IODP Proposal Cover Sheet

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Title:	Continental Crust Formation at Intra-Oceanic Arc: Ultra-Deep Drilling to the Middle Crust of the Izu-Bonin-Mariana Arc
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Permission to post abstract on IODP Web site: ■ Yes ☐ No

Abstract: (*400 words or less)*

This proposal is for the ultra-deep drilling site of a series of IODP proposals in the Izu-Bonin-Mariana (IBM) arc that aim at comprehensive understanding of arc evolution and continental crust formation. We propose to drill a deep hole that penetrates through a complete sequence of intra-oceanic arc upper crust and into the *in situ* middle crust that may be a nucleus of continental crust. The average continental crust possesses an intermediate composition (~60 wt.% SiO_2), which raises the question of how intra-oceanic arcs produce continental crust if the dominant product of mantle wedge melting and a major proportion of intra-oceanic arc lava are basaltic (50 wt.% SiO_2). There is no pre-existing continental crust in the IBM upper plate, yet recent seismic studies of this arc reveal a thick middle crust layer with 6.0-6.8 km/s *Vp* that is hypothesized to be intermediate in composition. The primary goals of sampling the *in situ* arc crust through drilling are: (1) to identify the structure and lithologies of the upper and middle crust, (2) to test seismic models of arc crustal structure, (3) to constrain the petrologic and chronological relationship of the middle crust to the overlying upper crust, (4) to establish the evolution of arc crust by relating this site with other regional drill sites and exposed arc sections, and (5) to test competing hypotheses of how the continental crust forms and evolves in an intra-oceanic arc setting. These objectives address questions of global significance, but we have specifically identified the IBM arc system as an ideal locale to conduct this experiment. The composition of the pre-subduction upper plate was normal oceanic crust, and the tectonic and temporal evolution of this arc system is well-constrained. Moreover, the IBM system is considered as the best-studied intra-oceanic arc on Earth by extensive sampling of the slab inputs and arc outputs through field studies and drilling, and by a series of recent, focused geophysical surveys. We propose returning to the region of ODP Site 792 to drill, *via.* Eo-Oligocene upper crust, to the middle crust at proposed site IBM-4. The mid-crustal layer in this area is shallow enough to be reached by drilling, and heat flow is low enough for drilling to proceed at mid-crustal temperatures. Samples recovered from IBM-4 will complement the drilling objectives at other proposed sites in Eocene (IBM-2) and Neogene (IBM-3) arc crust and pre-arc oceanic crust (IBM-1), which are proposed separately.

Scientific Objectives: (*250 words or less*)

Petrologic objectives focus on (1) identifying the lithology, bulk composition, and structure of the rocks that comprise the *in situ* upper and middle crust beneath the Eo-Oligocene IBM arc; (2) establishing the age and thermal/petrologic history of the IBM middle crust and its temporal and petrologic relationship to the upper crust overlying it; (3) relating the petrology, structure, and composition of this mature arc crustal section to equivalent sequences from older (Eocene; IBM-2) and younger (Neogene; IBM-3) arc crust from the same system, to upper- and mid-crustal rocks exposed in accreted arc terranes, and to rocks that represent middle and bulk continental crust; and (4) testing models of the formation of arc middle crust, i.e., simple fractionation of mantle-derived basalt or andesite magmas vs. partial melting of mafic arc crust. The main geophysical objective focuses on using the recovered rocks and borehole data from this deep crustal site to evaluate geophysical models of the seismic velocity structure of the IBM arc crust, i.e., a layered structure with relatively homogeneous velocities within each layer *vs.* a gradational crustal velocity structure.

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

Proposed Sites:

Site Name	Position	Water Depth (m)	Penetration (m)			Brief Site-specific Objectives
			Sed	Bsm	Total	
IBM-4	32°24’N 140°23’E	1798	800	4700	5500	2000m penetration into the middle crust. 886 m of the necessary sampling at the IBM-4 Site has already been done by ODP Leg 126 Site 792

An IODP Proposal (698-Full3)

Continental Crust Formation at Intra-Oceanic Arc:
Ultra-Deep Drilling to the Middle Crust of the Izu-Bonin-Mariana Arc

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1. INTRODUCTION

The Earth's oceanic and continental crusts are fundamentally different. Basaltic oceanic crust, which is the most abundant igneous rock at the Earth's surface, is a direct product of mantle melting. Continental crust, on the other hand, occupies only 0.4% of the Earth's total mass and has an intermediate (~60wt.% SiO_2), 'differentiated' composition (e.g. Christensen and Mooney, 1995; Kelemen, 1995; Taylor, 1995; Rudnick, 1995). Since such intermediate igneous rocks typify magmatism at convergent plate boundaries, arcs may thus play a central role in continental crust formation (McLennan and Taylor, 1982). Yet the means by which the initial arc crust, composed of mantle-derived mafic magma, transforms into intermediate bulk continental crust composition remain largely unknown. The IODP Initial Science Plan (ISP) identified the origin of continental crust as a primary target of the program, stating: *'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'* (p.67).

In order to explain the intermediate composition of the bulk continental crust, two processes are postulated to occur: 1) Differentiated magmas of intermediate composition must be generated, either by fractionation of mafic melts or by anatexis of mafic crust, and 2) a significant fraction of mafic to ultramafic crust components must be removed from the crust (e.g., Rudnick 1995; Tatsumi, 2005). In addition, mantle-derived, primary andesites such as boninites could occupy an important part of the continental crust (e.g., Shirey and Hanson, 1984; Kelemen et al., 2003).

Island arcs are clearly better places to examine these hypotheses than continental arcs, as the effects of pre-existing crust, which should contribute to the crustal growth processes via complex interaction, are minimized at intra-oceanic arcs where the upper plate is initially basaltic. High-resolution seismic profiles along and across the inter-oceanic Izu-Bonin-Mariana (IBM) arc crust (Suyehiro et al., 1996; Kodaira et al., 2007; Takahashi et al., 2007) reveal a thick middle crust with a P-wave velocity (*Vp*) of 6.0-6.8 km/s, a value equivalent to the average *Vp* of continental crust and typical of plutonic rocks having intermediate compositions (Christensen and Mooney, 1995). This characteristic layer has thus been interpreted as intermediate in composition (Kitamura et al., 2003; Takahashi et al., 2007;

Tatsumi et al., 2008a). This interpretation is supported by the presence of tonalitic xenoliths in lavas and as exposures along intra-oceanic arcs such as the IBM and Kyushu-Palau systems (e.g., Sakamoto et al., 1999), and by the exposure of tonalitic plutons in the Tanzawa Mountains of central Honshu, where the IBM arc collides with Honshu Island (Kawate & Arima, 1998; Tani et al., 2010). Furthermore, the presence of a characteristic middle crust layer with *Vp*=6.0-6.8 km/s has been documented for other oceanic arcs such as Tonga (Crawford et al., 2003) and Kurile (Nakanishi et al., 2009). These lines of evidence provide a compelling foundation supporting the challenging hypothesis that the ingredients for continental crust are indeed created in modern intra-oceanic arcs. The ISP states: '*IODP will drill into juvenile oceanic arcs, ideal sites for addressing this question… Probing the possible new "continental root" beneath juvenile oceanic arcs by IODP will be a tremendous step towards understanding the origin of the andesitic continental crust'* (p.67). Indeed, scientific ocean drilling is necessary to further resolve the questions of crustal evolution at intra-oceanic arcs because it is the only method that will provide a continuous, *in situ* record of petrological, geophysical and geochemical properties of upper and middle arc crust. This *in situ* record can then be used as a reference site for many other arcs worldwide. Such a comprehensive and undisturbed crustal profile cannot be obtained or investigated in an oceanic arc setting by any other means.

This proposal, which is the direct outcome of extensive international dialog at seven workshops held in 2002 (Honolulu), 2006 (Yokohama, San Francisco), 2007 (Tokyo, Honolulu), 2009 (San Francisco) and 2010 (Tokyo), describes the consensus rationale and scientific objectives for an ultra-deep, riser drilling project designed for decoding crustal structure and evolution of the arc crust at the intra-oceanic IBM subduction system (Fig. 1). The IODP Science

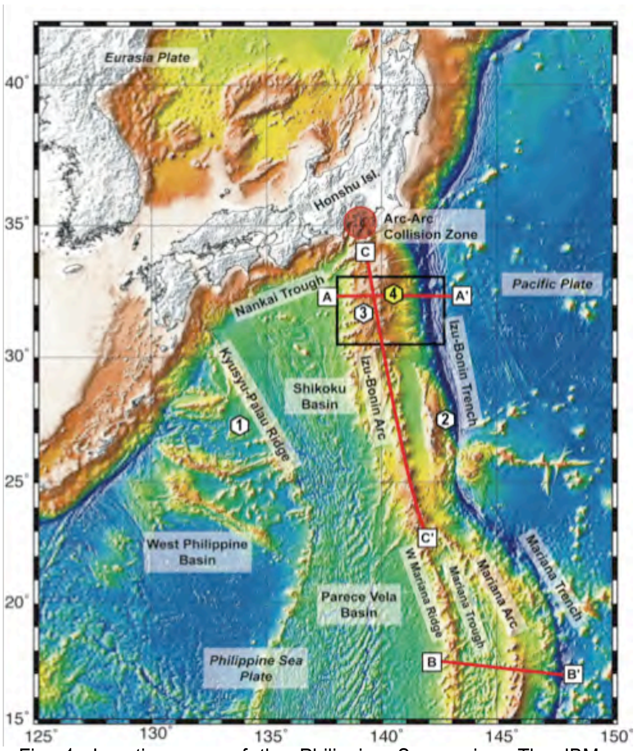

Fig. 1. Location map of the Philippine Sea region. The IBM arc-trench system forms the convergent margin between Pacific and Philippine Sea plates. Backarc basins such as Shikoku Basin, Parece Vela Basin and Mariana Trough were created by seafloor spreading between the formerly contiguous remnant arc (Kyushu-Palau and West Mariana ridges) and the active IBM arc. At its northern tip, the IBM arc has collided with the Honshu since 15 Ma. Red lines locate some of the refraction and wide-angle reflection seismic data shown in Figs. 3 and 4. Numbers show a series of proposed drilling sites as Project IBM.

Planning Committee (SPC) evaluated the original proposal 698-Full2 and two addenda and stated: '*SPC recognizes the strengths of this proposal, but notes that the objectives and/or site characterization of the proposal and additions, in their present form, differ enough from the original version as evaluated by SSEP and external reviewers that a revised proposal is required for adequate assessment.*' In response to this review, we provide here a revised proposal that includes a comprehensive discussion of new data that updates the site characterization relative to the original proposal. The new seismic data crossing the precise location of the proposed drilling site indicate that the top of the characteristic middle crust layer is significantly shallower (~3.5 km) than identified in older, near-site seismic data discussed in the original proposal (~6-7 km). We emphasize that, although the depth of this reference point has shallowed, the over-arching scientific objectives, rationale, and execution plan for the proposed drilling remain unchanged.

2. TECTONIC FRAMEWORK AND CONTEXT OF THE IBM SYSTEM

2.1. The IBM system

The IBM arc system extends 2800 km from the Izu Peninsula to Guam Island (Fig. 1). This system is uniquely suited to the study of arc crustal evolution for several reasons. IBM is a juvenile intra-oceanic arc system that is characterized by a well-developed, low-velocity middle crust with *Vp*=6.0-6.8 km/s of intermediate composition (Suyehiro et al., 1996; Kodaira et al., 2007; Takahashi et al., 2007), which is typical of many intra-oceanic arcs (Figs. 2 and 3). Moreover, the IBM system has been the subject of intense study because it is the intra-oceanic arc focus site of the US-NSF MARGINS 'Subduction Factory' experiment and for the Japanese Continental Shelf Project. This international focus has resulted in an extensive scientific legacy of land- and sea-based research in this region.

