline andesites were erupted along the Bonin Ridge Escarpment, as the arc magmatic axis localized and retreated from the trench.

Post 45 Ma andesites (and basalts), unlike Chichijima boninite and HMA, do not show the influence of pelagic sediment melt from the slab (Fig. 5); instead, the mantle source seems to have only been affected by hydrous fluid derived mainly from subducted altered oceanic crust. Post-44 Ma lavas are isotopically similar to the HMA (Fig, 5) and were derived from a source mantle that was less affected by fluids or melts derived from subducted sediments.

Overall, modeling of these data (not shown) indicate that the geochemical and isotopic characteristics of the IBM arc along its entire length evolved in tandem with the formation of a new subduction zone and a new mantle flow regime by: 1) initial decompression melting without significant slab flux producing MORB-like basalt and fore-arc spreading (49-52 Ma), 2) 48-45 Ma mixing of fluids or melts from subducted sediments into an extremely depleted (harzburgitic) mantle to generate boninites, 3) Post-45 Ma continued influx of hydrous fluid input into increasingly fertile lherzolitic mantle to generate tholeiitic and calc-alkaline magma (Ishizuka et al., 2006), marking when a mature, stable arc magmatic system was finally established (Ishizuka et al., 2011).

The observations above and the geochronological data summarized earlier imply that shallow melting of depleted mantle with the aid of hydrous fluids from newly subducted slab to produce boninitic volcanism took place nearly simultaneously along the entire length of the IBM arc system during the earliest stage of arc evolution. Casey and Dewey (2009) argued that continued spreading in what is now the West Philippine Basin requires that the infant arc was lengthening throughout Paleogene time, so subduction initiation may have started at different times along the IBM arc system. This is an important consideration for understanding how and when the entire IBM convergent plate margin formed but does not diminish the importance of understanding how a new subduction zone began along the Bonin Ridge. Note also that, although we have established a general volcanic stratigraphy, it is evident from Fig. 2 that this is composite, based on outcrops and small sections of drill core from a number of localities. There is no reference stratigraphic section to check this subduction initiation stratigraphy and, in particular, identify the nature of the boundaries between the Units and demonstrate that Units have not been missed. That is the aim of this proposal.

2.2 Tectonic evolution

It has been generally accepted (Bloomer et al. 1995; Pearce et al., 1999; Stern 2004; Hall et al., 2003) that the IBM subduction zone began as part of a hemispheric-scale foundering of old, dense lithosphere in the Western Pacific (Fig. 5). The beginning of large-scale lithospheric subsidence, not true subduction but its precursor, is constrained by the age of igneous basement of the IBM forearc to have begun in Eocene time, just before 50 Ma ago (Bloomer et al. 1995; Cosca et al. 1998; Ishizuka et al., 2006). The sequence of initial magmatic products is similar everywhere the forearc has been sampled, implying a dramatic episode of asthenospheric upwelling and melting, associated with arc magmatism and seafloor spreading over a zone that was hundreds of km broad and thousands of km long. It is clear from the extensive geochronology for IBM forearc rocks, that this episode took place ~45-50 Ma ago It is this part of the tectonic history of the IBM arc that the proposed drilling is intended to sample.

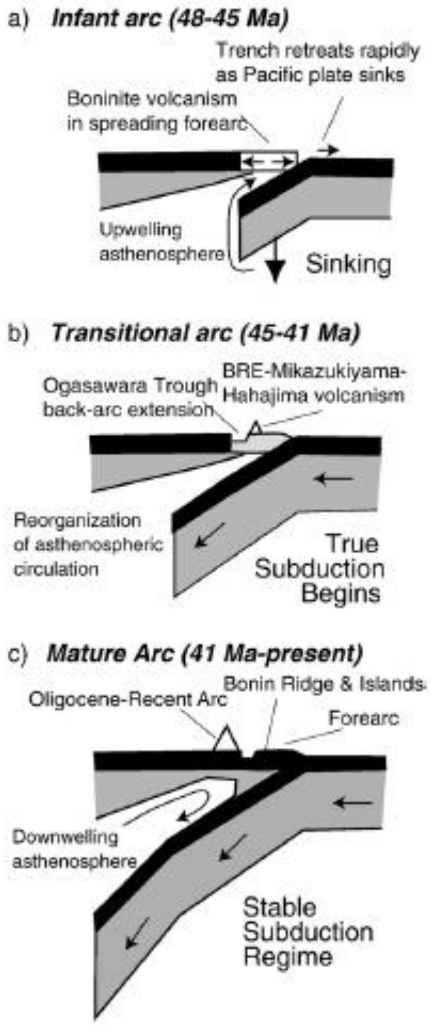


Fig. 6. Interpretation of the tectonic evolution of the Bonin Ridge by Ishizuka (2006) based on the concept of Stern and Bloomer (1992). According to this model, subduction initaition is followed by sinking of the slab with slab-parallel subduction and hence normal arc volcanism only beginning later. Later discoveries of Fore-arc Basalts (FAB) in the Bonin forearc have pushed the infant arc back to 52-45Ma, the period addressed by this drilling proposal in an attempt to test this model in detail.

Interestingly, these time-space trends in IBM fore-arc composition can be found in many ophiolite terranes. The world's largest ophiolite, the Semail ophiolite of Oman/UAE has long been know to exhibit a stratigraphy of FAB-type tholeiites overlain by depleted arc tholeiites (e.g. Alabaster et al., 1982) and recent discoveries of boninites in the upper part of the sequence (Ishikawa et al., 2002) confirm the full trend from tholeiite to boninites. Other large, complete ophiolites with complex forearc-type stratigraphies involving tholeiites and boninites include the Troodos Massif of Cyprus, the Pindos Mountains in Greece, and the Bay of Islands Ophiolite in Newfoundland, and there are numerous others distributed through most of the world's mountain belts (e.g., Pearce et al, 1984; Dilek and Flower, 2003) many with associated VMS and/or podiform chromite mineralization. In fact, inner trench wall dredging provides good analogues for the best preserved SSZ oceanic crust, but the complete lava section at BON-1 and BON-2 is needed to explain the transition from ocean crust to arc volcanism seen in many SSZ ophiolites.

The presence of boninites is in itself an important tectonic indicator, requiring a combination of shallow melting, high water content and depleted mantle. Boninites are defined by IUGC as having >52wt.% silica, <0.5wt.% TiO_2 and >8wt.%MgO. They can usefully be distinguished from basalts on a diagram of Ti8 v Si8 where Ti8 and Si8 refer to the oxide concentrations at 8wt.%MgO (Pearce and Robinson 2010). On this projection (Fig. 7), the earliest lavas may be seen to be basalts (the FAB) which plot in the MORB field. Later lavas (from about 48-42Ma) plot as boninites before compositions eventually become basaltic again with eruptions at, for example, Hahajima (H). This appears to be a characteristic of subduction initiation but to propely interpret its tectonic significance we need the full lava stratigraphy to know whether the basalt-boninite transition is gradational, episodic or has both magma sources available simultaneously. Drill core would also enhance the opportunity to obtain glasses which can be used for analyses of water and fluid-mobile elements.

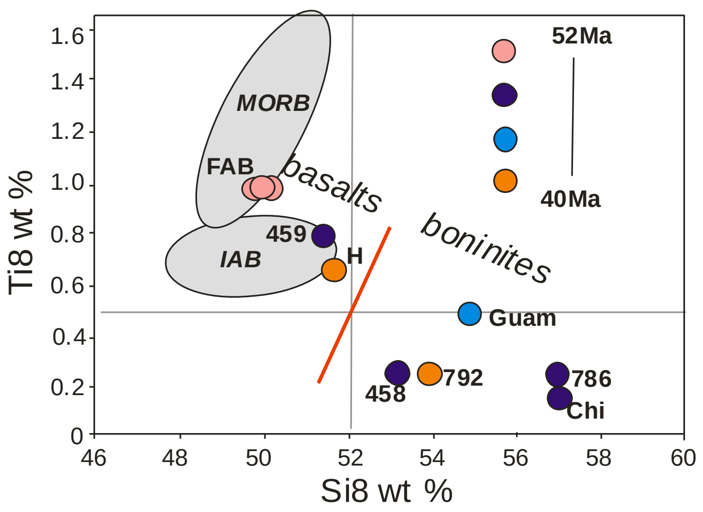


Fig. 7. Basaltic v boninitic character as a function of age of the lava following subduction initiation. Basalts (FAB) erupt first and at the end (Hahajia-H) but otherwise boninites dominate. Boninites are characteristic of subduction initiation and the full stratigraphy would enable their tectonic significance to be explained better. Colour code and labels are as in Fig. 2.

After a brief period of spreading, magmatic activity began to retreat from the trench, at the same time changing composition, perhaps first from FAB to boninite, then boninite to (locally) felsic and then calc-alkaline and tholeiitic arc magmas. Magma evolution was accompanied by migration of the magmatic locus away from the trench. Rare 40-43 Ma adakites were recovered from a Bonin forearc seamount. Eventually, perhaps some 10 million years after subduction initiation, the locus of magmatism reached the equivalent location of the present magmatic arc. This left vast tracts of infant arc crust 'stranded' to form the IBM forearc, so that it cooled and experienced only minor tectonic activity while the arc-basin system continued to evolve magmatically to its present crustal structure (Taylor 1992). Thus the forearc was 'frozen' in a primitive state and did not evolve into the more complex arc with tonalitic middle crust (targeted by proposal #698). Understanding the formation of forearc crust is clearly critical for understanding the formation of subduction zones (and the magmatic responses to this), growth of arcs, evolution of continental crust and ophiolite origins.

2.3 Structure and Thickness of Forearc Crust

The most detailed trench-orthogonal images of IBM forearc crustal structure in the region of interest come from a seismic refraction/reflection study by Kamimura et al. (2002). This survey was accomplished with two 130km-long, orthogonal arrays of OBSs (23 total OBS; 106x20kg chemical explosions and 1835 pulses from 2x17liter airguns were used as seismic sources) in a region ~150km north of the site we propose to drill (Fig. 4c). In Fig. 8, the approximate relative position of proposed drill-sites, BON 1 & 2 is projected onto the E-W line but it must be recognized that their crustal structure may be slightly different than that shown in Fig. 5. An equivalent geophysical survey for BON 1 & 2 will ideally be needed to evaluate crustal structure at the drill sites and is being planned.

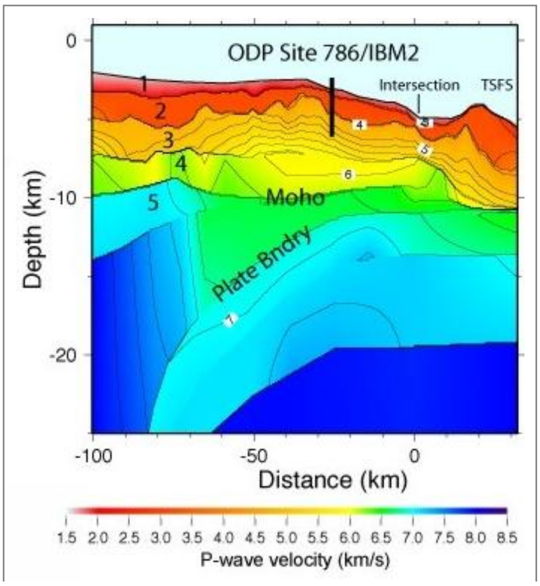


Fig. 8. P-wave velocity structure obtained by non-linear inversion along the E-W line of Kamamura, some 150km north of BON-1 and BON-2 Sites and an equivelent distance south of ODP Site 7686 (Fig. 1). BON-1 and BON-2 lie between Site 786 and the point marked 'intersection' if projected onto this section. The colors indicate seismic velocities in Km/s and the numerals 1-5 indicate seismic layers (1=sediments, 2=lavas and dykes, 3-4 = gabbro (?including tonalite), 5=perdiotite. Lavas +sheeted dykes at the longitude of BON-1 & 2 are up to 2km thick; hence we expect to drill a maximum of 1.5km of lavas to reach sheeted dykes.

With that caveat, we infer from the study of Kamimura et al. (2002) that the crust beneath the proposed drill-sites is 6-8 km thick – slightly thicker than normal oceanic crust. In detail, the crust beneath this part of the forearc can be divided into 5 identifiable layers (Fig. 5). The first layer (1.8-2.0 km/s) is mostly composed of thin sediments; this layer is actually very variable and both BON-1 and BON-2 are chosen to have c. 250m of sediment in order to facilitate the spudding-in of the drill and casing of the uppermost part of the holes. The second layer (V_P= 2.6-3.3 km/s) is 1-2 km thick and probably consists of fractured volcanic rocks and dikes; this contributes to our estimate of 1.25 ± 0.25 km as the likely lava thickness that we will need to drill in order to reach the sheeted dykes.

The third layer (4.3-6.1 km/sec) varies considerably in thickness, from 2 to 5 km. The velocities of the third layer correspond to those for the “tonalitic” layer in the arc farther west (Suyehiro et al., 1996), with which continuity may exist, but we hesitate to identify Layer 3 beneath the forearc as being part of the tonalitic layer without further information. The velocities of the fourth layer vary from 5.8 to 6.4 km/s, indicative of altered gabbroic rocks. The fifth layer, with a velocity of 7.0 km/s, thins and velocities decrease from west to east. This layer pinches out west of the proposed drill site. The sixth layer comprises the mantle wedge in the west and the plate boundary layer (PBL) in the east. The velocity of the mantle wedge is 8.0 km/s in the westernmost part of the survey and decreases in velocity towards the trench, with a velocity of ~6.8 km/sec immediately beneath the proposed drill-site. The velocity of 6.8 km/sec is not typical for the mantle, and is taken to indicate that the mantle beneath the proposed drill site is pervasively serpentinized.

The best evidence for trench-parallel variations in seismic structure come from a recent wide-angle seismic experiment, using densely deployed OBSs, along the Bonin forearc, at a longitude which is c. 20 - 30 km west of the proposed sites (see the N-S seismic line in Fig. 1 for location). Figure 9 shows the seismic velocity and reflectivity images of this profile (Kodaira et al., 2010). For ease of description, the model is divided into units A to E, mainly on the basis of seismic velocity, and laterally continuous reflectors aligned sub-parallel to isovelocity contours are partly used for defining the layer boundaries.