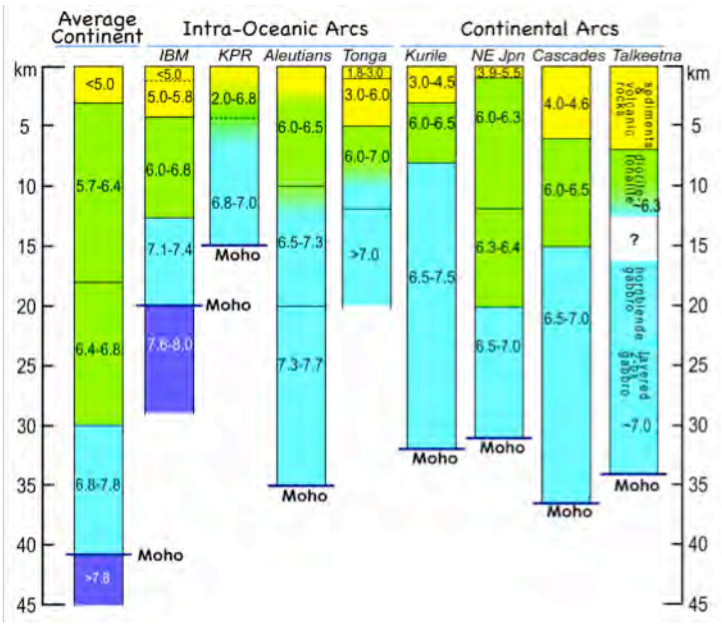

Fig. 2. Schematic seismic velocity structure of representative continental crust, intra-oceanic and continental arcs. The middle crust with *Vp*=6.0-6.8 km/s (green), which is the average velocity of the continental crust, characterizes the arc crust, suggesting the continental crust is creating in subduction zones. Data from: Christensen and Mooney, 1995; Crawford et al., 2003; Holbrock et al., 1999; Iwasaki et al., 2001; Nakanishi et al., 2009; Parsons et al., 1998; Shillington et al., 2003; Takahashi et al., 2007.

The tectonic history and evolution of the IBM arc and associated back-arc basins is better known than in any other intra-oceanic arc system. Past drilling investigations of IBM arc crust have advanced our understanding of early arc crust (e.g., Taylor, Fujioka et al., 1990; Arculus et al., 1992). Moreover, the combination of geochemical studies of primitive IBM arc/back arc lavas and drilling into sediment and altered oceanic crust sequences in the subducting Pacific plate has provided important new constraints on mass balance across the modern IBM subduction zone (e.g., Elliott et al., 1997; Taylor and Nesbitt, 1998; Plank et al., 2000; Kelley et al., 2003; Hauff et al., 2003; Kelley et al., 2005; Savov et al., 2005; Plank et al., 2007; Ishizuka et al., 2003, 2006, 2009; Tamura et al., 2005, 2007; Tatsumi et al., 2008a; Tatsumi and Suzuki, 2009). These recent studies address the transfer of material from the subducting plate to the sub-arc mantle, and from the mantle to the surface as primitive basaltic magma.

2.2. Seismic structure and inferred compositions of crust and upper mantle

High-resolution, active-source, wide-angle seismic experiments revealed the architecture of the IBM system (Suyehiro et al., 1996; Kodaira et al., 2007; Takahashi et al., 2007; Sato et al., 2009). One distinctive structural feature of this arc is the presence of a middle crust layer with *Vp* of 6.0-6.8 km/s (Fig. 3), which has been further confirmed throughout the entire IBM arc (Fig. 4). An additional novel feature of the sub-IBM seismic structure is the occurrence of an uppermost mantle layer having an average *Vp* of 7.2-7.6 km/s, significantly lower than that of typical sub-oceanic uppermost mantle (>7.6 km/s). Importantly, this low-V layer is bordered by the Moho discontinuity at the top and a seismic reflector at the base (Fig. 4).

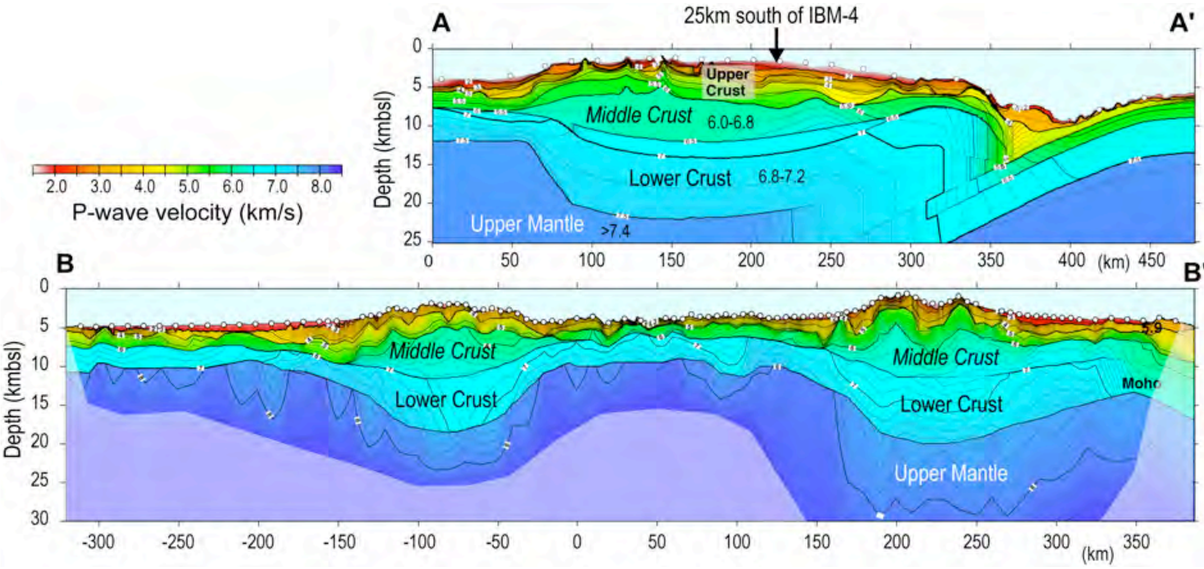

Fig. 3. *Vp* structure of AA' and BB' sections (Fig. 1) of the IBM after Suyehiro et al. (1996) and Takahashi et al. (2008), respectively. Distribution of a middle crust layer with *Vp of* 6.0-6.8 km/s characterizes the IBM arc crust. AA' represents the cross-arc section 25km south of the proposed IBM-4 site.

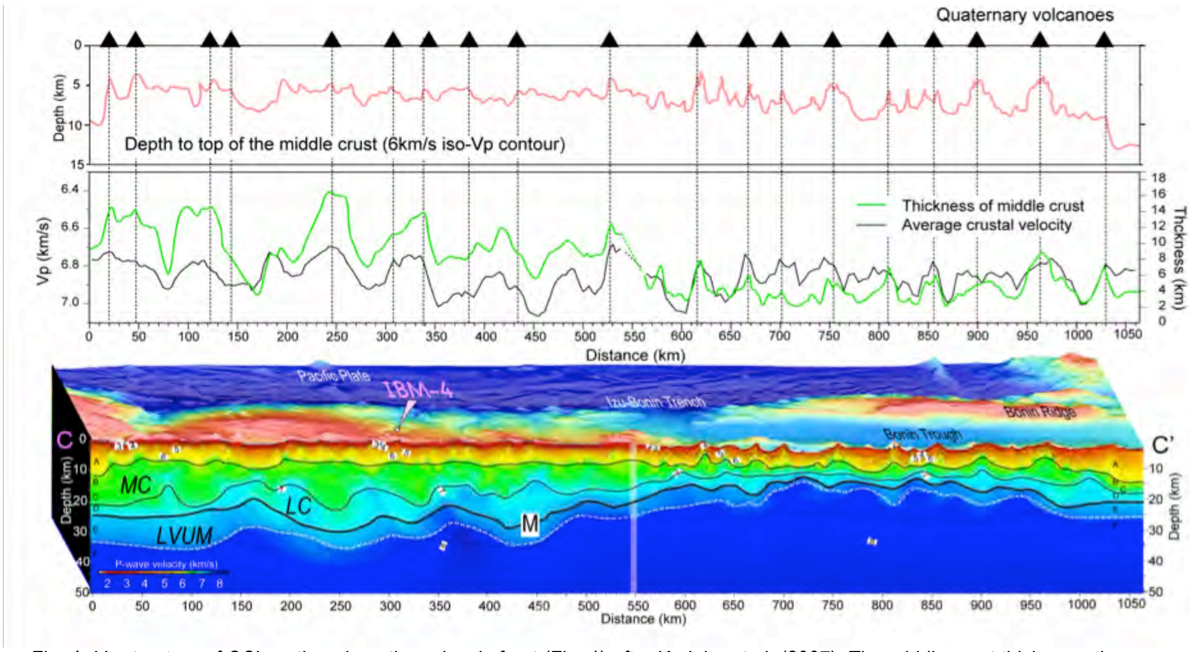

Fig. 4. *Vp* structure of CC' section along the volcanic front (Fig. 1) after Kodaira et al. (2007). The middle crust thickness, the average *Vp* of the total crust and the depth to the top of the middle crust correlate well with the volcano distribution (filled triangles). MC, middle rust; LC, lower crust; LVUM, low-V upper mantle; M, Moho discontinuity.

The observed seismic structure of the sub-IBM crust and mantle has been petrologically modeled as a two-stage process (Tatsumi et al., 2008a), by which a mantle-derived basalt fractionates ~20% olivine cumulate to form the initial mafic arc crust (LC in Fig. 5) and then basaltic underplating causes anatexis of this initial crust to produce an andesitic melt. Such an andesite could solidify to form the characteristic IBM middle crust with a composition similar to that of the bulk continental crust (MC in Fig. 5), and the anatectic residue, together with olivine cumulates, could form the uppermost mantle layer (LV-UM in Fig. 5). The *Vp* calculated for the modeled compositions for each layer of the IBM crust are consistent with the observed values (Fig. 5a), providing a strong and testable hypothesis for how intra-oceanic arcs may create continental crust.

Regional dredges of fault scarps also reveal exposures of tonalite both at the IBM arc and the Kyushu-Palau Ridge (KPR; Table 1). The KPR is a remnant paleo-IBM arc separated

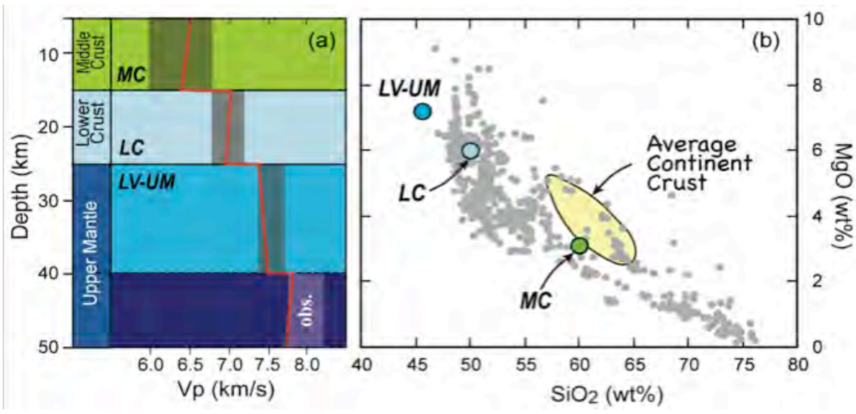

Fig. 5. Generalized *Vp* structure and compositions of the sub-IBM crust/mantle after Tatsumi et al. (2008a). (a) Observed (hatched) and calculated (red line) *Vp* of crust/mantle. (b) Middle and lower crust (MC and LC) and uppermost mantle (LV-UM) compositions inferred from IBM rock compositions (grey circles) and a plausible melting/differentiation regime.

from the modern volcanic arc by back-arc opening of the Shikoku Basin (Fig. 1). A seismic study across the KPR obtained a velocity structure that is similar to that of IBM, including a ~6 km/s middle crust layer and a thick, high velocity lower crust (Nishizawa et al., 2007). The observed structural similarities at IBM and KPR suggest that the intermediate middle crust began to develop early in the evolution of the IBM system, prior to the Shikoku basin opening at ~25 Ma.