The structure in the northern half of the model is relevant to BON 1 & 2, which are located about 150km along the section. It is characterized by thin crust, of similar thickness to that imaged by Kamamura (Fig. 8). The total thickness of the units with crustal seismic velocity (<7.6 km/s; units A, B, and C) is less than ~10 km. In particular, the crustal units between Muko-jima and Chichi-jima (230–290 km on the profile) are remarkably thin (<7 km). Reflections from the base of unit C, which we interpret as Moho, in this part of the profile are not remarkably strong. Another characteristic structure in this part of the profile is layering of the uppermost mantle. The model of Figure 9 shows the average velocity of the 3-km-thick unit D to be 7.8 km/s. The top and bottom of this unit are not continuously imaged, but reflections from some parts of the boundary are clearly evident at several OBSs, for example reflectors at 15 km depth between 50 km and 150 km. Unit D and its reflectors are interpreted as structural discontinuities within the uppermost mantle, because the average velocity of unit D immediately above the reflectors (7.8 km/s) is too high for crustal material. The petrological significance of this layer could correspond to a pyroxene-rich region inferred to define the crust-mantle transition beneath some arcs (e.g., Tatsumi et al. 2008). Unit E, which is in the deepest part of the well-resolved area, has a velocity higher than 8 km/s, as expected for mantle peridotite.

The model also shows abrupt thickening of the crust units in the central part of the profile which can be attributed mainly to thickening of unit C (lower crust). The southern part of the profile is intermediate between those of the northern and central parts. It should be noted that the seismic structure modeled to the north of Chichi-jima is not fully consistent with a structure recently reported by Takahashi et al. (2009) that crosses the Bonin ridge. Kodaira et al. (2010) discussed that a possible explanation for this apparent inconsistency is that the tomographic modeling of the across arc-profile by Takahashi et al. (2009) did not resolve the abrupt eastward thinning of crust beneath the Bonin ridge.

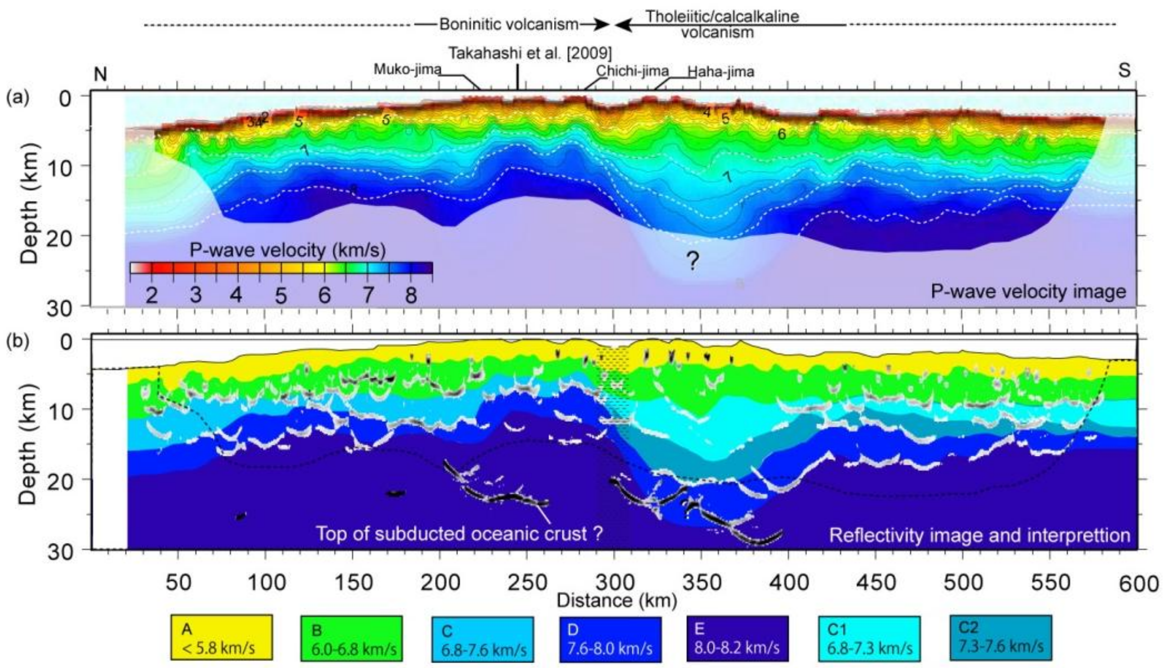


Figure 9 Trench-parallel fprearc seismic sections. (a) P-wave velocity image. The shaded area indicates the poorly resolved area identified by the checkerboard test. (b) Reflectivity image superimposed on a layered structure constructed from the velocity and reflectivity images. Unit A must consist of sediment, volcaniclastics and volcanic rocks (Kodaira et al., 2007); Unit B is likely to consist of felsic-to-intermediate plutonic rocks; Unit C is mafic plutonic rocks and amphibolites; Unit D may be pyroxenite; and Unit E is mantle peridotite. The wide-angle OBS profile is the near-NS profile in Fig 1. BON 1 & 2 are located about 150km along the section and c. 30km to the east.

3. CHOICE OF DRILL SITES

We considered several options for achieving the science objectives articulated in 696-Full2, following the criticisms of SSEP review 13 Nov. 2008 of our original proposal to deepen ODP site 786B in the Izu forearc to the north "…*it is imperative to find a site optimal for the aims of this specific study. The proposed IBM-2 site is complicated by the presence of a volcanic edifice, which results in an expanded and potentially locally variable stratigraphy that is probably not best suited to an efficient reconstruction of a representative history of the fore-arc or in providing a typical stratigraphy for comparison with ophiolites*." The SSEP review continued *"The newly added findings of the distinct FAB that predate boninites (BON) seem to provide a key, new scientific objective that should be studied in this proposal in connection with the early arc crust formation. For this purpose, drilling of several sites, on thick and thin crust, to address the importance of the FAB-BON (-and THOL) associations seems worth considering since along strike variation of the fore-arc in the inception stage of the arc crust is important. Thus the SSEP would like to see a comprehensive re-assessment of potential drilling location(s) in response to the evolving science of this proposal.*

We recommend considering one or two more possible site(s) suitable for this study from the area encircled in Figure 3a of the proposal. The site(s) for the deep drilling must be chosen and operated in the ideal site where the nature of fore-arc crust alone is well preserved. And justification of the site selection should be done for the purpose of the scientific objectives proposed."

We have set aside consideration of targeting 786B as a result of this criticism and undertook a group critical reassessment (during a meeting in Tokyo July 22, 2010 attended by Ishizuka, Kodaira, Pearce, Reagan, Stern, and Tamura) of three sites in the IBM forearc farther south: 1) the southern Mariana forearc SE of Guam; 2) the Mariana forearc along 18°N (DSDP 458 and 459); and 3) the Bonin forearc along c. 29°N. Only the latter site meets the recommendation of being "…*in the area encircled in figure 3B of the proposal*." We were not clear how important this consideration was, because no rationale for limiting site consideration to this was given, so we considered all three alternative sites equally.

All have their merits. The southern Mariana forearc option has the advantage of being the type locality for the work of Reagan et al. (2010), which defined Fore Arc Basalt (FAB) and demonstrated that it underlies boninite, at least at this locality (see also Reagan et al., 2007;

Ohara et al., 2006, 2008). We rejected this site because of a lack of crustal refraction studies and no prospect that such studies will be undertaken anytime in the foreseeable future. The Bonin forearc option has the advantage of being in the same region as the island of Chichijima (Bonin Island), the type locality for the key boninite rock type. It is part of a complete ophiolite section which has been sampled by dredging and diving. Unfortunately, a planned MCS survey was delayed because of the NE Japan tsunami of March 11, 2011 but is in the process of being rescheduled in 2013 for Shuichi Kodaira's group (JAMSTEC). The Mariana forearc at 18°N has the advantage of having been drilled by DSDP, so that there is already a scientific platform upon which to build. Geophysical surveys including MCS profiling, have been carried out by Chapp et al. (2008) and further surveying has just been completed by Dan Lizzaralde's group providing crossing lines at both sites. Both the Bonin and central Mariana forearcs are therefore good targets.

Two important hypotheses to be tested by drilling are: (1) subduction initiation produces a consistent volcanic stratigraphy: (from oldest to youngest) fore-arc basalt (FAB), transitional lavas, low-Ca boninites, enriched high-Mg andesites & related rocks, and normal are volcanic rocks (Reagan et al., 2010); and (2) this sequence was originally stacked vertically before erosion and therefore represents an in-situ ophiolite. Choosing between the two drilling targets therefore focused on where the most complete volcanic stratigraphic section could be sampled. We discussed the pros and cons of these two locales and chose the Bonin locale as the primary targets and the central Marianas for contingency. We were especially attracted by the fact that Shinkai 6500 diving during 2009 has identified the sheeted dike-FAB contact in the inner wall of the Bonin trench, at a location where the drill can spud into an overlying sediment pond and sample the lower part of the forearc volcanic succession; we do not know the position of this contact in the Mariana forearc at 18°N. We debated whether DSDP sites 458, 459, or the Bonin forearc are the best places to start drilling through the contact of boninites overlying FAB, and two considerations lead us to also prefer the Bonin forearc site: 1) low-Ca boninites are found there, whereas only high-Ca boninites are found overlying DSDP 458; and 2) most of the boninite-FAB transition zone has already been sampled at DSDP 458 and 459. Note, however, that DSDP site 459 offers the opportunity to continue sampling this transition into true FAB and on into related intrusive rocks.

Note that it could be argued that on-land drilling on the Bonin islands west of the proposed drill sites present an alternative strategy. Such a proposal is likely to be opposed by environmental groups because the islands are now protected as a UNESCO World Heritage site. There is also no guarantee that island drilling would penetrate the oldest products of subduction initiation that are known to exist to the east at BON-1. Moreover, the Bonin Island basement is likely to have been modified by later arc magmas, the main criticism of the original 696-FULL(2) proposal. Thus BON-1 and BON-2 are best located to test ophiolite models. DSDP 459 provides a site survey-ready alternate site of near-comparable scientific significance.

4. SCIENTIFIC OBJECTIVES AND TESTABLE HYPOTHESES

Drilling the volcanic section in the Bonin forearc has a number of objectives, all linked to understanding the magmatic response to formation of a new subduction initiation (SI): a) to understand the composition of SI magmas, b) specifically to test the hypothesis that Fore-arc basalts are erupted first, followed by more arc-like lavas, including boninite. These results will be used to c) understand how mantle circulation and melting evolves during SI, from early decompression melting of fertile asthenosphere (FAB formation) to late melting due to hydrous fluxing of depleted mantle (boninite formation). Drilling results will also be used to d) test the hypothesis that forearc lithosphere created during subduction initiation is the birthplace of supra-subduction zone ophiolites. These objectives have been modified somewhat from those articulated in 696-Full2 but remain focused on understanding forearc crustal structure, SI magmatic evolution and how this can be recognized in ophiolites. This work will allow the geoscientific community to exploit these breakthroughs in understanding SI. These objectives are discussed further below.

Objective 1: To obtain a high-fidelity record of magmatic evolution during subduction initiation by coring volcanic rocks down to underlying intrusive rocks, including radiometric and biostratigraphic ages.

Recent advances in studying the IBM forearc document that these volcanic sections show important vertical compositional variations. We know that the IBM forearc exposes rocks that formed when this subduction zone began ~52 Ma (Stern and Bloomer, 1992; Ishizuka et al., 2011). Reagan et al. (2010) built on this understanding to document that the volcanic succession exposed in the inner trench wall of the southernmost Mariana forearc comprises a volcanic succession that changes from MORB-like tholeiites at the base (FAB) to increasingly arc-like basalts and boninites near the top. Reagan et al. (2010) inferred that the 450-700m sections cored at DSDP sites 458 and 459 in the Mariana forearc sampled the transition between the FAB and BON successions. Similar successions are common in ophiolites, which are increasingly recognized as fossil forearcs (Stern et al., in press; see below). The significance of this simple succession has not been heretofore appreciated because of a lack of direct information on forearc volcanic stratigraphy, mainly because this was not a priority for dredging and diving. The results of Reagan et al. (2010) provide the first reconstruction of this stratigraphy, and motivated dredging and diving in the Bonin forearc to see if a similar magmatic stratigraphy was present there. As discussed in the Section on Petrologic Evolution, and Ishizuka et al. (2011), these results support the conclusions of Reagan et al. (2010). Drilling and coring this volcanic succession will provide a crucial test of this hypothesis, by providing a more-continuous section of these lavas and intrusives. It is also important to further constrain the rates at which the forearc magmatic succession was emplaced. This sequence seems to take ~7 m.y. to form during SI; after which magmatic activity retreats ~200km to the ultimate position of the arc magmatic front. Recovered cores should provide more material for U-Pb zircon, $^{40}Ar/^{39}Ar$, and biostratigraphic age determinations.

Objective 2: Use the results of Objective 1 to test the hypothesis that "Fore-arc basalts" (FAB) tholeiites lie beneath boninites, and (Objective 3) to understand chemical gradients within these units and across their transitions.

We expect to find a thick section of FAB at the base of the Bonin forearc volcanic succession, and a thinner sequence of arc-like and boninitic lavas at the top. To understand the significance of these vertical variations, we need to know how the transition from one magma type to the next occurs: is it a step-function or is there a slow transition from one magma type to the next? If it is a transition, is it continuous, gradual, and progressive, or is the transition accomplished by alternations of one magma type with another? Within the main FAB sequence, is there any evidence that the subduction component increases with stratigraphic height and thus time? Similarly, does the boninite section change in any systematic way up-section, for example from High-Ca boninite at the base to Low-Ca boninite near the top? The nature of these transitions and variations provide important constraints for how mantle and subducted sources and processes changed with time as SI progresses.

Objective 4: Use drilling results to understand how mantle melting processes evolve during subduction initiation. Assuming that we are able to accomplish Objectives 1 and 2, we will use these results to better understand the mantle responds to subduction initiation, with an emphasis on quantitative petrologic and geodynamic modeling. For example, a thick basal FAB succession indicates that adiabatic decompression is the most important process at the very beginning of SI in IBM, whereas an upper section of boninites indicates flux melting was important just before SI transitioned into normal arc magmatism. Whatever information is obtained from the cores will be used to construct more realistic geodynamic and petrologic models for IBM SI by engaging experts in these fields.

Objective 5: To test the hypothesis that forearc lithosphere created during subduction initiation is the birthplace of supra-subduction zone ophiolites. Much has rightly been made of the highly successful efforts of IODP and its precursors in establishing the architecture and crustal accretion processes associated with mid-ocean ridges of varying spreading rates and linking these to ophiolites. As discussed earlier, it now appears that most ophiolites form when subduction begins and are preserved as forearc crust until these are obducted. One testable hypothesis is that ophiolites that formed during SI can be recognized by a volcanic stratigraphy that varies from MORB-like at the base to arc-like or boninitic near the top, similar to the sequence that we expect to recover from the IBM forearc. Most ophiolites are not well-enough preserved or studied to infer volcanic chemostratigraphies, but some are (Mesozoic Pindos, Mirdita, Semail, and Troodos; also Ordovician ophiolites of NE Appalachians). The first three of these show volcanic stratigraphies that are similar to the IBM forearc. Results from Bonin forearc drilling will allow us to prepare a more detailed volcanic chemostratigraphy expected for SI, which will allow more detailed comparisons with these ophiolites and encourage geoscientists to try to reconstruct the magmatic stratigraphies of other ophiolites.

The PEP comment on Proposal 696 FULL-3 was that we did not address an external reviewer's comment that the above does not make it clear 'how the objectives relate to testable hypotheses'. We thought we had done this but to, re-emphasise the point, *the IBM forearc carries much the best record at present for the processes that take place during and following the initiation of an intra-oceanic subduction zone. This community goal is highlighted in Challenge 11 of the 2013-2023 IODP science plan: How do subduction zones initiate, cycle volatiles, and generate continental crust? The problem is that limited exposure means that this record is incomplete and so our principal objectives are to use the drilled lava stratigraphy to complete the record and so understand how crustal accretion and magma genesis evolved during this period. This is a grand hypothesis of considerable importance to* *geologists and petrologists working on land that most of the world's biggest and best exposed ophiolites formed in this setting, but this cannot be tested fully without a complete Western Pacific lava stratigraphic record. By achieving our objectives, we can assess the extent to which ophiolite accretion and magma genesis evolved in a similar way to our type example of subduction initiation and so test the subduction initiation model for ophiolite complexes.*

5. SITE SURVEYS

The Bonin Ridge is an unusually prominent fore-arc massif in the Izu-Bonin arc that exposes early arc volcanic rocks on Chichijima, Hahajima, and smaller islands. These outcrops represent the best preserved and exposed sequence of igneous rocks associated with subduction initiation on Earth. However, only part of the subduction-initiation igneous record is preserved on the islands. Submarine parts of the IBM forearc (of which this ridge is part) contain a more complete record of subduction initiation but by necessity, these parts have only been investigated by ocean drilling (e.g. DSDP Leg 60: Natland and Tarney, 1981; ODP leg 125 Arculus et al, 1992; Pearce et al., 1992), dredging (Bloomer, 1983; Ishizuka et al., 2011), and diving (Ishizuka et al., 2006; Reagan et al., 2010). The Bonin Ridge itself has not been drilled but has been investigated by dredging and manned submersible diving.

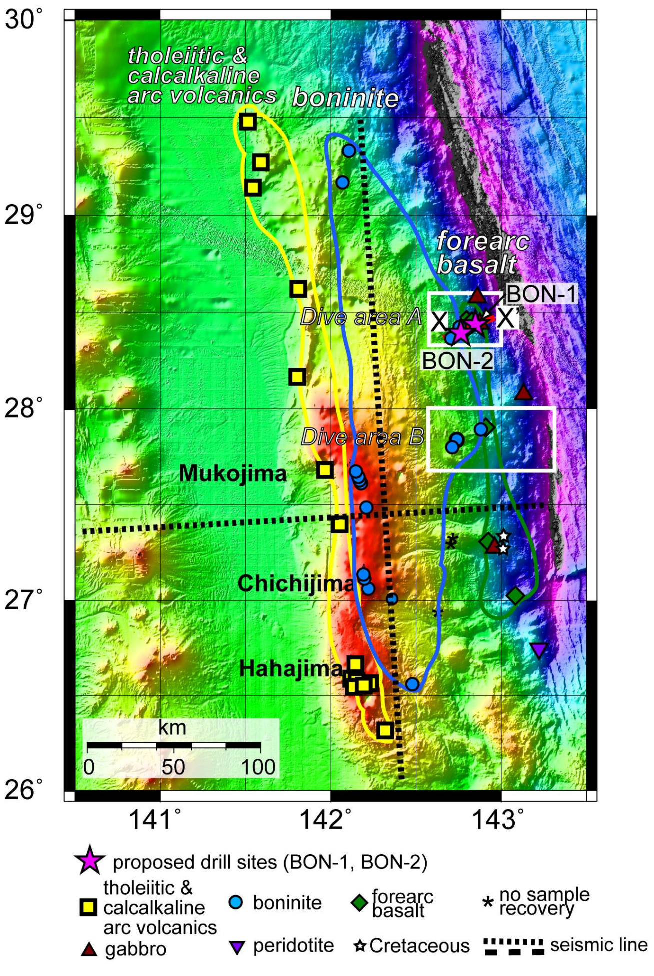


Fig. 10 Rock types recovered from dredging and diving expeditions to the Bonin forearc, showing an ophiolitic structure to the forearc. Proposed drill sites BON-1 and BON-2 are shown. Boxes depict the areas chosen for more detailed site survey dives (see next Figure).

Fig. 10 summarizes the distribution of rocks sampled in three expeditions: YK 04-05, the first manned submersible (SHINKAI 6500) diving survey of the western escarpment of the Bonin Ridge (Ishizuka et al., 2006); R/V Hakuho-maru

KH07-2, which dredged 19 stations along the length of Bonin Ridge; and YK09-06, which included four dives in the proposed BON-1 and BON-2 area. They show, in particular that:

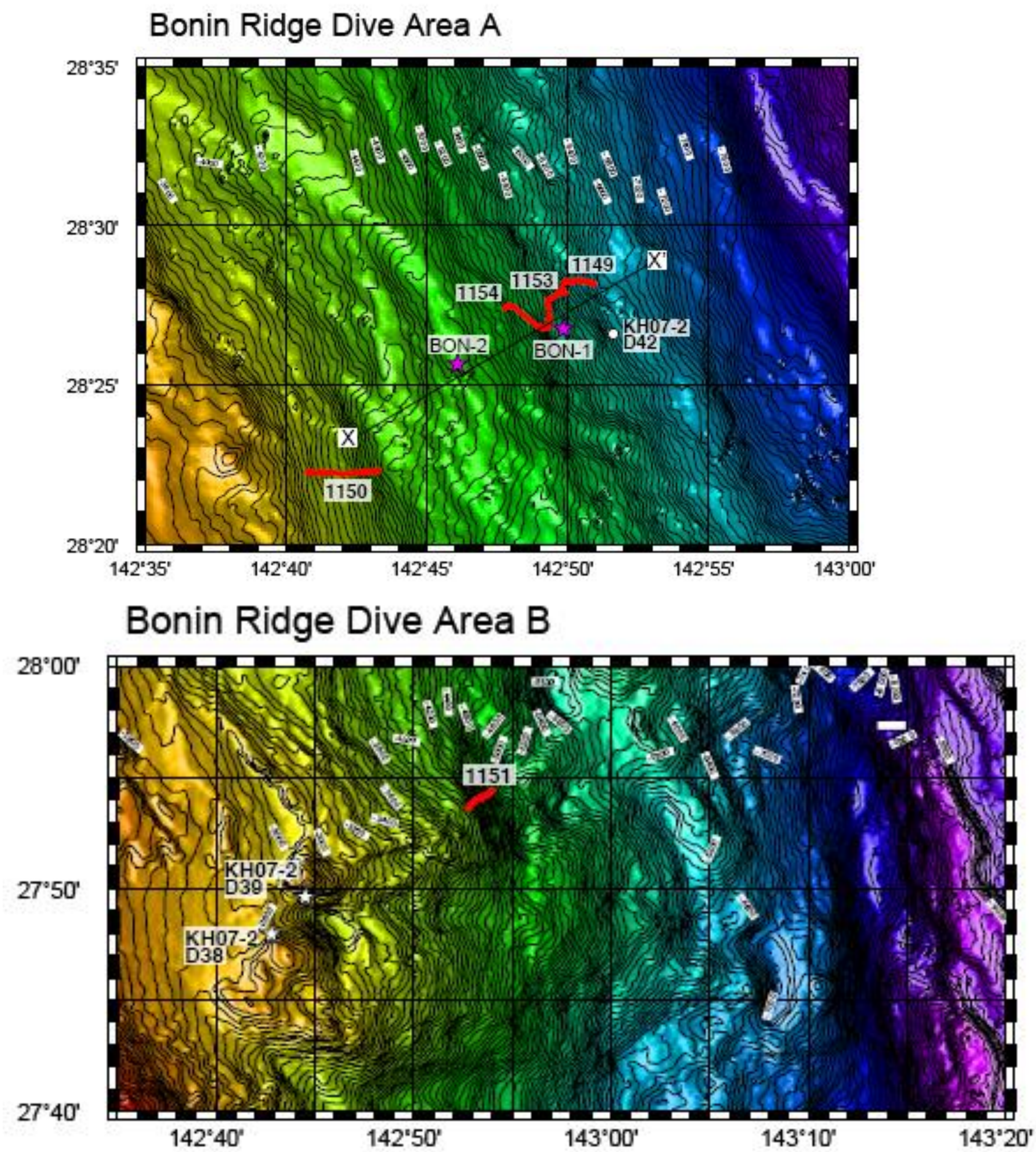
1. Overall there is an ophiolite-like sequence in the inner trench wall of lavas, dykes, gabbros and peridotites.

2. Of the lavas and dykes, MORB-like tholeiites occupy the deepest part of the trench-side slope of the Ridge, i.e., easternmost part of the ridge. These are chemically indistinguishable from FAB as defined by Reagan et al. (2010).

3. Boninites crop out to the west and upslope of the FAB/MORB outcrops.

4. Younger tholeiitic~calc-alkaline basalt to rhyolite outcrops occupy the westernmost part of the Bonin Ridge, and are especially well-exposed on the western escarpment.

Fig. 11. Results of diving site survey cruises to the Bonin forearc (Miyajima, 2009). The chosen sites, BON-1 and BON-2 are in Dive Area A. Other numbers refer to sample sites.



5. This spatial distribution of rock types is also found around 32°N, where boninitic rocks were drilled at site 786 and MORB-like basalts were recovered near the trench by Shinkai 6500, although these originally were interpreted as trapped crust of the Philippine Sea plate (DeBari et al., 1999). However, the Bonin section provides the better drilling location, having a simpler structure and more detailed sampling.

BON-1 and BON-2: Based on the dredging results described above, we carried out, in 2009, a diving survey using submersible Shinkai 6500 to examine and better establish the igneous forearc stratigraphy exposed on trench-side slope of the Bonin Ridge (YK09-06 cruise: May 24-June 10, 2009; Ishizuka et al., 2011). Two dive areas were located near the proposed drill sites, shown as boxes in Fig. 10 and in more detail in Fig. 11. In the northernmost survey area (Area A) near 28°25'N, 4 dives (Dive 1149, 1150, 1153, 1154) looked at the lower to upper crustal section formed in the earliest stage of oceanic island arc formation. The deepest dive (1149) sampled gabbro and basalt/dolerite, and appears to have traversed the boundary between the two units. The lower slope traversed during 1149 is composed of fractured gabbro (Fig. 5A), whereas pillow lava was observed in the uppermost part of this dive at c. 6000m deep (Fig. 5C). Dives 1153 and 1154 surveyed up-slope of D1149 (Fig. 4, top). These two dives found outcrops of numerous diabasic dykes and fractured basaltic lava cut by dykes between water depths of 6000 and 5500m (Fig. 5B). The shallowest dive (1150) recovered volcanic breccia and conglomerate with boninitic and basaltic clasts (Fig. 5D). The boundary between boninite and basalt is estimated to lie c. 4800 m deep, because no basalt was recovered shallower than this.