Table 1. Radiometric ages of intermediate to felsic plutonic rocks from IBM

Location	Occurrence	Tectonic Setting	Rock type	SiO_2 (wt.%)	Radiometric Age (Ma)*
Tanzawa	intrusive	collision zone	Gabbro-Tonalite	43.0-71.1	4.1-5.6 (Zr)
Kogarasu	intrusive	collision zone	Granodiorite	62.7-63.9	4.2 (Zr)
Mineoka belt	xenoblock	collision zone	Tonalite	58.3-59.6	33.8-40.5 (Zr)
Miyakejima	xenolith	volcanic front	Gabbro-Tonalite	-	-
Mikurajima	xenolith	volcanic front	Gabbro	47.8-54.3	-
Minami-Hachijyo caldera	xenolith	volcanic front	Tonalite	-	0.04 (Hb Ar)
Niijima	xenolith	reararc chain	Tonalite	63.5-75.7	<1 (Zr)
Manji Smt.	intrusive	paleo-reararc chain	Tonalite	62.3-76.7	6.5-6.7 (Zr)
Omachi Smt.	intrusive	paleo-volcanic front	Gabbro	50.6	38.6 (Zr)
Chichijima	xenolith	paleo-volcanic front	Tonalite	-	-
Sofugan Tectonic Line	xenolith	volcanic front	Tonalite	-	6.0 (Wh Ar)
North Mariana Trough	intrusive	back-arc rift	Gabbro-Tonalite	47.3-72.9	1.5-1.7 (Zr)
Komahashi-Daini Smt.	intrusive	paleo-volcanic front	Tonalite	56.5-75.2	38.9 (Zr)

* (Zr) = Zircon U-Pb; (Hb Ar) = Hornblende Ar-Ar; (Wh Ar) = Whole-rock Ar-Ar.

2.3. Tectonic history

The IBM system began as part of a hemispheric-scale foundering of old, dense lithosphere in the Western Pacific (Bloomer et al. 1995; Stern 2004). The beginning of large-scale lithospheric subsidence, not true subduction, is constrained to have begun just after 50 Ma (Bloomer et al. 1995; Cosca et al. 1998). After ~5 million years of spreading and a period of transition (45-42 Ma), magmatic activity localized at, and built, the first modern-style island arc, allowing the forearc lithosphere to cool, beginning in Late Eocene time (Taylor, 1992; Ishizuka et al., 2006). The age of initiation of down-dip subduction brackets the revised age of 47 Ma for the change in Pacific Plate motion from a northerly to more westerly direction recorded by the bend in the Emperor-Hawaii seamount chain (Wessel et al., 2006).

The IBM arc was stable until about 30 Ma, when active back-arc developed spreading along a NNW-SSE axis in the W. Philippine Sea (Deschamps et al. 2002; Taylor and Goodliffe 2004). Spreading began in the south, forming the Parece Vela Basin, and propagated north (Okino et al. 1998). Spreading began in the northernmost part of the IBM arc at about 25 Ma and propagated south to form the Shikoku Basin (Kobayashi et al. 1995; Okino et al. 1999). This episode of back-arc spreading also split off the KPR as a 'remnant arc.' The Shikoku Basin and Parece Vela Basin spreading systems intersected at about 20 Ma, when spreading shifted from an E-W to a NE-SW orientation and slowed significantly (Okino et al. 1999). The cessation of spreading at about 15 Ma coincided with dramatic tectonic activity along the northern boundary of the Philippine Sea Plate, including major rotations of the Japanese islands associated with the opening of the Sea of Japan. This also caused the northernmost IBM arc to collide with Honshu beginning at ~15 Ma (Itoh, 1986). A new episode of rifting of the southern IBM arc began at ~7 Ma, with seafloor spreading forming the Mariana Trough back-arc basin at about 3-4 Ma (Bibee et al. 1980; Yamazaki and Stern 1997), splitting off the W. Mariana Ridge as a remnant arc.

2.4. Magmatic evolution

The IBM arc displays a time-progressive geochemical and volcanic evolution from arc initiation through maturation. This evolution is intimately linked with the mass fluxes from slab and mantle sources. For example, the four major IBM magma series (boninitic, low-K tholeiitic, medium-K calc-alkaline, and K-rich series) originate from sources that are distinct in terms of source-sensitive isotopes and trace elements. The initial IBM magmatism is characterized by the occurrence of ‘fore-arc basalt’ with MORB-like but subduction-flavored compositions (Reagan et al., 2010). Two outstanding events in the arc's tectonic evolution (i.e., arc splitting and backarc formation) caused further changes in the sub-arc mantle reservoir resulting in the transition from boninitic to tholeiitic volcanism, coupled with time-sensitive trends in isotope and element tracers (Schmidt, 2001). Changes in Sr and Pb isotopes likely reflect changing slab input (Schmidt, 2001; Taylor and Nesbitt, 1998), whereas the increase in Nd isotope ratios likely reflects the evolution from the ultra-depleted, boninitic mantle source of the Eocene to the moderately-depleted, Indian MORB-type mantle source of the Neogene. In addition to these, other causes such as inherent mantle heterogeneity of Indian MORB-type mantle (Hickey-Vargas, 1998), complex mantle processing related to arc inception (Stern, 2004), and co-existence of distinct mantle types (Straub, 2003), may also contribute to the isotopic variations. The prominent K-variability of arc lavas through space and time also relates to variable source input. One simple model relates the K-variability to a changing flux from the slab that alternates between fluid-like (K-poor) and melt-like (K-rich) components, reflecting variable P-T conditions along the slab surface in response to subduction geometry (Straub, 2003; Ishizuka et al., 2003). Alternatively, K-rich source components may also be present in the Indian MORB-type mantle that is advected into the subarc mantle wedge (Taylor and Nesbitt, 1998; Hochstaedter et al., 2000, 2001).

2.5. Tanzawa plutonic complex: accreted IBM deep crust?

The Tanzawa plutonic complex (TPC), central Japan, is a suite of tonalitic-gabbroic plutons exposed in a globally unique arc-arc collision zone, where the IBM arc is colliding against the Honshu arc (Fig. 1). A recent paleomagnetic and biostratigraphic study has shown that the progressive Tanzawa block collision took place from 7 Ma to 4 Ma (Yamamoto and Kawakami, 2005). The TPC is chiefly composed of tonalitic plutons, as well as subordinate tonalitic and gabbroic units and has been widely accepted as an exposed middle crust section of the IBM arc because of geochemical similarities between the TPC and IBM rocks (Kawate and Arima, 1998; Tamura et al., 2010) and previously reported pre-collisional Miocene K-Ar ages (Yamada and Tagami, 2008). If so, then on-land surveys of the TPC, including drilling, would offer a much easier and more appropriate approach to accessing the arc middle crust than the direct sampling of the deep IBM arc crust by ocean drilling. Newly obtained zircon U-Pb ages from TPC plutons, however, cluster at ca. 5–4 Ma, clearly showing that the main pulse of TPC emplacement was simultaneous with the progressive collision of the Tanzawa block (Tani et al., 2010). The TPC thus does not represent the deeper, *in situ* section of the IBM arc crust; instead, the TPC is the product of syn-collisional magmatism that may have been caused by remelting of the accreted IBM deep crust during the arc-arc collision (Tani et al., 2010; Tamura et al., 2010). Direct sampling of the *in situ* arc middle crust is therefore still necessary in order to access unmodified arc lithologies.

3. DRILLING OBJECTIVES

3.1. Overall drilling plan

3.1.1. Site selection strategy

In order to achieve the goals of this project, the proposed drill site must meet two essential criteria. First, the middle crust with Vp=6.0-6.8 km/s must be accurately located in conjunction with other layers characteristic of the IBM arc crust, including low-velocity uppermost lower crust, high-velocity lower crust, low-velocity uppermost mantle, and reflectors separating these layers. Second, the characteristic middle crust must be reachable within the operating limits of the riser vessel Chikyu, which requires <2500m water depths, <10000m from the sea surface to the top of the target mid-crustal layer, and <250°C borehole temperature.

Based on the above requirements and consideration of other proposed drilling sites in the IBM arc crust, we have selected Site IBM-4, along the cross-arc section of the northern

Izu arc at ~32°N (Fig. 1), as a location that best meets the drilling requirements and project objectives. This across-arc section has been extensively surveyed both by drilling and non-drilling-based investigations. Previous ocean drilling campaigns, mostly from along this section, have provided breakthroughs in our understanding of arc evolution (Legs 60, 125, and 126) and have prompted geophysical studies of the regional crustal structure (Suyehiro et al. 1996). Two key observations along this section indicate that this latitude is the most suitable for the proposed drilling:

(1) The age of the upper crust decreases systematically with increasing distance from the trench. Volcanic rocks having MORB-like chemistry, which may represent the pre-existing oceanic crust or the initial arc basalt for the IBM arc system, were recovered from the trench slope of this across-arc section (DeBari et al., 1999; Reagan et al., 2010) . A series of drill sites (ODP Leg 125) documented the distribution of Middle Eocene (45-48 Ma; Taylor, Fujioka et al., 1990) juvenile arc basement at site 786 and Late Eocene (37 Ma; Ishizuka et al., 2006) mature arc upper crust at site 792, located on the Eo-Oligocene volcanic front between site 786 and the present volcanic front.

(2) The seismic survey of the crust and upper mantle along this section indicates the layered structure that typifies the crust/mantle of the entire IBM arc (Fig. 2), and provides the necessary geophysical reference for the depth of the target mid-crustal layer. The upper boundary of the middle crust layer (Vp=6.0 km/s) is accurately located in this region by two consistent across-arc seismic profiles (Suyehiro et al., 1996; Continental Shelf Project, in prep.), and is reachable by riser drilling in the mature, Eo-Oligocene arc section.

With these constraints in mind, we propose locating site IBM-4 proximal to ODP Site 792 (Figs. 1 and 6). Site 792 was drilled to 886 mbsf through Quaternary to Eocene volcaniclastic sediments that buried a volcanic edifice identified in MCS seismic surveys. The hole penetrated 82 m into basement and recovered basaltic to andesitic lava flows. The site is 1798 m below sea level, and is located about 60 km east (trenchward) of the Quaternary Aoga-shima volcano. The buried edifice is an Oligocene to Eocene volcanic center along the N-S Shinkurose Ridge (Honza and Tamaki, 1985).

The basement at site 792 starts with massive lava and breccia intercalated with thin hyaloclastite layers (Taylor, Fujioka et al., 1990). Rock types range from basalt to rhyolite but are mostly calc-alkaline andesite. The lavas are non-vesicular and porphyritic with a phenocryst mineralogy of plagioclase + clinopyroxene + orthopyroxene + magnetite ± quartz. Quartz in these lavas exhibits rounded, disequilibrium textures, suggesting a xenocrystic origin. The lavas are similar in average composition to the Oligocene turbidites above them (Gill et al., 1994), and in trace element and isotopic composition to Oligocene glass shards in distal tephra drilled at Site 782A (Schmidt, 2001; Bryant et al., 2003; Straub, 2003). All of these differ from Neogene upper crustal volcanic front lavas in having lower Ba/La, flatter REE patterns (vs. light REE depletion in the Neogene), lower HFSE concentrations relative to MgO (e.g., TiO_2), and lower $^{143}Nd/^{144}Nd$ and $^{206}Pb/^{204}Pb$ ratios. They overlap in these respects with non-boninitic Eocene volcanic rocks. Since the recovered rocks from site 792 are variable in composition, penetration of the entire upper crust is necessary for establishing the average composition of the upper crust, which is critical towards understanding crustal differentiation processes.

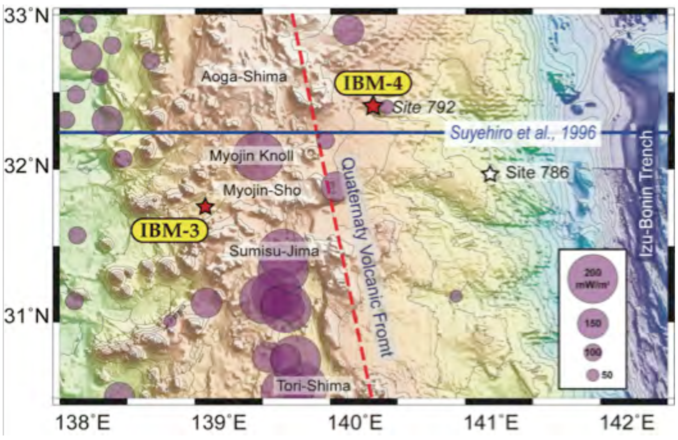

Fig. 6. Location map of the proposed drilling site (IBM-4). Other sites proposed as a project IBM (IBM-3) and drilled in ODP are also shown. The existing heat flow measurement data suggest high heat flow along the volcanic front of IBM. IBM4 is located 25 km north of the previously surveyed sesmic line (Suyehiro et al., 1996)

This site was selected as the optimal location for reaching the IBM middle crust for several reasons:

- **Structure.** Since the proposed site is located close to the across-arc seismic line (Fig. 6), the crustal structure beneath this site is expected to be similar essentially to that shown in the seismic cross section of Suyehiro et al. (1996), which has a seismic structure representative of the IBM crust (Figs. 3 and 4). With an estimated total basement depth of 8 km, using depth constraints from Suyehiro et al. (1996), this site would penetrate the entire upper crust and into ~2 km of the middle crust. However, the seismic crustal structure proposed by Suyehiro et al. (1996) was obtained by a forward method and could not evaluate the uncertainty for the depth to each crustal layer. Furthermore, along-arc variation in crustal structure will contribute to uncertainty in the depth to the middle crust layer. In order to overcome these existing problems, we conducted seismic experiments in 2008 that directly cross the proposed IBM-4 site and discuss these results in section 3.1.2.
- **Temperature.** Borehole temperature measurements and three excellent Uyeda-probe temperature measurements down to 110 mbsf define heat flows of 30-70 mW/m^2 (Fig. 6). This predicts borehole temperatures at 8 km basement depth of <250°C, which are low

enough to be drillable using existing technology. It is, however, evident that further heat flow measurements in this region are required in order to identify the optimal drilling site.

- **Age.** Constraints on the age of upper crustal basement rocks at Site 792 (37 Ma; Ishizuka et al., 2006) indicate that this crustal section formed in the Late Eocene to Oligocene. Based on the age, the composition of lavas from Site 792, and the seismic velocity structure of the crust, we anticipate that the arc crust was mature at this time. The temporal evolution of the upper and middle crust composition may be directly examined by comparison with mid-crustal rocks proposed to be recovered at Eocene site 786 (Fig. 6), which represents the early construction of IBM crust.
- **Depth.** At 1798 m below sea level, the region of Site 792 is well within the 2.5 km water depth limit required for riser drilling.

Although the mid-crustal layer appears thicker and shallower beneath the active arc (Fig. 3), higher geothermal gradients expected closer to the active Izu arc may potentially preclude a drilling target location any further to the west than Site 792 (IBM-4V; Figs. 3 and 6). The *Vp*=6.0 contour also appears shallower to the east of proposed site IBM-4 (IBM-4F; Figs. 3 and 6), although it is also much thinner. The crust will likely be older to the east, and the middle crust in this region may be composed of rocks produced by the early IBM magmatism, and thus may be less mature. Water depths are also deeper further to the east and, where the *Vp*=6.0 km/s contour appears shallowest, water depth may be too deep for riser drilling. We have carefully weighed the advantages and disadvantages of a range of possible locations along this section of the arc, and have concluded that the current location of IBM-4 is optimal given the existing data and constraints.

3.1.2. Seismic imaging of an Upper-Eocene volcanic body with domal structure and the depth to the top of middle crust

In order to better image the intra-crustal structure and to precisely define the upper/middle crust boundary beneath the IBM-4 site, seismic experiments were conducted in 2008 using the JAMSTEC research vessel, KAIREI (Fig. 7). An OBS array was set at 1-km intervals. These data obtained from two sections, IBM4-EW5 and IBM4-NS5, which cross the proposed IBM-4 site are shown (Figs. 7-9).

Fig. 8 shows a time-migrated MCS section along the EW profile through the proposed site IBM-4, which clearly images a basement high beneath the site, as well as an extensive arc-parallel normal fault system consistent with an extensional regime. The MCS section,

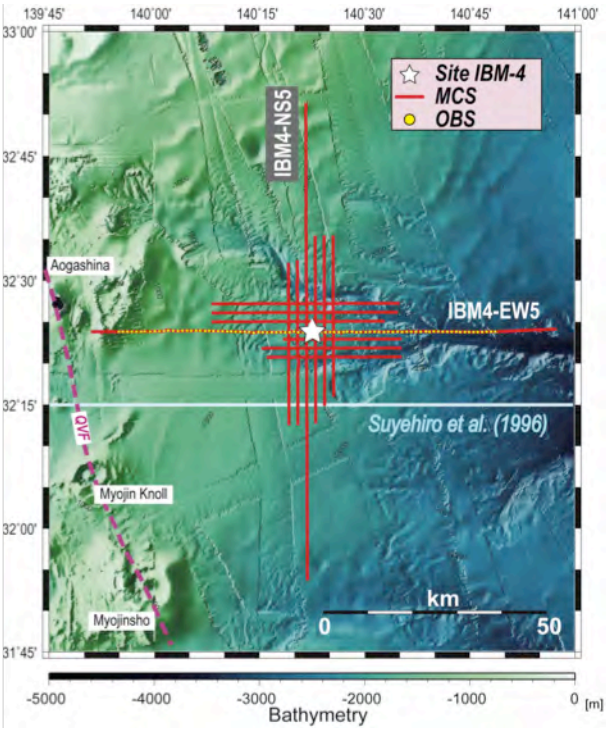

Fig. 7. Location of the proposed Site IBM-4 (open star) and MCS-OBS seismic lines surveyed in 2008 and Suyehiro et al. (1996). QVF, Quaternary volcanic front of the IBM arc.

together with the core recovered from ODP Site 792, indicate that the section above the basement high comprises silt, clay, pumiceous sand/sandstone and pumiceous gravel, of ages from the Quaternary to the Oligocene (Units I to IV in Fig. 8). At the top of the basement high, andesitic lavas were sampled at ~800 mbsf (Unit VI in Fig, 8). A 3-D view of the seismic reflection sections crossing the IBM-4 site (Fig. 9) demonstrates that the basement high beneath the Site forms a conical domal structure. Recovery of andesitic lava from the base of ODP Site 792 led Taylor (1992) to speculate that this site hit an ancient volcano, a conclusion that is confirmed by our seismic imaging of the conical structure and our interpretation of these MCS sections (Figs. 8 and 9). K-Ar dating of the andesitic lavas (Taylor, Fujioka et al, 1992) yielded ages of 33.3 ±1.2 Ma (whole rock) and 37.7 ±2.3 Ma (amphibole), but re-dating of the samples using the Ar-Ar method (Ishizuka, unpublished) indicates crystallization ages of 37.3-41.7 Ma for these andesitic lavas. Therefore, the domal structure imaged beneath the IBM-4 Site is an upper Eocene volcanic body.

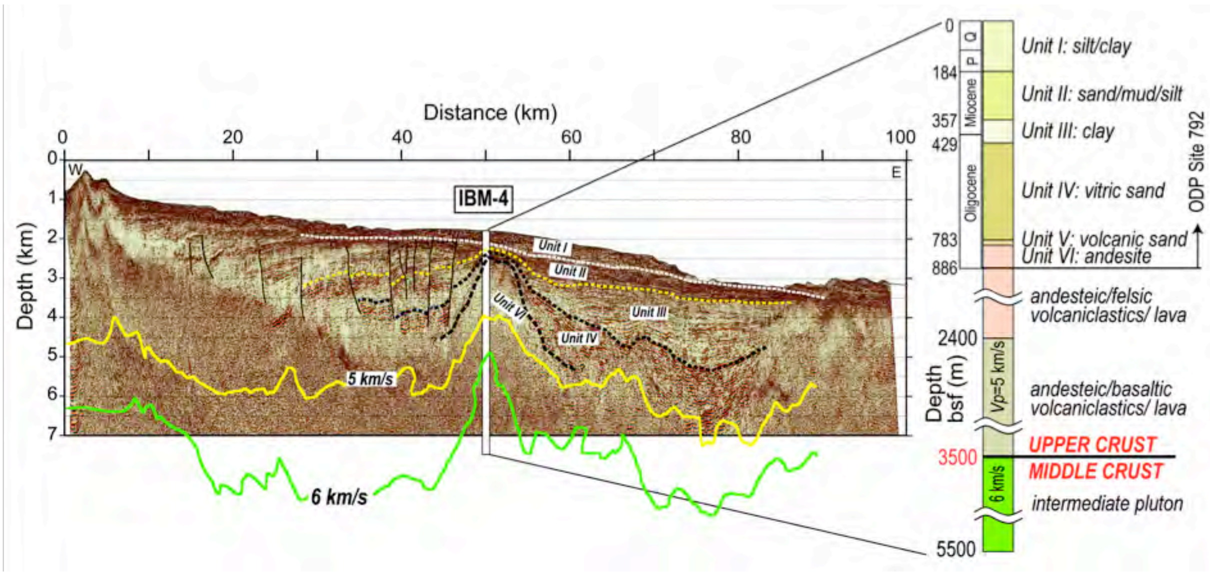

Fig. 8. Lithological interpretation of the seismic image along the IBM4-EW5 section based on the results of ODP792 (Taylor et al., 1992). Iso-*Vp* contours of 5 km/s and 6 km/s obtained by wide-angle OBS data are also shown.

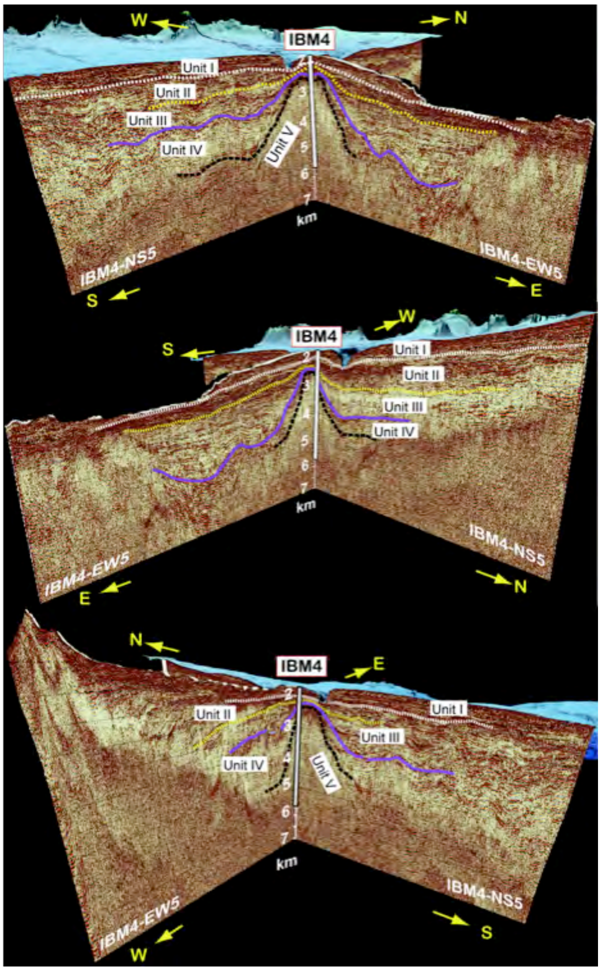

Fig. 9 3D view of the seismic reflection sections crossing the IBM-4 Site. See Fig. 8 for characteristics of each unit. A conical basement high, which is likely to be composed of lavas and volcaniclastics, is well documented, suggesting the presence of an Eocene volcanic body beneath the IBM-4 Site.