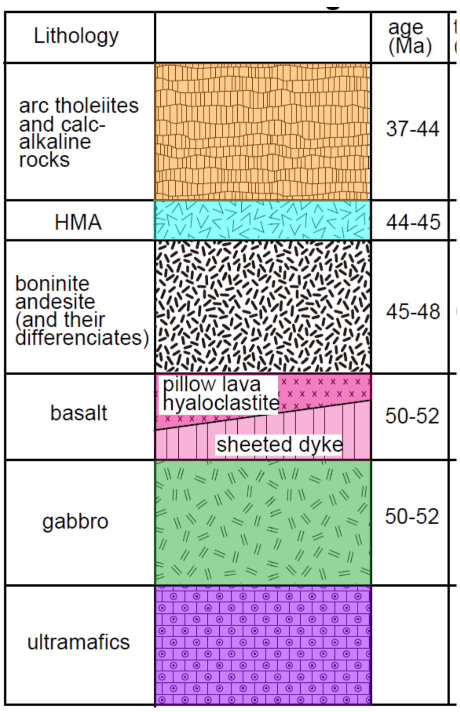


Fig. 12. Schematic section (not to scale) of the Bonin Ridge drill-site area

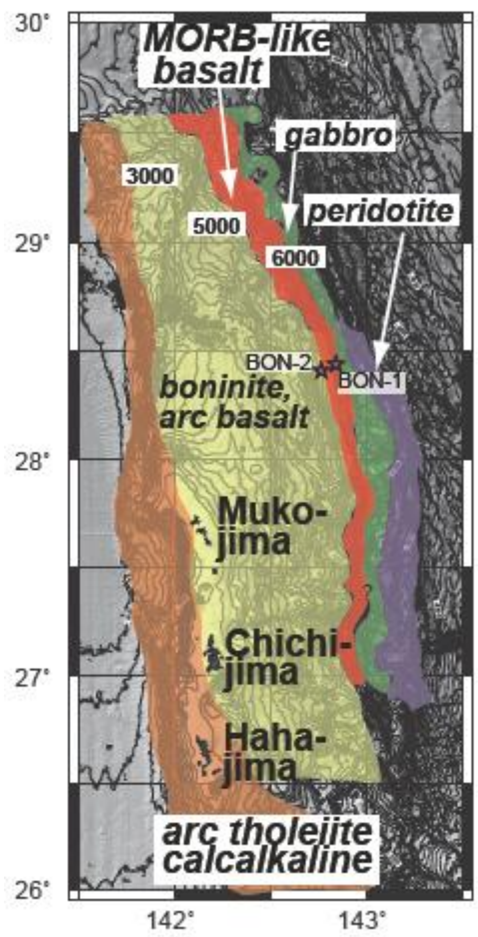
In area B near 27°54'N, the lower slope of a small knoll (probably a boninitic edifice) was surveyed by Dive 1151 (4760-4300m) with a goal of observing the transition between the lower FAB/MORB basalts and the overlying boninitic section. This slope was covered with blocks of volcanic breccia containing both boninitic and basaltic clasts. The expected transition of basaltic and boninitic magmatism might exist somewhere between 5500 and 4760m, or it may be covered with the observed volcaniclastics.

Combined with results from other dives and dredging, a relatively simple forearc crustal igneous stratigraphy can be envisaged (Figs. 12 and 13), The section from bottom to top consists of: 1) mantle peridotite; 2) gabbroic rocks; 3) a sheeted dyke complex; 4) basaltic lava flows (FAB); 4) volcanic breccia and conglomerate with boninitic and basaltic clasts; and 5) boninite and tholeiitic andesite lava flows and dykes. The uppermost part of this section is exposed in the Bonin Islands. These observations indicate that almost all of the forearc crust down to and deeper than the Moho is preserved and exposed in the inner trench wall of the Bonin Ridge.

The principal PEP criticism of 696-FULL3 was the lack of any MCS crossing lines at the BON-1 and BON-2 sites, especially as the proposal stated that the MCS site survey was to have been completed in 2011. In fact, this would have been accomplished as promised but for the NE Japan tsunami of 11th March 2011, which (as noted earlier) caused the cruise program to be suspended and created a cruise backlog. PEP stated in its comments that the proposal should be resubmitted only when the site surveys had been completed. This would be no problem but for the fact that this would cause the proposal to miss the JOIDES Resolution Western Pacific 'window'. Following discussions, it was agreed that we should resubmit anyway with an update of the site survey plans.

The present situation is that a site survey cruise for shooting two crossing MCS lines at the BON-1 and BON-2 sites in 2013 was unanimously endorsed in principle at a JAMSTEC meeting on 29th March 2012. The scheduling meeting will take place in late May at which time it will be possible to inform PEP of the precise FY2013 ship time schedule. We note that, being an igneous sequence, there are no safety issues and the other MCS lines from the region do not show any clear subsurface geology within the proposed drilling depths other than the base of the sediment - so the main use will be the precise determination of sediment thickness, which is, of course, extremely important, even if MCS is an expensive way to obtain it .

Fig. 13 (next page). Simplified regional geological map of the drill-site area showing the location of proposed sites BON-1 and BON-2.



6. DRILLING STRATEGY

As noted above, we plan to achieve our goal of sampling the full volcanic stratigraphy by drilling two offset holes (BON-1 and BON-2), each in the order of 750m of lava overlain by c.250m of sediment (Fig. 14). The precise location of the holes was constrained by the presence of sediment ponds. BON-1 is designed to first encounter FABs and reach the sheeted dykes, so drilling the oldest rocks in the sequence. BON-2 will start in boninites and finish in FABs, so completing the sequence. We expect this to enable us to obtain a full section in a single expedition, something that could not be guaranteed with a single 1750m hole. In the unlikely event of either of these being unsuccessful we have identified a contingency hole at DSDP Site 458 459 in the Mariana forearc.

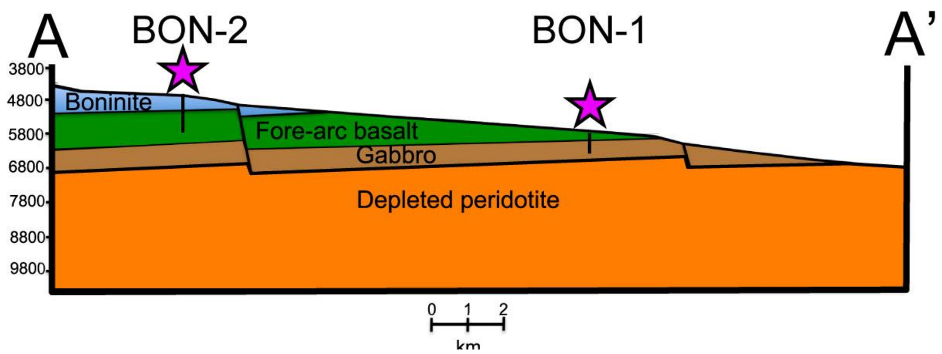


Fig. 14. Schematic cross-section showing the location of offset holes BON-1 and BON-2. BON-1 will drill FAB lavas into sheeted dykes to record the first magmatic products of subduction initiation; BON-2 will drill from boninites into sheeted dykes to record the transition from subduction initiation magmatism to normal arc magmatism.

Previous experience indicates that engineering considerations in IBM forearc sites are likely to be favourable (Fig. 15). Drilling at DSDP Site 459 penetrated sediments then basalts similar to those expected in BON-1 at a rate of c. 700mbsf in about six days. Drilling at DSDP Site 458 achieved similar penetration rates down to c. 450mbsf. Drilling at ODP Site 786B, which penetrated sediments then boninites similar to those expected in the upper part of

BON-2, drilled to >800 mbsf with a single drill bit in 11 days. This was a particularly stable hole, probably because fluid circulation filled veins and healed fractures This experience leads us to conclude that drilling without a riser will not have drilling, safety, or environmental problems.

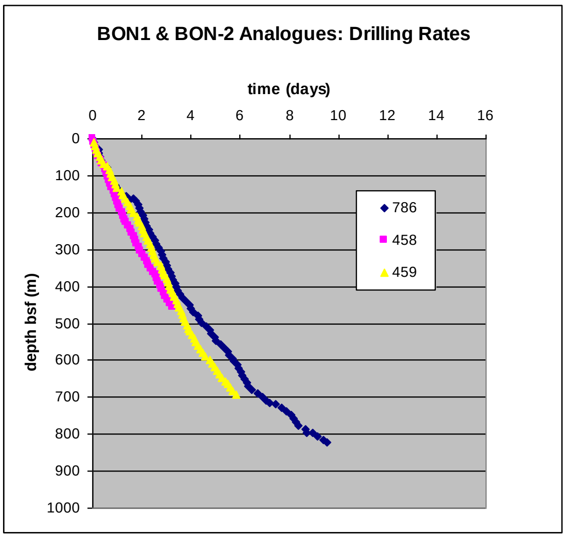


Fig. 15. Drilling record for forearc Sites 786 (Izu-Bonin forearc) and 458 & 459 (Mariana forearc), as a means of estimating drilling rates for BON-1 and BON-2 which have similar lithologies.

The temperature at the bottoms of the holes should not be a problem: the temperature gradients in outer forearcs are the lowest on the planet. Temperature measurements down to 110 mbsf at ODP Leg 125 Site 792 (about halfway between the trench and the magmatic arc) define a heat flow of 56 mW/m^2, which gives a thermal gradient of 34^o/km for the thermal conductivity of the basement rocks. The thermal gradient further from the arc at BON-1 and BON-2 should be significantly lower, indicating that the temperature at the bottom of a 1000m-deep drill hole should be <50°C.

In detail, the rate of penetration in 786B indicates that the formation hardness changes at 400m and 690m (46.3m/day average). This is equivalent to 1.92m/hr compared to a typical average of 1.8m/h, the faster penetration perhaps due to the better cementation of rocks resulting from a long history of fluid circulation. Extrapolation of the penetration curve gives a estimated drilling time for 1000m hole of 14-15d for linear extrapolation and 16-20d for the more likely non-linear extrapolation. Of course, unexpected issues such as bit failure or hole problems could slow progress.

The scientific goals of this proposal are best achieved by obtaining a full lava stratigraphy. Moreover, for purposes of testing hypotheses and economic constraints, we need to be able to achieve this in a single c. 56 day expedition. Ophiolite studies coupled with the seismic studies reported here show that the lava thickness is likely to be 1.25± 0.25 km, probably beyond that likely to be achieved in single expedition, especially if casing in needed for hole stability and to provide a legacy hole. For these reasons, we choose instead to use the offset drilling approach, drilling BON-1 and BON-2. Each hole will still need casing in at least its uppermost 300m to ensure hole stability. Assigning 40 days for drilling allows for transit (Guam, Japan), casing and logging in a single Expedition.

We aim to run the standard set of wireline logs for crustal sections. Formation microscanner and borehole televiewer are essential for understanding the history of fracturing of, and hence fluid flow in, the forearc crust. These are necessary for preparing a complete lithostratigraphic log in the inevitable event of incomplete core recovery. Physical properties tools are needed for synthetic seismograms and ground-truthing seismic images.

The main risk in scientific terms would be a failure to penetrate the oldest volcanic rocks, at the lava-sheeted dyke boundary. To reduce this, we aim to drill BON-1 first and, if necessary, drill deeper than planned to achieve our objective. Less time would then be spent at BON-2 and any gap in the lava stratigraphy would be filled in by reference to Site 459 in the Mariana forearc. We do not, however, believe that the risk is high.

7. ALTERNATE SITE

It is evident from Fig. 15 that BON-1 and BON-2 are ideally located in that they provide the opportunity to spud into sediment and drill the full volcanic sequence in any area that has been well-sampled and -surveyed. Given the success at Sites 458, 459 and 786B with 1980s technology, it is unlikely that an alternate site will be needed. However, as noted in Section 3, we are fortunate that deeper drilling at DSDP Site 459 provides an alternate to the Bonin forearc and that the site already has crossing MCS lines. Having been successfully drilled already, new adjacent holes could be drilled to the depth of the existing holes, cased and then cored. Note that DSDP site 458 has already cored the transition between boninites and FAB, so only one alternate site is needed. This could be useful in the event that some time is spent at the Bonin sites, in which case there would not be time for a full two site program in the Mariana forearc.

8. EXPECTED OUTCOMES AND SUMMARY

Drilling the full forearc lava section at BON-1 and BON-2 will likely produce a full sequence of the subduction initiation lava stratigraphy which can then be subjected to the full range of petrological and geochemical analyses, and a range of dating methods. This should achieve the following outcomes:

- Test the hypothesis that FAB tholeiites lie beneath boninites, providing important empirical constraints on the relationship between subduction initiation and magmagenesis.

- Document the evolution of crustal accretion and magma genetic processes following subduction initiation.
- Provide data needed to determine the composition and petrogenesis of the early arc crust to help assess its role in crustal growth.
- Provide information on the nature of crustal accretion from hydrous magma, presently a missing end-member in oceanic crustal studies.
- Test the hypothesis that forearc lithosphere created during subduction initiation is the birthplace of supra-subduction zone ophiolites.

A particular feature of BON-1 & -2 is that they are potentially of interest to several communities: the Ridge community (e.g. InterRIDGE), because there has so far been no attempt to drill deep in oceanic crust generated by water-rich magma; the ophiolite (on-land geology) community, because analogues to the most common (supra-subduction zone) ophiolites have not yet been drilled *in situ*; the Subduction Factory community, because it provides new information on the foundations of volcanic arcs and the flux of fluids through forearc crust; and the geochemistry community because of the implications for crustal growth models. Potentially exciting items are to study the birth of, and roots of, volcanic arcs and the contribution of early arc volcanism to crustal growth.