The high-resolution wide-angle seismic data has successfully revealed the seismic velocity structure beneath the proposed site (Fig. 10), The results indicate that reflectors are distributed continuously along the 6 km/s *Vp* iso-velocity contour, suggesting that the region with *Vp* >6 km/s is defined reasonably as the middle crust layer. It should be stressed that this critical *Vp* and reflectors (i.e., the upper/middle crust boundary) are located 3.5 km below sea floor at Site IBM-4 (Figs. 8 and 10), whereas we originally proposed 6-7 km penetration as necessary for reaching the middle crust based on the seismic imaging of Suyehiro et al. (1996) (Figs. 3 vs. 10). The new data also show that the depth to the top of middle crust layer is shallower beneath Site IBM-4 than beneath the surrounding region (Figs. 8 and 10). This, together with the observation that the upper/middle crust boundary is 6-7 km deep at 25 km south of the IBM-4 site (Suyehiro et al., 1996; Fig. 3), suggests that the top of the middle crust rises to form a domal structure immediately beneath the volcanic body at Site

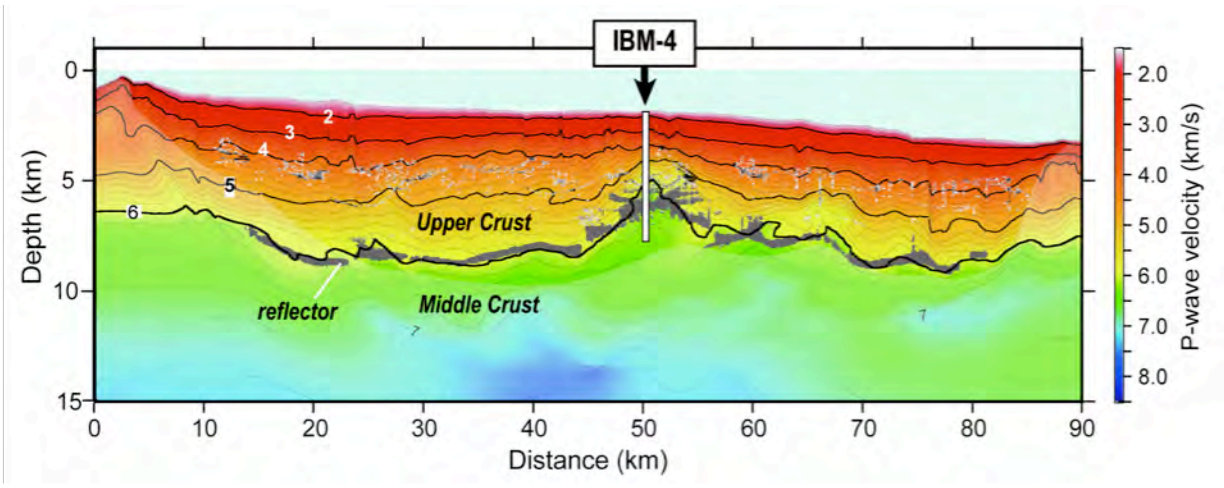

Fig. 10 Newly obtained high resoution seismic velocity and reflective images across the proposed IBM-4 Site. 3.5-km drilling may penetrate the entire upper crust to reach the middle cust. 800-m sampling has been already accomplished at ODP Site 792 (filled). Numbers show *Vp* values for iso-velocity contours.

IBM-4. This domal structure is also documented within the upper crust (Figs. 8 and 9). The new data suggest that direct sampling and significant recovery of middle crust lithologies at Site IBM-4, which are essential for achieving the ultimate goal of this project, are technologically highly feasible.

3.1.2. Implication of Site survey data: Sub-volcano as a major site of middle crust formation

The crustal structure beneath the proposed IBM-4 Site shows that the top of the middle crust (i.e., the upper/middle crust boundary) forms a domal structure beneath an Eocene volcano, but was this structure formed by 'normal' or 'unusual' process? In order to answer this question, we examine the relationship between volcano distribution and crustal structure in the Quaternary IBM volcanic arc.

Active source seismic studies by Kodaira et al. (2007a,b) have documented along-arc variations in middle crust thickness in the Izu-Bonin arc, and have demonstrated that the middle crust tends to be thicker, and the average *Vp* of the total arc crust tends to be lower beneath Quaternary volcanoes that erupt basaltic rocks. This observation suggests that the arc middle crust with compositions likely to be similar to the bulk continental crust is created predominantly beneath arc volcanoes. This characteristic along-arc variation in the crustal thickness also occurs beneath the rear-arc region (Fig. 4) (Kodaira et al., 2008). In order to better document the along-arc architecture of the middle crust, we re-processed Kodaira et al's data to examine the variation in the depth to the top of the middle crust along the current IBM volcanic front (Fig. 4 Top). Shallower depths to the top of the middle crust and domal appear to be characteristic features of arc crustal structure beneath arc volcanoes.

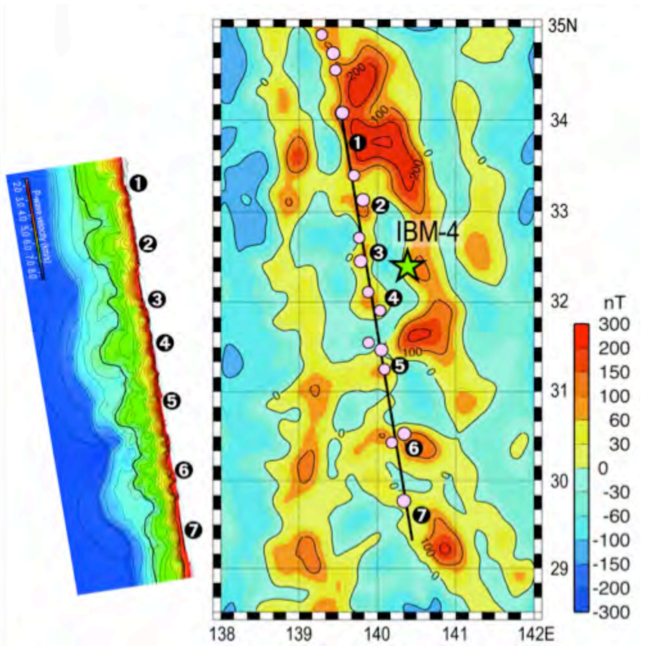

Fig. 11 Magnetic anomaly map obtained by Yamazaki and Yuasa (1998) and seismic velocity structure along the Quaternary volcanic front (solid line). Green star and pink circles indicate the proposed site IBM-4 and Quaternary volcanoes, respectively. Positive magnetic anomaly peaks corresponds well to a thicker part of the middle crust (green in the left figure) as shown by numbers.

The middle crust thickness of the IBM arc also correlates with magnetic anomalies (Kodaira et al., 2008).

Quaternary volcanoes of the IBM arc overlie positive magnetic anomalies (Fig. 11). Such a positive magnetic anomaly is also found at the proposed Site IBM-4 (Fig. 11), which is consistent with the interpretation that the IBM-4 Site was a major site of both volcanism and middle crust formation in the Late Eocene. Examination of magnetic properties of upper/middle crust rocks recovered from Site IBM-4 will provide key constraints on the cause of the characteristic magnetic anomalies throughout the IBM system.

The roots of a mature, but inactive, arc volcano are the ideal setting for testing between alternative models of arc crustal growth and maturation, which all depend on magmatic composition and activity within the heart of the arc crust. For example, Tatsumi et al. (2008a) proposed a hypothesis for arc crust evolution and continental crust formation that relies on underplating of hot, mafic magmas to partially melt the arc crust and create andesitic composition magmas and plutons (Fig. 12). Alternative models for low-velocity middle crust include high-temperature mafic plutons, or primary boninitic magmas that form plutons at depth. Immediately below the upper/middle crust boundary at a depth of 3750m (Fig. 8), we expect to sample plutons that form the 'root' of this volcano. The sub-volcano region of an arc is thus the major site of middle crust formation and the potential locus for growth of the continental crust, and the thicker, domal structured middle crust beneath arc volcanoes is thus the best target for addressing and testing between these alternative models of crust formation.

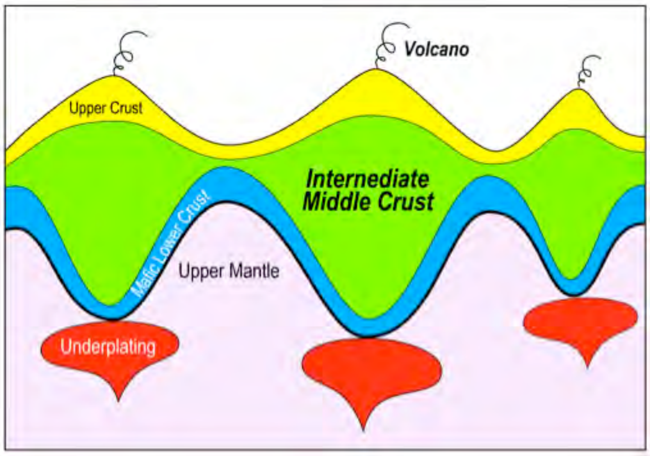

Fig. 12 A schematic along-arc crust-mantle section of the IBM arc. Basaltic underplating triggers crustal anatexis and causes both growth of intermediate middle crust and formation of arc volanoes. Sub-volcano region is thus the major site of arc crust differentiation that ultimately creates new continental crust.

3.2. Scientific objectives

This proposal is one of four related, regional proposals aimed at developing a comprehensive understanding of arc crust evolution and continental crust formation by drilling a series of deep sites into IBM crust at different developmental stages of the arc. With this proposal, we seek to characterize and interpret the origin of mature, intra-oceanic arc upper and middle crust, investigate the genetic link between arc volcanic and plutonic rocks, and establish this site as a unique petrological, geochemical, and geophysical reference section in arc crust.

3.2.1 Characterization of arc upper and middle crusts and their origins

A primary scientific objective of the proposed drilling is to identify and characterize the lithology, composition, physical properties, and structure of the IBM upper and middle crust. Such a comprehensive and integrative examination of a continuous, deep section of *in situ* arc crust has not previously been possible, but penetrating the in-place volcanic sequence and plutonic roots of the IBM arc will provide significant advances in our understanding of arc crustal structure and origins.

Upper crust

The IBM upper crust is divided into two seismic layers with *Vp*<5km/s and 5.0-5.8km/s, separated by the presence of a clear seismic reflector (Figs. 8 and 10). Although the deeper 5.0-5.8 km/s layer is hypothesized to consist of lava flows and intrusive rocks, the lithologies and compositions within this layer are totally unknown. The proposed deep drilling is the only way to decode the petrographical, geochemical, and structural characteristics of the *in situ* deep upper crust and a volcanic body. Lava compositions recovered from the shallow basement at Site 792 vary in composition from basalt to rhyolite (Taylor, Fijioka et al., 1990), suggesting that deep drilling could recover a broad spectrum of magma types distributed throughout the upper crust. This drilling will thus provide a unique opportunity to fully capture and characterize the extent of magmatic diversity in a single arc volcanic system, and to constrain the average bulk composition of magma constructing the upper arc crust.

The upper crust beneath IBM-4 is estimated to have been created in early Oligocene to late Eocene. The broad geochemical signatures of magmatism at these ages have been documented by analyzing volcaniclastic turbidites (e.g., Gill et al., 1994), and ashes (e.g., Bryant et al., 2003), but these sample types only relate to bulk magma or liquid compositions. On the other hand, petrographic data from phenocryst compositions and phase relationships in lava and intrusive whole-rock samples, which can be obtained by drilling, will provide further constraints on the genesis of these magmas. Several questions critical to understanding arc crust evolution may be specifically addressed by drilling (see Section 4 below): (1) are the mafic magmas parental to arc andesites boninitic or basaltic? (2) do these parental magmas evolve primarily via magma mixing or crystal fractionation? (3) what are the trace element and isotopic characteristics of Oligocene magmatism, and are they different from magmatism at the initial (Eocene) and later (Quaternary) magmatic stages?

Middle crust

Seismic velocity measurements (Kitamura te al., 2003) and petrological modeling (Tatsumi et al., 2008a) suggest that the mid-crustal 6.0-6.8 km/s layer documented for the entire IBM arc may be best explained by a concentration of intermediate to felsic plutons. Regional exposures of possible mid-crustal rocks at the Izu-Honshu arc-arc collision zone, and recovery of tonalite/granodiorite from IBM and KPR by dredging, further suggest that this layer may be intermediate in composition. Tonalite and its metamorphic equivalents, however, vary widely in bulk composition from 55-70% SiO_2 and there are several possible mechanisms for producing either intermediate magmas or low-velocity middle crust of different composition. These include: (1) fractional crystallization of mantle-derived basaltic magma, (2) anatexis of the mafic arc or pre-existing oceanic crust, (3) mixing between mantle-derived basaltic and crust-derived felsic magmas, (4) production of primary andesitic magmas such as boninites in the upper mantle or (5) mafic plutons at high temperature (~600-700°C). These hypotheses will be directly tested by petrographical, mineralogical, textural, and geochemical characterization of samples drilled from the upper- and middle-crust layers of the IBM arc (see Section 4, below). In order to examine the lithologic and petrologic variation within the middle crust layer, we plan to penetrate into this layer 2km beyond the upper/middle crust boundary (Fig. 8).