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696-Full4

IODP Site Summary Forms:
Form 1 - General Site Information

Please fill out information in all gray boxes
Revised 7 March 2002

New ☐ Revised ■

Section A: Proposal Information

Title of Proposal:	**Testing Subduction Initiation and Ophiolite Models by Drilling the Bonin Forearc**
Date Form Submitted:	29th Mar. 2012
Site Specific Objectives with Priority (Must include general objectives in proposal)	Coring the complete Bonin forearc volcanic section by offset drilling (**lower part in BON-1** and upper part in BON-2) in order to understand subduction initiation processes and test supra-subduction zone ophiolite models
List Previous Drilling in Area:	Site will be in the same IBM forearc terrane as DSDP Sites 458 & 459 and ODP Site 786B (Leg 125), though some distance from these sites

---

Section B: General Site Information

Site Name: (e.g. SWPAC-01A)	BON-1 Adjacent to ODP 786B	If site is a reoccupation of an old DSDP/ODP Site, Please include former Site #	Area or Location:	**Izu-Bonin forearc**
Latitude:	Deg: **28**	Min: **27.0N**	Jurisdiction:	**Japan**
Longitude:	Deg: **142**	Min **45.5E**	Distance to Land:	**75 km**
Coordinates System:	WGS 84, Other ( )			
Priority of Site:	Primary: x	Alt:	Water Depth:	**4780 m**

Section C: Operational Information

	Sediments		Basement
Proposed Penetration: (m)	250m What is the total sed. thickness? 250 m		750m
		Total Penetration:	m
General Lithologies:	Pelagic carbonate with thin ash layers		Basalt lavas, sheeted dykes

Coring Plan: *(Specify or check)*

XCB in shallow sediments, then RCB

1-2-3-APC ☐PC* XC☐ MD☐B* PCS ☐CB Re☐ntry ■RGB ☐ ☐

** Systems Currently Under Development*

Wireline Logging Plan:

Standard Tools		Special Tools				LWD	
Neutron-Porosity	■	Borehole Televiewer	■		■	Density-Neutron	☐
Litho-Density	■	Nuclear Magnetic Resonance	☐		■	Resistivity-Gamma Ray	☐
Gamma Ray	■	Geochemical	■		■	Acoustic	☐
Resistivity	■	Side-Wall Core Sampling	■				
Acoustic	■						
Formation Image	■			Others ( )		Others ( )	

Max.Borehole Temp. :

Expected value (For Riser Drilling)

________ °

Mud Logging: *(Riser Holes Only)*

Cuttings Sampling Intervals

from m to m, m intervals

from m to m, m intervals

Basic Sampling Intervals: 5m

Estimated days:	Drilling/Coring: 22	Logging 4:	Total On-Site 26:

Future Plan:

Longterm Borehole Observation Plan/Re-entry

Leave Site for re-entry

Hazards/ Weather:

Please check following List of Potential Hazards

Shallow Gas	☐	Complicated Seabed Condition	☐	Hydrothermal Activity	☐
Hydrocarbon	☐	Soft Seabed	☐	Landslide and Turbidity Current	☐
Shallow Water Flow	☐	Currents	☐	Methane Hydrate	☐
Abnormal Pressure	☐	Fractured Zone	☐	Diapir and Mud Volcano	☐
Man-made Objects	☐	Fault	☐	High Temperature	☐
H_2S	☐	High Dip Angle	☐	Ice Conditions	☐
CO_2	☐				

What is your Weather window? (Preferable period with the reasons)

Avoid late summer ((typhoon risk). Later Spring to Early Summer is optimal.

Form 2 - Site Survey Detail

IODP Site Summary Forms:

Please fill out information in all gray boxes

New ☐ **Revised** ■

Proposal #:696-FULL4	Site #: BON-1	Date Form Submitted: 29th Mar. 2012

	Data Type	SSP Requir-ements	Exists In DB	Details of available data and data that are still to be collected
1	High resolution seismic reflection			Primary Line(s) :Location of Site on line (SP or Time only) Crossing Lines(s):
2	Deep Penetration seismic reflection			JAMSTEC survey planned 2011
3	Seismic Velocity†			
4	Seismic Grid			
5a	Refraction (surface)			
5b	Refraction (near bottom)			Carried out 100km north of BON-1 (Kamamura et al., 2002) and c. 30km west of BON-1 (Kodaira et al., 2010)
6	3.5 kHz			Multi-narrow-beam data complied by Japan Coast Guard
7	Swath bathymetry			
8a	Side-looking sonar (surface)			
8b	Side-looking sonar (bottom)			
9	Photography or Video			
10	Heat Flow			ODP Leg 126 measurements give maximum value likely
11a	Magnetics			Map complied by AIST, Japan, is published.
11b	Gravity			Map complied by AIST, Japan, is published
12	Sediment cores			Cored at Site 786A, ODP Leg 125
13	Rock sampling			Dredging on R/V Hakuho-maru KH07-2, diving on YK 04-05 and YK09-06
14a	Water current data			Available on JODC web page (hhtp://www.jodc.go.jp)
14b	Ice Conditions			
15	OBS microseismicity			
16	Navigation			
17	Other			

SSP Classification of Site:	SSP Watchdog:	Date of Last Review:
SSP Comments:		

X=required; X*=may be required for specific sites; Y=recommended; Y*=may be recommended for specific sites; R=required for re-entry sites; T=required for high temperature environments; † Accurate velocity information is required for holes deeper than 400m.

Form 3 - Detailed Logging Plan

IODP Site Summary Forms:

New ☐ **Revised** ■

Proposal #: 696 FULL4	Site #:BON-1	Date Form Submitted:29Mar. 2012
Water Depth (m): 4780m	Sed. Penetration (m): 0	Basement Penetration (m): 750m

Do you need to use the conical side-entry sub (CSES) at this site? No
Are high temperatures expected at this site? No
Are there any other special requirements for logging at this site? No

If "Yes" Please describe requirements:______________________________

What do you estimate the total logging time for this site to be:_____4 days__

Measurement Type	Scientific Objective	Relevance (1=high, 3=Low)
Neutron-Porosity	Basalt lavas, sills and dykes; relate core to bulk crustal properties	1
Litho-Density	Basalt lava, sill and dykedensities for mechanical properties and synthetic seismogram	1
Natural Gamma Ray	Hydrothermal alteration and relate core to bulk crust	1
Resistivity-Induction	Electro-magnetic properties of basalt lavas, sills and dykes	1
Acoustic	Determination of in situ velocity and estimation of physical properties. Comparison with seismic velocity and create synthetic seismograms.	1
FMS	Imaging of structures and fractures. Core-log correlation of structural features. Detect borehole breakouts/ induces fractures to estimate stress condition.	1
BHTV	Imaging of structures and fractures. Core-log correlation of structural features.	2
Resistivity-Laterolog		
Magnetic/Susceptibility		
Density-Neutron (LWD)		
Resitivity-γ-Ray (LWD)		
Other: Special tools (CORK, PACKER, VSP, PCS, FWS, WSP	Side-Wall Core Sampling in the case of poor core recovery in critical intervals.	1

For help in determining logging times, please contact the ODP-LDEO Wireline Logging Services group at: borehole@ldeo.columbia.edu http://www.ldeo.columbia.edu/BRG/brg_home.html Phone/Fax: (914) 365-8674 / (914) 365-3182	Note: Sites with greater than 400 m of penetration or significant basement penetration require deployment of standard toolstrings.

IODP Site Summary Forms:

Form 4 – Pollution & Safety Hazard Summary

Please fill out information in all gray boxes

New ☐ **Revised** ■

Proposal #: 696-FULL4	Site #: BON-1	Date Form Submitted: 29Mar.2012

1	Summary of Operations at site: (Example: Triple-APC to refusal, XCB 10 m into basement, log as shown on page 3.)	XCB to basement (250 m), RCB to 500m, Case to 300m, RCB to 1000m
2	Based on Previous DSDP/ODP drilling, list all hydrocarbon occurrences of greater than background levels. Give nature of show, age and depth of rock:	None; igneous basement only
3	From Available information, list all commercial drilling in this area that produced or yielded significant hydrocarbon shows. Give depths and ages of hydrocarbon-bearing deposits.	None
4	Are there any indications of gas hydrates at this location?	No
5	Are there reasons to expect hydrocarbon accumulations at this site? Please give details.	No
6	What "special" precautions will be taken during drilling?	Standard
7	What abandonment procedures do you plan to follow:	Standard
8	Please list other natural or manmade hazards which may effect ship's operations:	None
9	Summary: What do you consider the major risks in drilling at this site?	None expected

Form 5 – Lithologic Summary

IODP Site Summary Forms:

New ☐ **Revised** ■

Proposal #696 FULL4:	Site #: BON-1	Date Form Submitted: 29th Mar. 2012

Sub-bottom depth (m)	*Key reflectors, Unconformities, faults, etc*	*Age*	*Assumed velocity (km/sec)*	*Lithology*	*Paleo-environment*	*Avg. rate of sed. accum. (m/My)*	*Comments*
0-250		0-48 m.y.	1.6	Vitric sandstone	Fore-arc	5-6	
250-875m		48-51m.y.		Forearc Basalts	Sea-floor spreading following subduction initaion		
875-1000		51m.y		Basalt sheeted dykes	Sea-floor spreading following subduction initiation		

IODP Site Summary Forms:

Form 1 - General Site Information

Please fill out information in all gray boxes
Revised 7 March 2002

New ☐ **Revised** ■

Section A: Proposal Information

Title of Proposal:	**Testing Subduction Initiation and Ophiolite Models by Drilling the Bonin Forearc**
Date Form Submitted:	29th March 2012
Site Specific Objectives with Priority (Must include general objectives in proposal)	Coring the complete Bonin forearc volcanic section by offset drilling (lower part in BON-1 **and upper part in BON-2**) in order to understand subduction initiation processes and test supra-subduction zone ophiolite models
List Previous Drilling in Area:	Site will be in the same IBM forearc terrane as DSDP Sites 458 & 459 and ODP Site 786B (Leg 125), though some distance from these sites

Section B: General Site Information

Site Name: (e.g. SWPAC-01A)	BON-2	If site is a reoccupation of an old DSDP/ODP Site, Please include former Site #	Area or Location:	**Izu-Bonin forearc**
Latitude:	Deg: **28**	Min: **24.5N**	Jurisdiction:	**Japan**
Longitude:	Deg: **142**	Min **36.5E**	Distance to Land:	**75 km**
Coordinates System:	WGS 84, Other ( )			
Priority of Site:	Primary: x	Alt:	Water Depth:	**3100 m**

Section C: Operational Information

	Sediments	Basement
Proposed Penetration: (m)	250m (drilling only) What is the total sed. thickness? 125 m	750m
		Total Penetration: m

General Lithologies:	Pelagic carbonate with thin ash layers	Boninite and basalt lavas

Coring Plan: *(Specify or check)*

Drill without coring to 800m adjacent to 786B, case,:then EITHER core by RCB to 1200m, ase, then core by RCB to 1500m OR core by RCB to 1750m+

1-2-3-APC ☐PC* XC☐ MD☐B* PCS ☐CB Re☐ntry ■RGB ☐ ☐

** Systems Currently Under Development*

Wireline Logging Plan:

Standard Tools		Special Tools			LWD	
Neutron-Porosity	■	Borehole Televiewer	■	Formation Fluid Sampling	Density-Neutron	☐
Litho-Density	■	Nuclear Magnetic Resonance	☐	Borehole Temperature & Pressure	Resistivity-Gamma Ray	☐
Gamma Ray	■	Geochemical	■	Borehole Seismic	Acoustic	☐
Resistivity	■	Side-Wall Core Sampling	■			
Acoustic	■					
Formation Image	■			Others ( )	Others ( )	

Max.Borehole Temp. : **Expected value (For Riser Drilling)** ________ °

Mud Logging: *(Riser Holes Only)*

Cuttings Sampling Intervals

from	m	to	m,	m intervals
from	m	to	m,	m intervals

Basic Sampling Intervals: 5m

Estimated days:	Drilling/Coring: 50	Logging 6:	Total On-Site56:

Future Plan:

Longterm Borehole Observation Plan/Re-entry

Leave Site for re-entry for deepening, possibly to Moho

Hazards/ Weather:

Please check following List of Potential Hazards

Shallow Gas	☐	Complicated Seabed Condition	☐	Hydrothermal Activity	☐
Hydrocarbon	☐	Soft Seabed	☐	Landslide and Turbidity Current	☐
Shallow Water Flow	☐	Currents	☐	Methane Hydrate	☐
Abnormal Pressure	☐	Fractured Zone	☐	Diapir and Mud Volcano	☐
Man-made Objects	☐	Fault	☐	High Temperature	☐
H_2S	☐	High Dip Angle	☐	Ice Conditions	☐
CO_2	☐				

What is your Weather window? (Preferable period with the reasons)

Avoid late summer ((typhoon risk). Later Spring to Early Summer is optimal.

Form 2 - Site Survey Detail

IODP Site Summary Forms:

Please fill out information in all gray boxes

New ☐ **Revised** ■

Proposal #:696-FULL4	Site #: BON-2	Date Form Submitted: 29th Mar. 2012

	Data Type	SSP Requir-ements	Exists In DB	Details of available data and data that are still to be collected
1	High resolution seismic reflection			Primary Line(s) :Location of Site on line (SP or Time only) Crossing Lines(s):
2	Deep Penetration seismic reflection			JAMSTEC Survey planned 2011
3	Seismic Velocity†			
4	Seismic Grid			
5a	Refraction (surface)			
5b	Refraction (near bottom)			Carried out 100km south of IBM-2 (Kamamura et al., 2002); more work close to IBM-2 planned by JAMSTEC
6	3.5 kHz			Multi-narrow-beam data complied by Japan Coast Guard; but not needed given that MCS available
7	Swath bathymetry			
8a	Side-looking sonar (surface)			
8b	Side-looking sonar (bottom)			
9	Photography or Video			
10	Heat Flow			ODP Leg 126 measurements give maximum value likely
11a	Magnetics			Map complied by AIST, Japan, is published.
11b	Gravity			Map complied by AIST, Japan, is published
12	Sediment cores			Cored at Site 786A, ODP Leg 125
13	Rock sampling			Dredging on R/V Hakuho-maru KH07-2, diving on YK 04-05 and YK09-06
14a	Water current data			Available on JODC web page (hhtp://www.jodc.go.jp)
14b	Ice Conditions			
15	OBS microseismicity			
16	Navigation			
17	Other			

SSP Classification of Site:	SSP Watchdog:	Date of Last Review:
SSP Comments:		

X=required; X*=may be required for specific sites; Y=recommended; Y*=may be recommended for specific sites; R=required for re-entry sites; T=required for high temperature environments; † Accurate velocity information is required for holes deeper than 400m.