3.2.2 Genetic relationship between the upper and middle arc crust

To what extent does the arc upper crust reflect or relate to the composition of middle crustal plutons at depth? Recovering samples from the entire upper crust and the underlying 6.0-6.8 km/sec layer will allow us to examine the age and genetic relationships between upper- and mid-crustal rocks. The compositional range and mean of the upper crust may be directly linked to plutonic compositions at depth through mineralogy, bulk composition, trace element systematics, isotopic characteristics, and age. The middle crust may represent the batholithic roots of individual volcanoes, manifested by an intimate link between plutonic and volcanic lithologies. Alternatively, the widespread nature of the characteristic middle crust layer throughout IBM and the recovery of intermediate plutonic rocks from the KPR suggest that this material was created early in the IBM history, and may represent a crustal root that is not directly related to subsequent magmatism. Examination of compositional relationships and genetic linkages between upper and middle crustal rocks at site IBM-4, together with data for volcaniclastic sequences and basement rocks recovered from other regional drill sites, we may develop a regional model of the middle crust composition and trace the chemical evolution of the mid-crustal layer through time along an across-arc section of the IBM arc.

3.2.3 A reference section for mature arc crust

Through the direct petrological, geochemical, and geophysical characterization of the crust at Site IBM-4, we will establish this site as a reference section in intra-oceanic arc crust. Integrated coring/sampling and logging data will provide an unparalleled, continuous record of mature arc crustal structure and composition. The cored rocks and borehole properties will be directly linked to the seismic velocity structure of the crust, providing the first *in situ* test of seismic velocity models against known lithologies and structures within the deep arc crust. Moreover, the integration of direct (i.e., core samples and borehole measurements) and indirect (i.e., regional seismic studies) data for this drill site will be critical to the extrapolation of crustal properties across the arc, to other regional crustal drill sites, to portions of the arc where drilling is presently impossible (i.e., beneath the active volcanic front), and to global arcs where seismic studies are planned or completed. This site will also provide an essential reference for accreted arc crustal terranes, such as Talkeetna, where the interior of the crust is exposed at the surface. Such exposed sections provide valuable petrological/geochemical information about crustal composition, but structures may be perturbed during accretion and these sequences are difficult to directly relate with geophysical studies of modern, active systems. Site IBM-4 will thus provide an essential key to interpreting seismic models and exposed sections of arc crust.

3.3. Drilling, coring, and logging plan

3.3.1. Timing of drilling operations

This unprecedented deep ocean borehole will be accomplished through a program of riser-based drilling and carefully planned casing, using up to seven different casing pipe sizes. Given the frontier nature of this drilling, the exact time needed to complete the borehole is uncertain, but may well exceed one year of drilling with full-coring, full-logging, and casing. Operational time for logging may require three weeks in total. Because this ultra-deep drilling is expected to penetrate to 5.5 km below seafloor, we expect that operations for NanTroSEIZE Stage 3 (ultra-deep drilling to 6 km below seafloor) will provide an accurate estimation for the operational timing.

It should be stressed that the IBM-4 site is proximal to ODP Site 792, which successfully penetrated 886 mbsf. We thus do not need to re-sample from this level and may start coring and logging at that depth.

3.3.2. Coring and logging strategy

Core-log-seismic integration is essential to the success of drilling at IBM-4 and to the overall objectives of Project IBM. Borehole seismic experiments are necessary for testing the seismic models of upper- to middle-crust structure and composition, as these data will be straightforwardly linked with seismic structures obtained through OBS and MCS data. Core-log integration is also a strategic approach to identifying the lithology and structure of drilled rocks. As core recovery is expected to decrease with depth, the identification of sedimentary structures, sediment/igneous contacts, morphology of lava flows, and igneous/dike/plutonic contacts will become increasingly difficult with fragmented cores. Core-log integration using borehole images provides the only means of reconstructing the continuous stratigraphy throughout the sequence of arc upper crust and middle crust. Deployments of downhole logging tools are recommended throughout the entire drilled section down to 5.5 km below seafloor. Standard measurements such as neutron porosity, litho-density, gamma ray, resistivity, and sonic velocity are required to determine rock physical properties. Borehole imaging using both electrical resistivity (FMI) and ultrasonic waves (UBI) is essential for visualizing the borehole wall over large and continuous scales. Geochemical logs will also provide information on changing rock composition with depth. One advantage of riser drilling is the ability to use the large diameter FMI tool, which provides borehole images up to a full 360° view. VSP and check shot logs are essential to correlating the existing seismic sections with the borehole velocity profile. Borehole temperature logging is also important for verifying the geothermal heat flow model. Side-wall coring will also be prepared in the case of poor core recovery in critical intervals.

3.4. Expectation and integration of results

With the proposed drilling, we expect to drill to a total penetration of 5.5 km below sea floor, through ~800 m of sediment, 2.7 km of upper crustal volcanic and shallow intrusive rocks, and 2 km of middle crustal plutonic rocks. The expected section represents a significant portion of mature arc crust, most of which has never before been reached through scientific ocean drilling. We will determine the structure and composition of mature, upper to middle arc crust and investigate the scales over which these features vary. Recovery in this riser drilling effort is anticipated to be high, but the entire borehole will also be analyzed *in situ* with a broad spectrum of logging tools, providing essential, continuous geophysical and geochemical data that will fill in recovery gaps in the core and provide superior constraints on the overall crustal structure at this site.

The proposed deep drilling will provide the first ever continuous, in-place section of mature upper and middle arc crust, and will provide unique opportunities to integrate these results over a range of scales. Recovered cores and drilling data will be fully integrated with downhole logs to extrapolate lithologies in recovery gaps and more clearly resolve major structural features within the crust. These data will also be linked to models of seismic velocity structure of the crust at the drill site. We expect to establish the overall structure of the arc crust (distinct layers vs. gradational changes in lithology/composition), and link these results to the regional seismic velocity structure across the IBM arc. This drilling will also recover the first *in situ* sequence of arc crust from lavas to plutonic rocks, which will be used to establish the composition and origin of the upper and middle crust and the genetic link between arc volcanics and plutonics. As a whole, results from this drilling will be integrated with other nearby proposed drill sites located in earlier and later stages of arc development, to build a comprehensive model of the growth of arc crust through time. Furthermore, the plutonic rocks recovered from Site IBM-4 will provide an essential reference for regional dredged and exposed plutonic rocks that will also provide constraints on the spatial distribution of lithologies in the arc middle crust and its evolution through time in IBM.

4. INTERPRETATION OF EXPECTED RESULTS

The proposed deep drilling will provide an unprecedented, continuous sequence of arc crust, which presents unique opportunities to test several hypotheses fundamental to interpreting the structure, composition, origin, and evolution of arc crust. The results of this drilling will provide essential new constraints on many features of the arc crust evolution that will be used both to address questions specific to Site IBM-4 and to establish the regional/global context and significance of the crust at this site. Here we discuss the specific hypotheses to be tested and new insights to be gained from the drilling results at Site IBM-4.

4.1. Relating seismology with *in situ* lithology

The seismic velocity structure of the Earth's crust is expected to vary as a function of its composition (Christensen and Mooney, 1995; Behn and Kelemen, 2003; Hacker and Abers, 2002; Tatsumi et al., 2008a). These theoretical and experimental models are widely used to interpret remote seismic studies of the crust in terms of crustal composition. No study, however, has yet directly related independent constraints on seismic velocity structure with *in situ* lithologies and borehole measurements to such great depth within the crust. We therefore propose to develop Site IBM-4 as a unique lithological reference site for the seismic velocity structure of arc crust, and to use this site to test the hypothesis that seismic properties of the crust relate to composition. We may further constrain the fracture density of the arc crust and its relationship to the overall seismic properties of the crust independent of (or in addition to) composition. Site IBM-4 presents a rare opportunity to link independent observations of a large-scale, natural system with laboratory and theoretical models. Establishing these links will allow us to extrapolate these results along and across the entire seismic section of the IBM arc (e.g., Figs. 3 and 4), and interpret other global arc seismic sections more clearly in terms of crustal composition (Fig. 2).

4.2 Origin of arc upper crust

The deep drilling at Site IBM-4 is expected to recover a complete section of the IBM arc upper crust. The basement rocks at ODP site 792 are mostly calc-alkalic andesites, which are the major volcanic products in mature volcanic arcs and are hypothesized to form the major part of the upper crust beneath IBM-4. The origin of calc-alkalic magmas, especially identification of their parental, mafic magmas, has been one fundamental problem in Earth sciences, as this is closely related to the origin of continental crust and the solid Earth evolution (e.g., Kelemen, 1995; Tatsumi and Kogiso, 2003; Tatsumi et al., 2008a). Recent progress in trace element and isotopic micro analysis of phenocryst will allow us to decode the characteristics and origin of mafic magmas parental to calc-alkalic andesites (Tatsumi et al., 2008b). At least three types of mafic magmas, generated by different processes, may contribute to produce Late Oligocene to Early Eocene calc-alkaline magma in the IBM arc (Fig. 13). Identification and characterization of these mafic end-members are

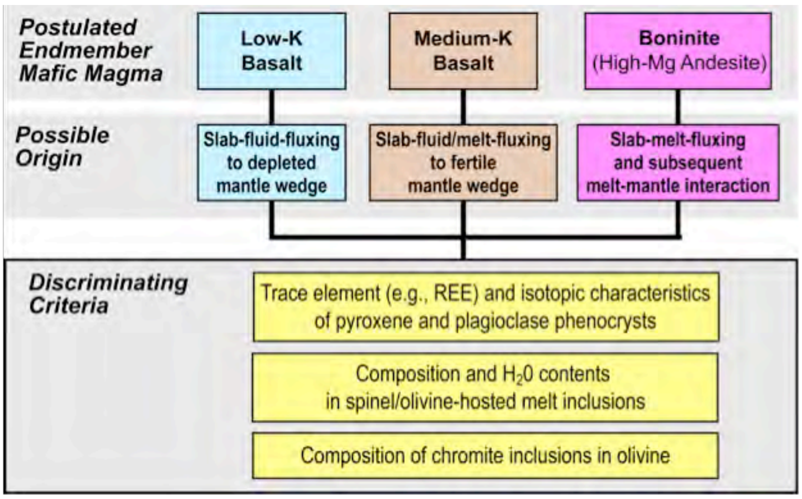

Fig. 13. Possible three mafic magmas that contribute to production of calc-alkalic andesites in the IBM arc. Analyses of andesitic rocks recovered from the upper crust at IBM-4 can provide strong constraints on identification of the end-member magma.

critical to understanding the evolution of the IBM arc.

4.3. Origins of arc middle crust

The ultra-deep drilling outlined in this proposal is expected to penetrate and recover samples of *in situ* plutonic rocks from the mature arc middle crust exhibiting a characteristic seismic velocity (*Vp*=6.0-6.8 km/s). Several hypotheses present a broad variety of potential origins for the plutonic rocks that form the arc middle crust (Tatsumi et al., 2008a). Of the broad range of bulk compositions permitted by the seismic velocities of this layer, there are three bulk compositions that reflect lithologies that are most likely to be present: boninitic, intermediate or tonalitic, and mafic or gabbroic. These different bulk compositions each implicate different processes contributing to the growth and evolution of arc crust (Fig. 14).

A mafic composition middle crust would comprise plutons of frozen/crystallized, primitive basaltic magma and cumulates, containing abundant modal olivine and clinopyroxene. In order for such rocks to exhibit seismic velocities of 6.0-6.8 km/s, however, they must exist in the middle crust at higher temperatures than are predicted by current heat flow data (~600-700°C).