Form 3 - Detailed Logging Plan

IODP Site Summary Forms:

New ☐ **Revised** ■

Proposal #: 696 FULL4	Site #:BON-2	Date Form Submitted: 29Mar 2012
Water Depth (m): 3100m	Sed. Penetration (m): 250	Basement Penetration (m): 750m

Do you need to use the conical side-entry sub (CSES) at this site? No
Are high temperatures expected at this site? No
Are there any other special requirements for logging at this site? No

If "Yes" Please describe requirements:______________________________

What do you estimate the total logging time for this site to be:_____4 days__

Measurement Type	Scientific Objective	Relevance (1=high, 3=Low)
Neutron-Porosity	Boninite and basalt porosity; relate core to bulk crustal properties	1
Litho-Density	Boninite and basalt densities for mechanical properties and synthetic seismogram	1
Natural Gamma Ray	Hydrothermal alteration and relate core to bulk crust	1
Resistivity-Induction	Electro-magnetic properties of boninite and basalt	1
Acoustic	Determination of in situ velocity and estimation of physical properties. Comparison with seismic velocity and create synthetic seismograms.	1
FMS	Imaging of structures and fractures. Core-log correlation of structural features. Detect borehole breakouts/ induces fractures to estimate stress condition.	1
BHTV	Imaging of structures and fractures. Core-log correlation of structural features.	2
Resistivity-Laterolog		
Magnetic/Susceptibility		
Density-Neutron (LWD)		
Resitivity-γ-Ray (LWD)		
Other: Special tools (CORK, PACKER, VSP, PCS, FWS, WSP	Side-Wall Core Sampling in the case of poor core recovery in critical intervals.	1

For help in determining logging times, please contact the ODP-LDEO Wireline Logging Services group at: borehole@ldeo.columbia.edu http://www.ldeo.columbia.edu/BRG/brg_home.html Phone/Fax: (914) 365-8674 / (914) 365-3182	Note: Sites with greater than 400 m of penetration or significant basement penetration require deployment of standard toolstrings.

Form 4 – Pollution & Safety Hazard Summary

IODP Site Summary Forms:

Please fill out information in all gray boxes

New ☐ **Revised** ■

Proposal #: 696-FULL4	Site #: IBM-2	Date Form Submitted: 29 Mar.2012

1	Summary of Operations at site: (Example: Triple-APC to refusal, XCB 10 m into basement, log as shown on page 3.)	XCB to basement (250 m), RCB to 500m, Case to 300m, RCB to 1000m
2	Based on Previous DSDP/ODP drilling, list all hydrocarbon occurrences of greater than background levels. Give nature of show, age and depth of rock:	None; igneous basement only
3	From Available information, list all commercial drilling in this area that produced or yielded significant hydrocarbon shows. Give depths and ages of hydrocarbon-bearing deposits.	None
4	Are there any indications of gas hydrates at this location?	No
5	Are there reasons to expect hydrocarbon accumulations at this site? Please give details.	No
6	What “special” precautions will be taken during drilling?	Standard
7	What abandonment procedures do you plan to follow:	Standard
8	Please list other natural or manmade hazards which may effect ship’s operations:	None
9	Summary: What do you consider the major risks in drilling at this site?	None expected; forearc already drilled at ODP Site 786 and DSDP 458 and 459

Form 5 – Lithologic Summary

IODP Site Summary Forms:

New ☐ **Revised** ■

Proposal #696 FULL4	Site #: BON-2	Date Form Submitted: 29th March 2012

Sub-bottom depth (m)	*Key reflectors, Unconformities, faults, etc*	*Age*	*Assumed velocity (km/sec)*	*Lithology*	*Paleo-environment*	*Avg. rate of sed. accum. (m/My)*	*Comments*
0-250		0-44 m.y.	1.6	Vitric sandstone	Fore-arc	5-6	
250-800		44-48m.y.		Boninites and related rocks	Infant arc volcanism		
875-1000		51m.y		Basalt sheeted dykes	Sea-floor spreading following suboduction initaion		

IODP Site Summary Forms:

Form 1 - General Site Information

Please fill out information in all gray boxes

Revised 7 March 2002

New ☐ **Revised** ■

Section A: Proposal Information

Title of Proposal:	**Testing Subduction Initiation and Ophiolite Models by Drilling the Bonin Forearc**
Date Form Submitted:	31th March 2012
Site Specific Objectives with Priority (Must include general objectives in proposal)	Coring the Mariana forearc volcanic section near **DSDP site 459** to drill through transitional boninite-basalt lavas into forearc basalts and associated intrusive rocks to investigate the subduction initiation processes and test supra-subduction zone ophiolite models
List Previous Drilling in Area:	Site will be within the backarc-arc-forearc transect that included DSDP sites 453-461.

Section B: General Site Information

Site Name: (e.g. SWPAC-01A)	**DSDP 459**	If site is a reoccupation of an old DSDP/ODP Site, Please include former Site #	Area or Location:	**Mariana forearc**
Latitude:	Deg: **17**	Min: **51.75N**	Jurisdiction:	**USA**
Longitude:	Deg: **147**	Min **18.09E**	Distance to Land:	**162 km**
Coordinates System:	WGS 84, Other ( )			
Priority of Site:	Primary: x	Alt:	Water Depth:	**4125 m**

Section C: Operational Information

	Sediments	Basement
Proposed Penetration: (m)	500m (drilling only) What is the total sed. thickness? 500 m	1000m (drilling then coring)
		Total Penetration: 1500 m
General Lithologies:	Pelagic carbonate with thin ash layers overlying tubidites	Boninite and basalt lava and diabase

Coring Plan: *(Specify or check)*

Drill without coring to 650m adjacent to DSDP 459, case, then EITHER core by RCB to 1200m, case, then core by RCB to 1500m OR core by RCB to 1500m+

1-2-3-APC □ | PC* □ | XCB □ | MDCB* □ | PCS □ | RCB ■ | Re-entry □ | HRGB □

** Systems Currently Under Development*

Wireline Logging Plan:

Standard Tools		Special Tools			LWD	
Neutron-Porosity	■	Borehole Televiewer	■	Formation Fluid Sampling	Density-Neutron	□
Litho-Density	■	Nuclear Magnetic Resonance	□	Borehole Temperature & Pressure	Resistivity-Gamma Ray	□
Gamma Ray	■	Geochemical	■	Borehole Seismic	Acoustic	□
Resistivity	■	Side-Wall Core Sampling	■			
Acoustic	■					
Formation Image	■			Others ( )	Others ( )	

Max.Borehole Temp. : **Expected value (For Riser Drilling)** ________ °

Mud Logging: *(Riser Holes Only)*

Cuttings Sampling Intervals

from m to m, m intervals

from m to m, m intervals

Basic Sampling Intervals: 5m

Estimated days:	Drilling/Coring: 50	Logging 6:	Total On-Site56:

Future Plan:

Longterm Borehole Observation Plan/Re-entry

Leave Site for re-entry for deepening, possibly to Moho

Hazards/ Weather:

Please check following List of Potential Hazards

Shallow Gas	□	Complicated Seabed Condition	□	Hydrothermal Activity	□
Hydrocarbon	□	Soft Seabed	□	Landslide and Turbidity Current	□
Shallow Water Flow	□	Currents	□	Methane Hydrate	□
Abnormal Pressure	□	Fractured Zone	□	Diapir and Mud Volcano	□
Man-made Objects	□	Fault	□	High Temperature	□
H_2S	□	High Dip Angle	□	Ice Conditions	□
CO_2	□				

What is your Weather window? (Preferable period with the reasons)

Avoid late summer ((typhoon risk). Later Spring to Early Summer is optimal.

Form 3 - Detailed Logging Plan

IODP Site Summary Forms:

New [X] **Revised** [ ]

Proposal #: 696 FULL4	Site #:DSDP 459	Date Form Submitted: 30March 2012
Water Depth (m): 4125m	Sed. Penetration (m): 500	Basement Penetration (m): 1000m

Do you need to use the conical side-entry sub (CSES) at this site? No
Are high temperatures expected at this site? No
Are there any other special requirements for logging at this site? No

If "Yes" Please describe requirements:______________________________

What do you estimate the total logging time for this site to be:______4 days___

Measurement Type	Scientific Objective	Relevance (1=high, 3=Low)
Neutron-Porosity	Boninite and basalt porosity; relate core to bulk crustal properties	1
Litho-Density	Boninite and basalt densities for mechanical properties and synthetic seismogram	1
Natural Gamma Ray	Hydrothermal alteration and relate core to bulk crust	1
Resistivity-Induction	Electro-magnetic properties of boninite and basalt	1
Acoustic	Determination of in situ velocity and estimation of physical properties. Comparison with seismic velocity and create synthetic seismograms.	1
FMS	Imaging of structures and fractures. Core-log correlation of structural features. Detect borehole breakouts/ induces fractures to estimate stress condition.	1
BHTV	Imaging of structures and fractures. Core-log correlation of structural features.	2
Resistivity-Laterolog		
Magnetic/Susceptibility		
Density-Neutron (LWD)		
Resitivity-γ-Ray (LWD)		
Other: Special tools (CORK, PACKER, VSP, PCS, FWS, WSP	Side-Wall Core Sampling in the case of poor core recovery in critical intervals.	1

For help in determining logging times, please contact the ODP-LDEO Wireline Logging Services group at: borehole@ldeo.columbia.edu http://www.ldeo.columbia.edu/BRG/brg_home.html Phone/Fax: (914) 365-8674 / (914) 365-3182	Note: Sites with greater than 400 m of penetration or significant basement penetration require deployment of standard toolstrings.

Form 4 – Pollution & Safety Hazard Summary

IODP Site Summary Forms:

Please fill out information in all gray boxes

New ■ **Revised** ☐

Proposal #: 696-FULL	Site #: DSDP 459	Date Form Submitted: 31March2012

1	Summary of Operations at site: (Example: Triple-APC to refusal, XCB 10 m into basement, log as shown on page 3.)	XCB to 650m, case, then EITHER core by RCB to 1200m, case, then core by RCB to 1500m OR core by RCB to 1500m
2	Based on Previous DSDP/ODP drilling, list all hydrocarbon occurrences of greater than background levels. Give nature of show, age and depth of rock:	None; igneous basement only
3	From Available information, list all commercial drilling in this area that produced or yielded significant hydrocarbon shows. Give depths and ages of hydrocarbon-bearing deposits.	None
4	Are there any indications of gas hydrates at this location?	No
5	Are there reasons to expect hydrocarbon accumulations at this site? Please give details.	No
6	What “special” precautions will be taken during drilling?	Standard
7	What abandonment procedures do you plan to follow:	Standard
8	Please list other natural or manmade hazards which may effect ship’s operations:	None
9	Summary: What do you consider the major risks in drilling at this site?	None expected; forearc already drilled at DSDP 458 and 459

Form 5 – Lithologic Summary

IODP Site Summary Forms:

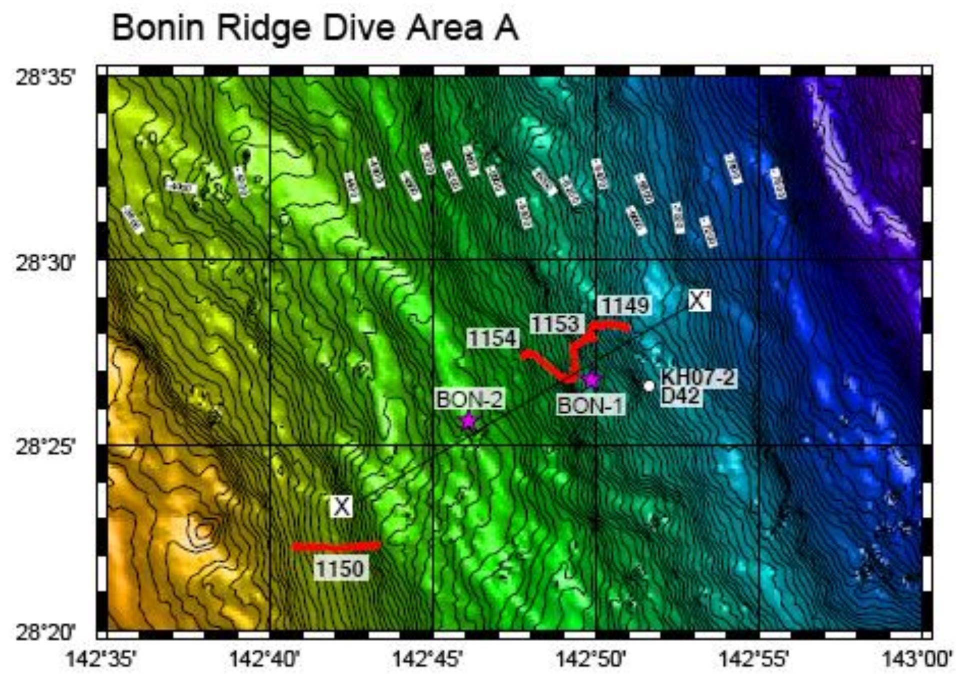
New ■ **Revised** □

Proposal #696 FULL:	Site #: DSDP 459	Date Form Submitted: 31March 2012

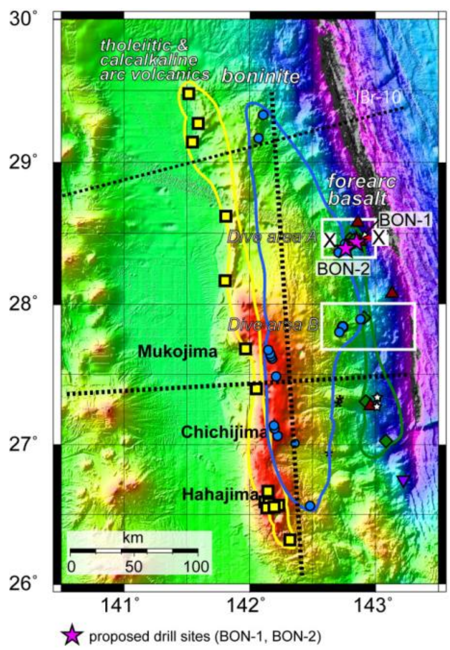
Sub-bottom depth (m)	*Key reflectors, Unconformities, faults, etc*	*Age*	*Assumed velocity (km/sec)*	*Lithology*	*Paleo-environment*	*Avg. rate of sed. accum. (m/My)*	*Comments*
0-250		0-44 m.y.	1.6	Vitric sandstone	Fore-arc	5-6	
250-800		44-48m.y.		Boninites and related rocks	Infant arc volcanism		
875-1000		51m.y		Basalt sheeted dykes	Sea-floor spreading following subduction initiation		