Boninitic magmas, which typically occur at IBM, are also primary melts of the Earth's mantle, although they have higher SiO_2 than basalts. Boninitic middle crust could arise in two different ways. It could either represent preserved boninitic crust from early in the arc history (e.g., crust preserved at Site 786), or it could reflect bonintic magmatism related to the Oligocene arc system. These two possibilities are easily distinguished through determination of the age and bulk composition of the plutonic and volcanic rocks (Fig. 14). Remnant early arc crust will be older than the volcanics and, in this case, it is unlikely that boninitic lavas would be present in the volcanic sequence. Arc-related boninitic magmatism, on the other hand, would be reflected in boninitic volcanic and plutonic rocks of similar age. Intermediate plutonic rocks are perhaps the most likely bulk composition for the middle crust, as evidenced by dredged and exposed tonalities and granodiorites from throughout the IBM system (e.g., Table 1). One way to create

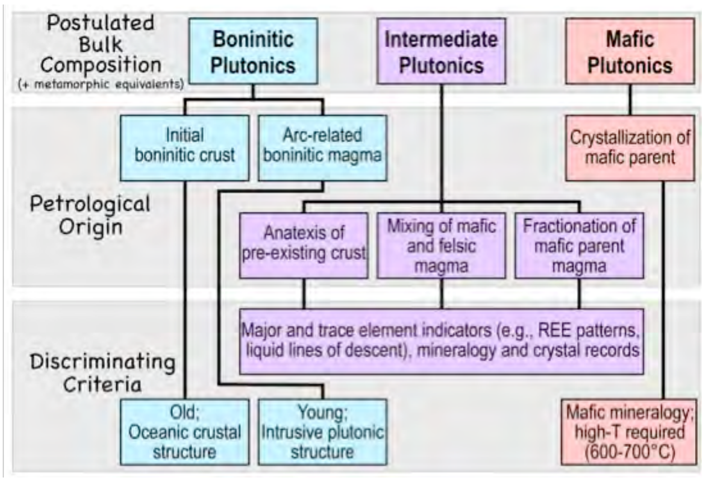

Fig. 14. Hypotheses for the origin of IBM middle crust.

intermediate composition magma is through fractional crystallization of mantle-derived mafic magma, which could take place in the arc lower crust. Another way to produce intermediate to felsic magma is through partial melting of mafic lower arc crust. Alternatively, intermediate magmas could be made by mixing between mantle-derived mafic magmas and crust-derived felsic melts. Discriminating between these processes will require careful examination of major/trace element and isotopic compositions of mineral, glass, and bulk rock samples, which will allow us to characterize magma sources (e.g., ultramafic *vs*. mafic) and distinguish records of magma mixing from liquid lines of descent (Fig. 14).

4.4. Volcanic-plutonic connections

The middle crust beneath an arc volcano may intuitively be expected to represent plutonic roots that are intimately related, both in composition and time, to the volcanics above. Yet, seismic studies of rifted, early arc crust from the KPR suggest that the low-velocity, 6.0-6.5 km/s middle crust material may have developed early in the arc history. The proposed drilling will allow us to test the genetic relationship between the volcanic and plutonic rocks of the IBM arc through detailed studies of the geochemical and age relations between upper and middle crust lithologies.

4.5. Context of existing IBM plutonic rocks

Plutonic rocks have been recovered throughout the IBM system by submarine dredging and sampling of on-land exposures of collisional terranes (e.g., Table 1). These rocks are interpreted to represent plutonic lithologies that once existed at depth in the arc crust, although in some cases, age data indicate they formed during or after the major collisional events that brought them to the surface (e.g., Tanzawa; Tani et al., 2010). Even so, these existing samples provide some information on the dispersal of plutonic lithologies throughout IBM. The recovery of *in situ* plutonic rocks from site IBM-4, however, will provide the missing crustal context for these plutonic samples, and will allow us to establish how representative the existing samples are of lithologies that exist at depth. Integrating age and compositional data for existing and drilled plutonic rocks will be essential for extrapolating the drilling results along and across the IBM system.

4.6. Evolution of arc crust

Four regional drilling proposals (695, 696, 697, and this proposal) collectively address the larger question of crustal growth through time at intra-oceanic arcs. Combining the observations of mature arc crustal structure and composition at site IBM-4 with proposed sites in the pre-existing oceanic crust (IBM-1), the early boninitic arc crust (IBM-2), and the Neogene rear-arc volcanic record (IBM-3) along a reconstructed arc transect (Figs. 1 and 15) provides a unique opportunity to investigate the processes and timing of crustal evolution in the IBM system. Assessing the development and maturation of arc crustal structure and composition through time would not be possible at any one drill site, but taken together, these four sites will provide a time series of arc crustal growth and capture the transformation and maturation of arc crust over the entire history of subduction at IBM.

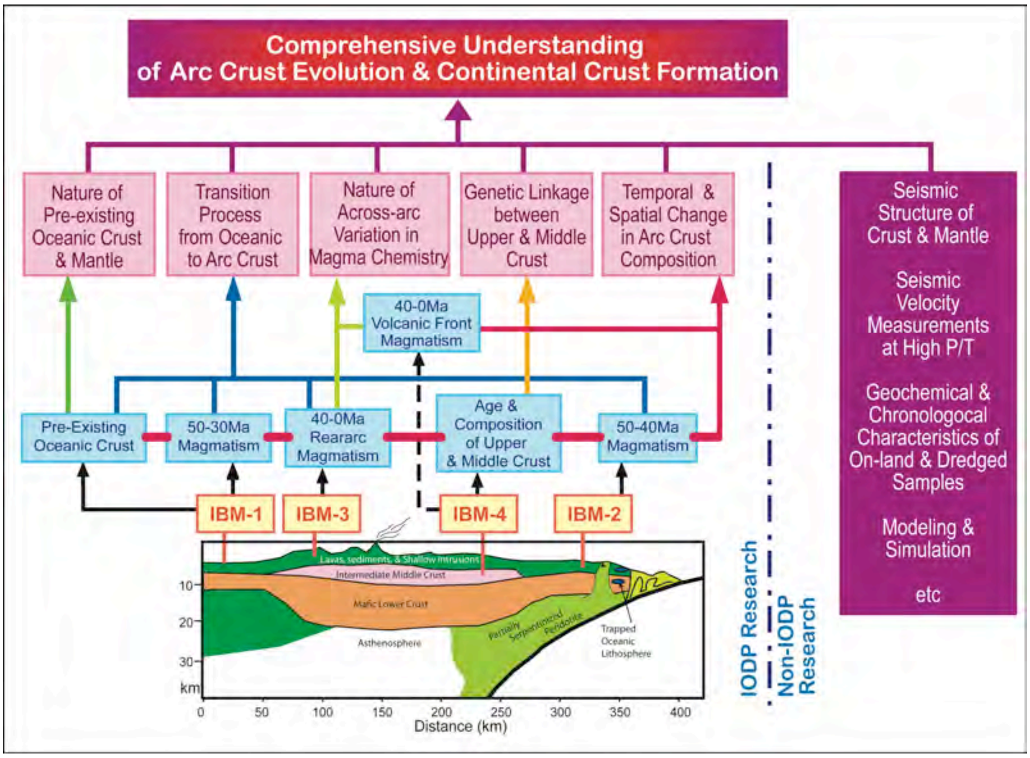

Fig.15. The relationship between four proposals in the IBM arc system, which are, in conjunction with non-IODP research projects, aiming at comprehensive understanding of arc crust evolution and continental crust formation. Note that the pink coloration in the section, corresponding to the middle crust having *Vp*=6.0-6.8 km/s.

5. DISCUSSION AND SUMMARY

This proposal aims to determine the structure, composition, and origin of mature, intra-oceanic arc crust, by recovering a continuous sequence of Eo-Oligocene arc crust from volcanics through shallow intrusives to plutonic rocks of the arc middle crust. Like many global intra-oceanic arcs, the middle crust of IBM is characterized by low seismic velocities (*Vp*=6.0-6.8 km/s) that have been interpreted to indicate a bulk intermediate composition. The formation of intermediate plutonic rocks in subduction zones is thought to be an important step in the process of continental crust formation, and determining the origin and evolution of the arc middle crust is therefore vital to advancing models of crustal growth processes on Earth.

Identifying a site suitable for achieving these goals is not simple. Active arc volcanic fronts are too hot to reach mid-crustal depths through drilling, and on-land exposures of arc crust are often structurally and lithologically perturbed during the collision and uplift that exposes them. Ocean-based, riser drilling of an inactive, intra-oceanic arc system is the only means by which we may recover an undisturbed, *in situ* sequence of arc crust to mid-crustal depths. Site IBM-4 has been identified as the optimal location to achieve the primary goals of the proposed drilling.

In the best possible case, the proposed drilling will provide a continuous, high-recovery sequence of arc volcanic and plutonic rocks down to a depth of 5.5 km below sea floor. The results of this drilling effort will provide an unprecedented petrological, geochemical and geophysical reference site in mature arc crust that will drive fundamental advances in our understanding of the condition and evolution of the Earth’s crust. At a minimum, we will recover a record of shallow to deep arc upper crust, and through local and global geophysical, geochemical, and petrological analogies, we will be able to model the lithologies at greater depths. For example, given the age, depth, and compositional control on the Talkeetna and Kohistan arcs (e.g., Bard et al., 1980; DeBari and Coleman, 1989; Clift et al., 2005; Greene et al., 2006; Rioux, 2006), and the modeled similarity in *Vp* profile between Talkeetna and IBM (see Fig. 3), the Talkeetna section may be a valuable complement to the results of the proposed Izu Bonin drilling. If the upper crustal IBM section provides lithologies similar to Talkeetna, then the analogy presented by the deeper exposed Talkeetna section will provide an important reference for middle and lower crustal lithologies that will allow us to reconstruct the complete crustal sequence of mature IBM crust.

6. SITE DESCRIPTION

Site IBM-4 is located east of the modern Izu-Bonin volcanic front, at 1798 m water depth, along a cross-section of the arc at 32°N and proximal to ODP Site 792. The seismic structure of the crust beneath this site is typical of the mature, active volcanic arc.

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1980	MS, Kyoto University
1978	BS, Kyoto University

IODP EXPERIENCE

2008-	IODP-MI BoG
2005-2010	SPPOC/SASEC member and vice-chair
2003-2005	SPC member
2001-2003	IPC member

MAIN INTEREST

Magmatological approaches to evolution of the solid Earth

PUBLICATIONS

International	120 refereed papers and 1 bock
Japanese	14 refereed papers and 3 bocks

Selected Publications

Tatsumi, Y., Suzuki, T. (2009) Tholeiitic vs calc-alkalic differentiation and evolution of arc crust: constraints from melting experiments on a basalt from the Izu-Bonin-Mariana arc, J. Petrol., 50, 1575-1603.

Tatsumi, Y., Takahashi, T., Hirahara, Y., Chang, Q., Miyazaki, T., Kimura, J-i., Ban, M., Sakayori, A. (2008) New Insights into Andesite Genesis: The role of Mantle-derived Calc-alkalic and Crust-derived Tholeiitic Melts in Magma Differentiation beneath Zao Volcano, NE Japan, J. Petrol., 49, 1971-2008.

Tatsumi. Y., Shukuno, H., Tani, K., Takahashi, N., Kodaira, S., Kogiso, T. (2008), Structure and growth of the Izu-Bonin-Mariana arc crust: 2. Role of crust-mantle transformation and the transparent Moho in arc crust evolution, J. Geophys. Res., 113, B02203, doi:10.1029/2007JB005121.

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Tatsumi, Y., Subduction factory: how it operates in the evolving Earth, GSA Today, 15, 4-10, 2005.

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Tatsumi, Y., Slab melting: its role in continental crust formation and mantle evolution, Geophys. Res. Lett., 27, 3941-3944, 2000.

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Tatsumi, Y., Shinjoe, H., Ishizuka, H., Sager, W.W., and Klaus, A., Geochemical evidence for a mid-Cretaceous superplume, Geology, 26, 151-154, 1998.

Tatsumi, Y. and Kogiso, T., Trace element transport during dehydration processes in the subducted oceanic crust: 2, origin of chemcial and physical characteristics in arc magmatism, Earth Planet. Sci. Lett., 148, 207-221, 1997.

Tatsumi, Y. and Eggins, S., Subduction zone magmatism, Blackwell, Boston, pp211, 1995.

Tatsumi, Y., Ito, K. and Goto, A., Elastic wave velocities in isochemical granulite and amphibolite: origin of a low-velocity layer at the slab/mantle wedge interface, Geophys. Res. Lett., 21, 17-20, 1994.

Tatsumi, Y., Murasaki, M., and Nohda, S., Across-arc variaton of lava chemistry in the Izu-Bonin Arc: identification of subduction components, J. Volcanol. Geotherm. Res., 49, 179-190, 1992.

Tatsumi, Y. and Kimura, N., Backarc rifting vs. continental breakup: petrological aspect for active rifting, Tectonophys.,197, 127-137, 1991.

Tatsumi, Y. and Nohda, S., Geochemical stratification in the upper mantle: evidence from Leg 115 basalts in the Indian Ocean, Proc., ODP, Sci. Results, 115, 63-69, 1990.

Tatsumi, Y., Otofuji, Y., Matsuda, T. and Nohda, S., Opening of the Sea of Japan back-arc basin by asthenospheric injection, Tectonophys., 166, 317-329, 1989.