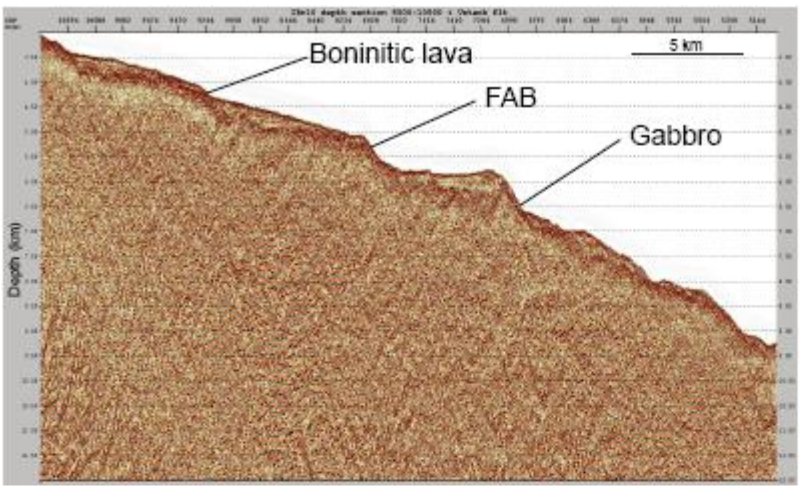
Site Survey Information

(a) Dive information (see text)



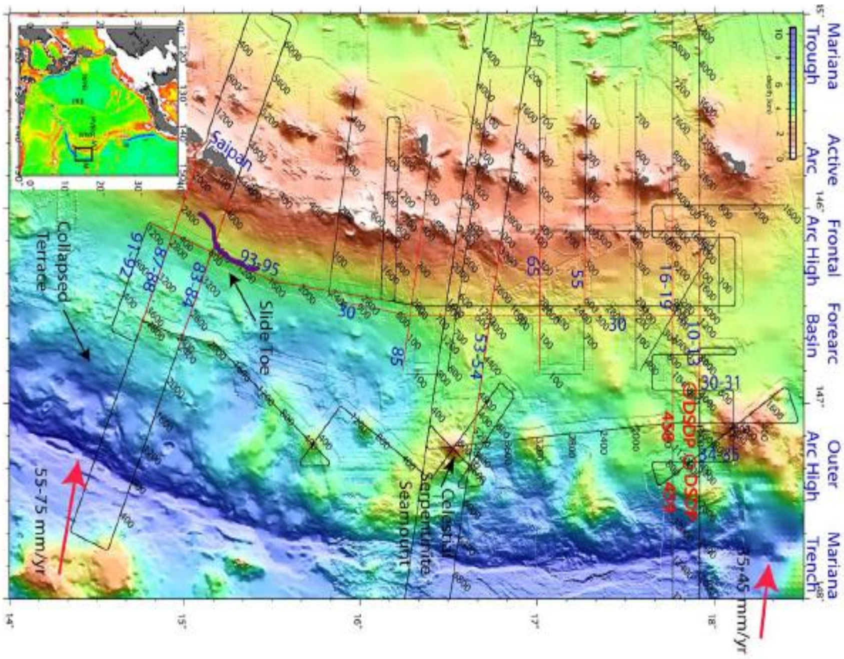
(b) LHS diagram shows the locations of MCS sections (dashed) in the region of the proposed drill sites. RHS diagram shows MCS section c. 80km north of BON-1 and BON-2. JAMSTEC will be carrying out a MCS survey in 2013 along the line of BON-1 and BON-2

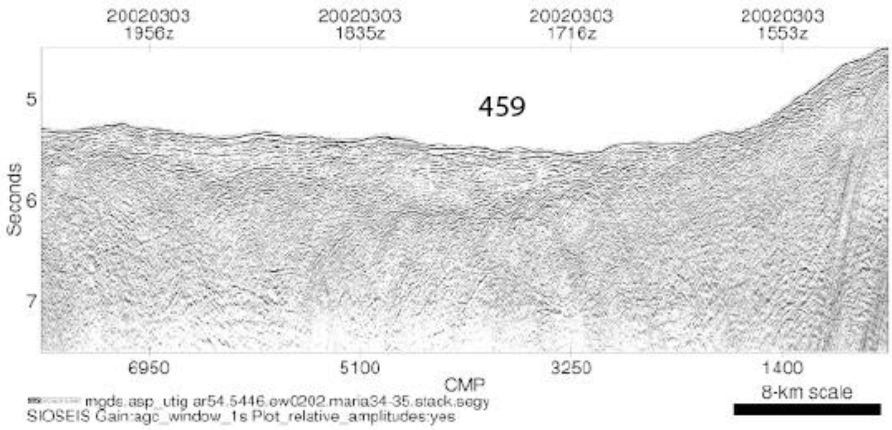


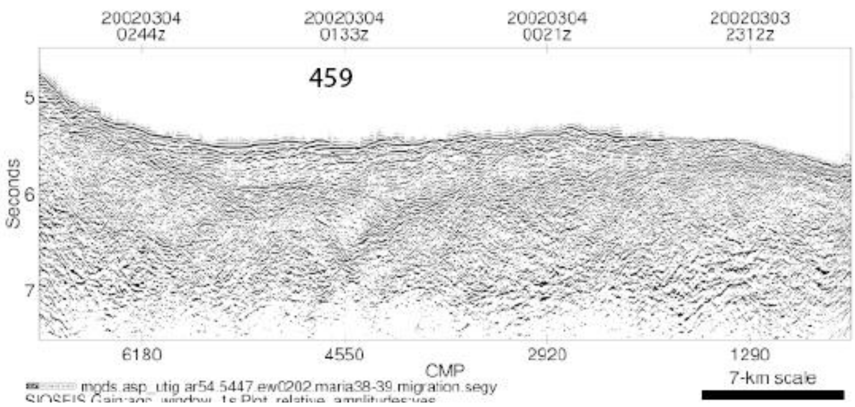


Site Survey Information (Alternate Site 459)

The map (rotated 90 degrees) shows the MCS lines run by Chapp et al. (2008), with crossing lines for DSDP Site 459 in the bottom right. Cross-cutting N-S (top) and E-W (bottom) MSC profiles are shown below. Note that new MCS profiles have been collected and are being processed.







Prof. Julian A. Pearce

Professor of Geochemistry, School of Earth, Ocean and Planetary Sciences, Cardiff University, PO Box 914, Cardiff CF10 3YE, UK

e-mail: PearceJA@cardiff.ac.uk Phone:+44-29-2087-5124

Born, May 30th, 1949 in Brighton, UK. Citizenship: UK

Qualifications

1967-1970 **BA** (Class I Hons. in Natural Sciences) University of Cambridge, England.

1970-1973 **PhD** School of Environmental Sciences, University of East Anglia, England. (*Some relationships between the geochemistry and tectonic setting of basic volcanic rocks: J.R. Cann, supervisor*).

Employment

1973-1974 Royal Society Post-doctoral Fellow at the Mineralogisk-Geologisk Museet, Oslo, Norway.

1974-1984 Lecturer in Earth Sciences at the Open University, Milton Keynes, UK.

1984. Visiting Professor, University of Grenoble, France.

1984-1989 Lecturer in Geology, then Reader in Geochemistry, at the University of Newcastle upon Tyne, UK.

1989-1999 Reader in Geochemistry at the University of Durham, UK.

2000- Professor of Geochemistry at Cardiff University, UK.

Relevant Experience

Participant on DSDP Leg 92.and Co-chief Scientist on ODP Leg 125 (contributor to 15 papers on Leg 125 results. including two in Nature).

Cruises (most as co-PI) to Galicia Margin, Lau Basin, Palau-Kyushu Ridge, Mid-Atlantic Ridge and Scotia Sea/Drake Passage; on land projects on a number of ophiolites, notably Troodos and Oman.

Many committee memberships and related duties within ODP and IODP, notably Chair of ODP Planning Committee and Head of the JOIDES office during 1996 and Head of the ESSAC office and Chair of ESSAC during 2006-7.

Member of the International Advisory Board for IFM-GEOMAR (2004-present) and Member of Review Committee for IODP Atlantic Core Complex Expeditions (2005).

Organisation of, a number of symposia on ocean crust and subduction processes.

Relevant Publications (post-2000)

Leat, P.T., Livermore, R.A., Millar, I.L. and Pearce, J.A., 2000. Magma supply in back-arc spreading segment E2, East Scotia Ridge. *J. Petrol*. **41**, 845-866.

Edwards, S.J., Pearce, J.A. and Freeman, J. 2000. New insights concerning the influence of water during the formation of podiform chromitite. *Geol. Soc. Am. Spec. Paper* **349**, 139-147.

Pearce, J.A., Leat, P.T., Barker, P.F. and Millar, I.L., 2001. Geochemical tracing of Pacific-to-Atlantic upper-mantle flow through the Drake passage. *Nature* **410**, 457-461.

Peate, D.W., Kokfelt, T.F., Hawkesworth, C.J., van Calsteren, P., Hergt, J.M. and Pearce, J.A., 2001. ^{238}U-^{230}Th - ^{226}Ra disequilibrium in Lau Basin glasses: the role of subduction-related fluids during melt generation in back-arc basins. *J. Petr*ol. **42**, 1449-1470.

Kempton, P.D., Pearce, J.A., Barry, T.L., Fitton, J.G., Langmuir, C. and Christie, D.M., 2002. εNd vs. εHf as a geochemical discriminant between Indian and Pacific mantle domains: results from ODP Leg 187 to the Australian-Antarctic Discordance. *Geochemistry, Geophysics, Geosystems* 3, Paper Number GC000320.

Kent, A.J.R., Peate, D.W., Newman, S., Stolper, E.M. and Pearce, J.A., 2002. Chlorine in submarine glasses from the Lau Basin: seawater contamination and constraints on the composition of slab-derived fluids. *Earth Planet. Sci. Lett*. 202, 361-377.

Pearce, J.A., 2002. Achievements and opportunities of scientific oceanic drilling. II-2: The Oceanic Lithosphere. *JOIDES Journal* **28**, 1, 61-66.

Pearce, J.A., 2003. Supra-Subduction Zone ophiolites: the search for modern analogues. *Geol. Soc. Amer. Spec. Paper* **373,** 269-293.

Coogan, L.A.,' Banks,G.J., Gillis, K. M., MacLeod, C. J. and Pearce, J.A. 2003. Hidden melting signatures recorded in the Troodos ophiolite plutonic suite: evidence for widespread generation of depleted melts and intra-crustal melt aggregation. *Contrib. Mineral. Petrol*. **144**, 484-505.

Niu, Y., O'Hara, M.J. and Pearce, J.A., 2003. Initiation of subduction zones: a consequence of lateral compositional buoyancy contrast within the lithosphere. *J. Petrol*. **44**, 851-866.

Leat, P.T., Pearce, J.A., Barker, P.F., Millar, I.L., Barry, T.L. and Larter, R.D., 2004. Magma genesis and mantle flow at a subducting slab edge: the South Sandwich arc-basin system. *Earth Planet. Sci. Lett*. Doi:10.1016/j.epsl.2004.08.016.

Pearce, J.A., 2005. Mantle preconditioning by melt extraction during flow: theory and petrogenetic implications. *J. Petrol*. Doi:10.1093/petrology/egi007.

Pearce, J.A., Stern, R.J., Bloomer, S.H. and Fryer, P., 2005. Geochemical mapping of the Mariana arc-basin system: implications for the nature and distribution of subduction components. *Geochem. Geophys. Geosyst.* **6**, Q07006, doi:10.1029/2004GC000895.

Pearce J.A. and Stern, R.J., 2006. The origin of back-arc basin magmas: trace element and isotope perspectives. AGU Geophys. Monograph Ser. **166**, 63-86.

Barry, T., Pearce J.A., Leat, P.T., Millar, I.L., 2006. Hf isotope evidence for selective mobility of high-field-strength-elements in a subduction setting: South Sandwich Islands, *Earth Planet. Sci. Lett.* **252**, 223-244.

Sanchez Martinez, S., Arenas, R., Diaz Garcia, F., Martinez Catalan, J.R., Gomez-Barreiro, J. and Pearce, J.A., 2007, New geochemical data of the Careón ophiolite: supra-subduction zone setting for the youngest Rheic ocean floor. *Geology* **35**, 53-56.

Pearce, J.A., Kempton, P.D. and Gill, J.B., 2007. Nd-Hf evidence for the origin and distribution of mantle domains in the S.W. Pacific. *Earth Planet. Sci. Lett.* **260**, 98-114. doi: 10.1016/j.epsl.2007.05.023.

Pearce, J.A., 2008. Geochemical Fingerprinting of oceanic basalts with implications for the classification of ophiolites and search for Archean oceanic crust. *Litho*s **100**, 14-

Pearce JA, Robinson PT, 2010. The Troodos ophiolitic complex probably formed in a subduction initiation, slab edge setting. Gondwana Research. [doi:10.1016/j.gr.2009.12.003].

Prof. Robert J. Stern

Professor of Geosciences, Geosciences Dept., University of Texas at Dallas, Richardson TX 75083-0688 USA

e-mail: **RJStern@utdallas.edu** Phone : +1- 972-883-2442

Born, February 2, 1951 in Sacramento, California, USA. Citizenship: U.S.

Qualifications

1968-1970: Studies in Political Science, University of California at Davis

1971-1974: **B.S**. in Geology (with honors), University of California at Davis

1974-1979: **Ph.D**., Earth Science, University of California at San Diego

(Thesis title: "Late Precambrian Ensimatic Volcanism in the Central Eastern Desert of Egypt"; Thesis adviser: A.E.J. Engel)

Employment

1979-1981: Post-doctoral fellow, Department of Terrestrial Magnetism, Carnegie Institution of Washington.

1982 - 1987: Assistant Professor, Programs in Geosciences, University of Texas at Dallas..

1987 - 1991: Associate Professor with Tenure, Programs in Geosciences, University of Texas at Dallas.

1991 - Present: Professor with Tenure, Programs in Geosciences, University of Texas at Dallas.

1997 –2005 : Head of Geosciences Department, University of Texas at Dallas.

2005: Blaustein Fellow, Stanford University.

2006: Tectonics Observatory Fellow, California Institute of Technology.

Relevant Experience

Co-organiser US-Japan Workshop on Geophysical and Geochemical studies of the Izu-Bonin-Mariana Arc System (with M.Arima): July 27-August 2, 1996, Hayama, Japan. (85 participants; NSF funded).

Co-organiser NSF-IFREE-Margins Workshop on the Izu-Bonin-Mariana Subduction System (with J. Gill, S. Klemperer, and D.Wiens): (09/02), Honolulu (98 participants, NSF funded).

Co-organiser MARGINS-IFREE mini workshop on IODP drilling in the IBM Arc System at fall AGU meeting (12/04).

Co-organiser MARGINS-IFREE mini workshop on Interdisciplinary Research in the IBM Arc System at fall AGU meeting (12/06).

Co-organiser NSF-MARGINS-IFREE Workshop on the IBM Arc System, Nov. 7-10, 2007, Honolulu HI.

Participant in many research cruises to the IBM arc and forearc, and field experience on supra-subduction zone ophiolites in the Neoproterozoic of NE Africa and Arabia.

Relevant Publications (post-2000)

Ohara, Y., Stern, R.J., Ishii, T., Yurimoto, H. and Yamazaki, T. 2002. "Peridotites from the Mariana Trough: First look at the Mantle beneath an active Backarc Basin" Contributions to Mineralogy and Petrology 143, 1-18.

Stern, R.J., 2002. "Subduction Zones" Reviews of Geophysics, 40, 10.1029/2001RG000108

Ito, E., Stern, R.J. and Douthitt, C., 2003. 'Insights into Operation of the "Subduction Factory" from the Oxygen Isotopic Values of Southern Izu-Bonin-Mariana Arc' The Island Arc v. 12, 383-397.

Stern, R.J., Fouch, M.J. and Klemperer, S., 2003. "An Overview of the Izu-Bonin-Mariana Subduction Factory" in J. Eiler and M. Hirschmann (eds.) Inside the Subduction Factory, Geophysical Monograph 138, American Geophysical Union, 175-222.

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Stern, R.J. 2004. Subduction Initiation: Spontaneous and Induced. Earth Planet. Sci. Lett. 226, 275-292

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Wade, J., Plank, T., Stern, R.J., Tollstrup, D., Gill, J., O'Leary, J., Moore, R.B., Trusdell, F., Fisher, T.P. and Hilton, D.R. 2005. The May 2003 eruption of Anatahan volcano, Mariana Islands: Geochemical Evolution of a Silicic Island Arc Volcano. J. Volcanology and Geothermal Research 146, 1-3, 139-170.

Stern, R.J., Kohut, E.J., Bloomer, S.H., Leybourne, M., Fouch, M. and Vervoort, J. 2006. Subduction factory processes beneath the Guguan Cross-chain, Mariana Arc: no role for sediments, are serpentinites important? Contributions to Mineralogy and Petrology, 151, 202-221.

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Kohut, E.J., Stern, R.J., Kent, A.J.R., Nielsen, R.L., Bloomer, S.H. and Leybourne, M. 2006. Evidence for Decompression Melting in the Southern Mariana Arc from High-Mg Lavas and Melt Inclusions. Contributions to Mineralogy and Petrology. 152, 201-221

Ishizuka, O., Kimura, J.-I., Li, Y.B., Stern, R.J., Reagan, M., Taylor, R.N., Ohara, Y., Bloomer, S.H., Ishii, T. Hargrove III, U.S., and Haraguchi, S., 2006. Early stages in the Evolution of Izu-Bonin Arc volcanism: new age, chemical, and isotopic constraints. Earth Planet. Sci. Lett. 250, 385-401

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Tatsumi, Y. and Stern, R.J., 2006. Manufacturing continental crust in the subduction factory: was continent born in the ocean? Oceanography 17, 104-112

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Ohara, Y., Tokuyama, H. and Stern, R.J., 2007. Preface: Thematic Section: Geology and geophysics of the Philippine Sea and adjacent areas in the Pacific Ocean. The Island Arc 16, 319-321.

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Current Post:

Employer: Geological Survey of Japan/AIST
Position held: senior researcher
Date of Employment: 1 April, 1994
also invited researcher at IFREE, JAMSTEC (since 1 June, 2006) and
associate professor at Tsukuba University (since 1 April, 2006)

Education and Qualification:

1992 B. Sc. (Geology) at Faculty of Science, University of Tokyo
1994 M. Sc. (Geology) at Geological Institute, School of Science, University of Tokyo
1999 D.Sc.(Geology) for a thesis entitled "Temporal and spatial variation of volcanism and related hydrothermal activity in the back-arc region of the Izu-Ogasawara Arc –application of laser-heating $^{40}Ar/^{39}Ar$ dating technique– at the Geological Institute, School of Science, University of Tokyo in March, 1999.
2000-2002 Post Doctoral Research Fellow at the Southampton Oceanography Centre
2000 Awarded the prize for young scientist from the society of Resource Geology
2003 Awarded the prize for young scientist from the Volcanological Society of Japan

Speciality: Ar/Ar geochronology, igneous geochemistry

List of selected publication

1. Ishizuka, O., Yuasa, M., Tamura, Y., Shukuno, H., Stern R.J., Naka, J., Joshima, M., Taylor, R.N. (2010) Migrating shoshonitic magmatism tracks Izu-Bonin-Mariana intra-oceanic arc rift propagation, *Earth and Planetary Science Letters*, 294, 111-122.
2. Ishizuka, O., Yuasa, M., Taylor, R.N., Sakamoto, I. (2009) Two contrasting magmatic types coexist after the cessation of back-arc spreading, *Chemical Geology*, 266, 283-305.
3. Ishizuka, O., Geshi, N., Itoh, J., Kawanabe, Y., Tuzino, T., (2008) The magmatic plumbing of the submarine Hachijo NW volcanic chain, Hachijojima, Japan: long distance magma transport?, *Journal of Geophysical Research*, 113, B08S08, doi:10.1029/2007JB005325.
4. Ishizuka, O. (2008); Volcanic and tectonic framework of the hydrothermal activity of the Izu-Bonin arc, *Resource Geology*, 58, 206-219.
5. Ishizuka, O., Taylor, R.N., Milton J.A., Nesbitt, R.W., Yuasa, M., Sakamoto, I. (2007) Processes controlling along-arc isotopic variation of the southern Izu-Bonin arc. *Geochemistry, Geophysics, Geosystems*, Q06008, doi:10.1029/2006GC001475.
6. Ishizuka, O., Kimura, J.I., Li, Y.-B., Stern, R.J. Reagan, M.K., Taylor, R.N., Ohara, Y., Bloomer, S.H., Ishii, T, Hargrove III, U.S., Haraguchi, S. (2006) Early stages in the evolution of Izu-Bonin arc volcanism: new age, chemical and isotopic constraints, *Earth and Planetary Science Letters*, 250, 385-401.

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EDUCATION

University of California, Santa Cruz, California, 1982-1987, Ph.D. - 1987, Dissertation title: *Turrialba Volcano, Costa Rica: Magmatism at the southeast terminus of the Central American arc*. Advisor: James Gill

University of Arizona, Tucson, Arizona, 1979-1982, M.S. - 1982, Thesis title: *Geology and Geochemistry of early arc volcanic rocks from Guam*. Advisor: Arend Meijer

University of California, Santa Barbara, California, 1975-1978, B.A. with High Honors - 1978

EMPLOYMENT

- Department chair and Professor of Geochemistry and Igneous Petrology, 2009 - present, Department of Geoscience, University of Iowa, Iowa City.
- Professor, 2007 – 2009, Department of Geoscience, University of Iowa.
- Associate Professor, 1995 - 2007, Department of Geoscience, University of Iowa.
- Guest Investigator, Fall 2000 & Spring 2008, Woods Hole Oceanographic Institute, Woods Hole, Massachusetts
- Assistant Professor, 1987 to 1995, Department of Geology, University of Iowa.
- Physical Science Technician, Summers - 1983 and 1984, U.S. Geological Survey, Vancouver, Washington.
- Geologist, Summer 1982, GeothermEx Inc., Richmond, California.
- Geologist, 1981, Freeport Exploration Co., Tucson, Arizona.
- Geologist, 1979, Noranda Exploration, Denver, Colorado.
- Geologist, 1978, WGM Inc., Anchorage, Alaska.

PROFESSIONAL AFFILIATIONS

- The Geological Society of America
- American Geophysical Union
- American Association for the Advancement of Science
- Geochemical Society
- Japan Geoscience Union
- IAVCEI

SELTECTED PUBLICATIONS RELATED TO PROJECT

Reagan, M.K., Ishizuka, O., Stern, R.J., Kelley, K.A., Ohara, Y., Blichert-Toft, J., Bloomer, S.H., Cash, J., Fryer, P., Hanan, B., Hickey-Vargas, R., Ishii, T., Kimura, J-I., Peate, D.W., Rowe, M.C., and Woods, M., 2010, Fore-arc basalts and subduction initiation in the Izu-Bonin-Mariana system. *Geochemistry Geophysics Geosystems.* v. 11, doi: 10.1029/2009GC002871, 17 pp.

Reagan, M.K., Cooper, K.M., Pallister, J.S., Thornber, C.R., and Wortel, M., 2008, Timing of degassing and plagioclase growth in lavas erupted from Mount St. Helens, 2004–2005, from ^{210}Po–^{210}Pb–^{226}Ra disequilibria, *in* Sherrod, D.R., Scott, W.E., and Stauffer, P.H., A volcano rekindled: the first year of renewed eruption at Mount St. Helens, 2004-2006: *U.S. Geological Survey Professional Paper 1750*, p. 847-856.

Reagan, M.K., Turner, S., Legg, M., Sims, K.W.W., and Hards, V.L., 2008, ^{238}U- and ^{232}Th-decay series constraints on the timescales of crystal fractionation to produce the phonolite erupted in 2004 near Tristan da Cunha, South Atlantic Ocean. *Geochimica et Cosmochimica Acta*. v. 72, p. 4367-4378.

Reagan, M.K., Hanan, B.B., Heizler, M.T., Hartman, B.S., Hickey-Vargas, R., 2008, Petrogenesis of volcanic rocks from Saipan and Rota, Mariana Islands and implications for the evolution of nascent island arcs. *Journal of Petrology*. v. 49, p. 441-464.

Reagan, M., Duarte, E., Soto, G., and Fernández, E., 2006, The eruptive history of Turrialba volcano, Costa Rica, and potential hazards from future eruptions. in Rose. W.I., Bluth, G.S.J., Carr, M.J., Ewert, J.W., Patino, L.C., and Vallance, J.W., *Geological Society of America Special Paper: 412 Volcanic Hazards in Central America*, p. 235-247.

Ishizuka, O., Kimura ,J., Li, Y.B., Stern, R.J., Reagan, M.K., Taylor, R.N., Ohara, Y., Bloomer, S.H., Ishii, T., Hargrove III, U.S., Haraguchi, S., 2006, Early stages in the evolution of Izu–Bonin arc volcanism: New age, chemical, and isotopic constraints *Earth and Planetary Science Letters*, v. 250, p. 385-401.

Reagan, M.K., Tepley III, F.J., Gill, J.B., Wortel, M., Garrison, J., 2006, Timescales of degassing and crystallization implied by ^{210}Po-^{210}Pb-^{226}Ra disequilibria for andesitic lavas erupted from Arenal volcano. *Journal of Volcanology and Geothermal Research*, v. 157, p. 135-146.

Reagan, M. K., Tepley III, F.J., Gill, J.B., Wortel, M., Hartman, B., 2005, Rapid time-scales of basalt to andesite differentiation at Anatahan volcano, Mariana Islands. *Journal of Volcanology and Geothermal Research*, v. 146, p. 171-183.

Reagan, M.K., Sims, K.W., Erich, J., Thomas, R.B., Cheng, H., Edwards, R. L, Layne, G., and Ball, L., 2003, Timescales of differentiation from mafic parents to rhyolite in North American continental arcs. *Journal of Petrol*ogy, v. 44, p. 1703-1726.

Reagan, M.K., and Meijer, A., 1984, Geology and geochemistry of early arc rocks from Guam. *Geol. Soc. Am. Bull.*, v. 95, p. 701-713.

Meijer, A., and Reagan, M.K., 1983, Origin of K_2O-SiO_2 trends in volcanoes of the Mariana Arc. *Geology*, v. 11, p. 67-71.

Meijer, A., Reagan, M., Ellis, H., Shafiqullah, M., Sutter, J., Damon, P., and Kling, S., 1982, Chronology of volcanic events in the eastern Philippine Sea. in Hayes, D.E. (ed.), The tectonic and geologic evolution of Southeast Asian seas and islands: part 2: *American Geophysical Union Monograph* 27, p. 349-359.

Meijer, A., Anthony, E.Y., and Reagan, M.K., 1982, Petrology of the volcanic rocks from the fore-arc sites. in Hussong, D.M., Uyeda, S., et al., *Initial reports of the Deep Sea Drilling Project*, v. 60, p. 337-354.

Meijer, A., and Reagan, M., 1981, Petrology and geochemistry of the island of Sarigan in the Mariana Arc: calc-alkaline volcanism in an oceanic setting. *Contributions to Mineralogy and Petrology*, v. 77, p. 337-354.

Published Geological Maps

Siegrist, H.G. Jr. and Reagan, M.K., 2007, Geologic map and sections of Guam, Mariana Islands. Published by University of Guam.

SYNERGISTIC ACTIVITIES

Co-chief scientist YK06-12 and YK08-8 cruises of R.V. Yokosuka and Shinkai 6500
Served on MARGINS steering committee 2003-2006
Cos-sponsor of special sessions at the fall AGU. IAVCEI and Goldschmidt meetings on topics related to the project
Lead guest editor for special issue of Journal of Volcanology and Geothermal Research entitled: Arenal Volcano, Costa Rica: Magma Genesis and Volcanological Processes, 2005-2006
Co-convener for a special session at the: IAVCEI General Assembly in Santiago Chile, 2004.
Co-organizer for SOTA (State of the Arc) 2003 meeting at Mount Hood Oregon, August 16-21, 2003
Advised thesis research projects involving petrology and geochemistry for 13 current or former graduate students and 14 undergraduate students