Tatsumi, Y.,Migration of fluid phases and genesis of basalt magmas in subduction zones, J. Geophys. Res., 94, 4697-4707, 1989.

Tatsumi, Y., Nohda, S. and Ishizaka, K., Secular variation of magma source compositions beneath the northeast Japan arc, Chem. Geol., 68, 309-316, 1988.

Tatsumi, Y., Formation of volcanic front in subduction zones, Geophys. Res. Lett., 13, 717-720, 1986.

Tatsumi, Y., Hamilton, D.L. and Nesbitt, R.W., Chemical characteristics of fluid phases from a subducted lithosphere and origin of arc magmas: evidence from high-pressure experiments and natural rocks, J. Volcanol. Geotherm. Res., 29, 293-309, 1986.

Tatsumi, Y., Sakuyama, M., Fukuyama, H. and Kushiro, I., Generation of arc basalt magmas and thermal structures of the mantle wedge in subduction zones, J. Geophys. Res., 88, 5815-5825, 1983.

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Professional Preparation

Education
Ph.D., Earth Sciences, Boston University, Boston, MA, January 2004
B.A., cum laude, Geology, Macalester College, St. Paul, MN, May 1997

Fellowships and Awards
Carnegie Fellowship, Carnegie Institution of Washington (2003-2005)
Caltech OK Earl Postdoctoral Fellowship (declined)
Sigma Xi Award, Boston University Science and Technology Day (2002 and 2003)
Presidential University Graduate Fellowship, Boston University (2000-2001)
National Science Foundation Graduate Research Fellowship (1999-2003)
American Federation of Mineralogical Societies Scholarship (1999-2001)
Grinnell Fellowship, University of Kansas (1998-1999)
Fulbright Grant (Philippines; 1997-1998)
Beltmann Physical Sciences Research Grant, Macalester College (1996)

Professional Societies
American Geophysical Union, Geochemical Society, Mineralogical Society of America
Geological Society of America, Sigma Xi

Appointments

2008-	Assistant Professor of Oceanography, Graduate School of Oceanography, University of Rhode Island
2005-2008	NSF Advance Assistant Research Professor, Graduate School of Oceanography, University of Rhode Island
2007-	Visiting Investigator, Department of Terrestrial Magnetism, Carnegie Institution of Washington
2003-2005	Post-Doctoral Fellow, Carnegie Institution of Washington
1999-2003	Graduate Research Fellow, Boston University

Fields of Specialization

Igneous petrology; major, trace, and volatile element geochemistry; microanalysis

Shipboard Experience

2006: Shipboard Scientist and Submersible Diver, *RV Yokosuka*; *Shinkai 6500* submersible dives along the southern Mariana arc
2004: Shipboard Scientist, *RV Yokosuka; Shinkai 6500* submersible dives along the Izu-Bonin arc
1999: Shipboard Scientist, *JOIDES Resolution*; Igneous Petrologist, ODP Leg 185, Izu-Bonin-Mariana margin

Selected Publications

Kelley, K. A., Plank, T., Newman, S., Stolper, E., Grove, T. L., Parman, S. & Hauri, E. (2010). Mantle melting as a function of water content beneath the Mariana arc. *Journal of Petrology* 51, 1711-1738, doi:10.1093/petrology/egq036.

Reagan, M. K., O. Ishizuka, R. J. Stern, K. A. Kelley, Y. Ohara, J. Blichert-Toft, S. H. Bloomer, J. Cash, P. Fryer, B. B. Hanan, R. Hickey-Vargas, T. Ishii, J.-I. Kimura, D. W. Peate, M. C. Rowe, and M. Woods (2010), Fore-arc basalts and subduction initiation in the IBM system, *Geochem. Geophys. Geosys.*, 11, Q03X12, doi:10.1029/2009GC002871.

Kelley, K. A., and E. Cottrell (2009), Water and the oxidation state of subduction zone magmas, *Science*, 325, 605-607, doi:10.1126/science.1174156.
Cottrell, E., K. A. Kelley, A. T. Lanzirotti, and R. A. Fischer (2009), High-precision determination of iron oxidation state in silicate glasses using XANES, *Chem. Geol.*, 268, 167-179, doi:10.1016/j.chemgeo.2009.08.008.
Plank, T., K. A. Kelley, R. W. Murray, and L. Q. Stern (2007), Chemical composition of sediments subducting at the Izu-Bonin trench, *Geochem. Geophys. Geosys.*, 8, doi:10.1029/2006GC001444.
Kelley, K.A., Plank, T., Grove, T.L., Stolper, E.M., Newman, S., and Hauri, E.H. (2006), Mantle melting as a function of water content beneath back-arc basins. *Journal of Geophysical Research*, 111, B09208, doi:10.1029/2005JB003732.
Wiens, D. A., K. A. Kelley, and T. Plank (2006), Mantle temperature variations beneath back-arc spreading centers inferred from seismology, petrology, and bathymetry, *Earth Planet. Sci. Lett.*, 248, 30-42, doi:10.1016/j.epsl.2006.04.011.
Kelley, K.A., T. Plank, L. Farr, J.N. Ludden, and H. Staudigel, 2005, Subduction Cycling of U, Th and Pb, *Earth Planet. Sci. Lett.*, *234*, 369-383, doi:10.1016/j.epsl.2005.03.005.
Kelley, K. A., T. Plank, J. N. Ludden, and H. Staudigel (2003), Composition of altered oceanic crust at ODP Sites 801 and 1149, *Geochem. Geophys. Geosys.*, 4, doi:10.1029/2002GC000435.
Fisk, M., and Kelley, K.A. (2002), Probing the Pacific's oldest MORB glass: Mantle chemistry and melting conditions during the birth of the Pacific plate. *Earth Planet. Sci. Lett.*, 202, p. 741-752.

Synergistic Activities

Member of the NSF-MARGINS/GeoPRISMS Program Steering Committee
MARGINS distinguished lecturer, 2009-2011
Served on the AGU Fall Meeting Program Committee, 2006 and 2007
Co-convener of special sessions at AGU, Goldschmidt Conference, and IAVCEI
Peer reviewer for NSF proposals and academic journals (G-cubed, Contributions to Mineralogy and Petrology, Chemical Geology, Journal of Volcanology and Geothermal Research, AGU Monograph, Geology)
Active participant in focused scientific community workshops (MARGINS, GERM, SOTA, MYRES, RIDGE2000, IODP)

Collaborators and Other Affiliations

Collaborators (Last 48 Months)

Richard Arculus, Australian National University; Jon Castro, Smithsonian Institution; Elizabeth Cottrell, Smithsonian Institution; Jim Gill, University of California at Santa Cruz; Tim Grove, Massachusetts Institute of Technology; Erik Hauri, Carnegie Institution of Washington; Charlie Mandeville, American Museum of Natural History; Fernando Martinez, SOEST, Univ. of Hawaii; Sally Newman, California Institute of Technology; Steve Parman, Brown University; Mark Reagan, University of Iowa; Nobu Shimizu, Woods Hole Oceanographic Institution; Edward Stolper, California Institute of Technology; Robert Stern, University of Texas, Dallas; Yoshi Tatsumi, IFREE-JAMSTEC, Japan

Graduate and Postdoctoral Advisors

Ph.D.: Terry Plank, Boston University (now at LDEO)
Postdoctoral: Erik Hauri, Carnegie Institution of Washington

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:	Continental Crust Formation at Intra-Oceanic Arc: Ultra-Deep Drilling to the Middle Crust of the Izu-Bonin-Mariana Arc
Date Form Submitted:	Sept 30t, 2010
Site Specific Objectives with Priority (Must include general objectives in proposal)	1) To identify the lithology, bulk composition, and structure of the mid-crustal layer beneath IBM and to establish the relationship of the recovered rocks to the seismic velocity structure of IBM arc crust. 2) To estimate the age of mid-crustal rocks and its chronological and petrogenetic relationship to the upper crust sequence that overlies it; 3) To identify the process of formation of mid-crustal rocks To document the evolution of the middle crust by comparing compositions of the drilled middle crust beneath the Oligocene basement with the presumably equivalent sequences recovered through deeper drilling of older crust at Site 786B (Eocene) and younger Neogene crust exposed in the arc-arc collision zone.
List Previous Drilling in Area:	ODP Legs 125, 126, and 132

Section B: General Site Information

Site Name: (e.g. SWPAC-01A)	**IBM-4** **(ODP Site 792)**	If site is a reoccupation of an old DSDP/ODP Site, Please include former Site #	Area or Location:	Izu-Bonin
Latitude:	Deg:32	Min:24	Jurisdiction:	Japan
Longitude:	Deg:140	Min:23	Distance to Land:	60 km
Coordinates System:	WGS 84,	Other ( )		
Priority of Site:	Primary:	Alt:	Water Depth:	1798 m

Section C: Operational Information

	Sediments	Basement
Proposed Penetration: (m)	800 What is the total sed. thickness? 800 m	4700
		Total Penetration: 5500 m
General Lithologies:	Volcaniclastic turbidite	Massive lava and breccia Tonalite-gabbro

Coring Plan: *(Specify or check)*

1-2-3-APC □ VPC* □ 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)* 180~260°C

Mud Logging: *(Riser Holes Only)*

Cuttings Sampling Intervals

from 800 m to 5500 m, 5 m intervals

from ____ m to ____ m, ____ m intervals

Basic Sampling Intervals: 5m

Estimated days:

Drilling/Coring:?	Logging:?	Total On-Site:?

Future Plan: *Longterm Borehole Observation Plan/Re-entry Plan*

Seismic experiments for elucidation of detailed crustal structure using the borehole

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)

May to August is optimal. (typhoon risk in late August to September)

Form 2 - Site Survey Detail

IODP Site Summary Forms:

Please fill out information in all gray boxes

New ☐ *Revised* ■

Proposal #: 698	Site #: IBM-4	Date Form Submitted: Sept. 30 2010

	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			Primary Line(s): Location of Site on line (SP or Time only) Crossing Lines(s): Site survey data were acquired for ODP Site 792 Additional seismic data using 204 streamer cable plan to be acquired in 2007.
3	Seismic Velocity†			
4	Seismic Grid			
5a	Refraction (surface)			
5b	Refraction (near bottom)			Data from a nearby profile are being processed by JAMSTEC
6	3.5 kHz			Location of Site on line (Time)
7	Swath bathymetry			Multi-narrow-beam data complied by Japan Coast Guard
8a	Side-looking sonar (surface)			
8b	Side-looking sonar (bottom)			
9	Photography or Video			
10	Heat Flow			
11a	Magnetics			Map complied by AIST, Japan, is published.
11b	Gravity			Map complied by AIST, Japan, is published.
12	Sediment cores			
13	Rock sampling			
14a	Water current data			Available on JODC web page (hhtp://www.jodc.go.jp)
14b	Ice Conditions			
15	OBS microseismicity			Acquired by JAMSTEC, and data are now processing.
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 #: 698	Site #: IBM-4	Date Form Submitted: Sept. 30 2010
Water Depth (m): 1798	Sed. Penetration (m): 800	Basement Penetration (m):4700

Do you need to use the conical side-entry sub (CSES) at this site? Yes ☐ No ■

Are high temperatures expected at this site? Yes ■ No ☐

Are there any other special requirements for logging at this site? Yes ■ No ☐

If "Yes" Please describe requirements: VSP, FMI, UBI

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

Measurement Type	Scientific Objective	Relevance (1=high, 3=Low)
Neutron-Porosity	Andesite to basalt lava and dyke and tonalite to gabbro porosity; relate core to bulk crustal properties	1
Litho-Density	Andesite to basalt lava and dyke and tonalite to gabbro density 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 andesite to basalt lava and dyke and tonalite to gabbro	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.	2
BHTV		
Resistivity-Laterolog		
Magnetic/Susceptibility		
Density-Neutron (LWD)		
Resitivity-Gamma 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 Borehole Temperature & Pressure: Estimate formation temperature and pressure Borehole Seismic: 1. VSP core-log-surface seismic integration: core velocity, velocity by VSP and surface seismic data integration 2. repeated/long term seismic experiments using borehole seismometer	1 1 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 #: 698	Site #: IBM-4	Date Form Submitted:Sept. 30, 2010

1	Summary of Operations at site: (Example: Triple-APC to refusal, XCB 10 m into basement, log as shown on page 3.)	Rise drilling (deepening ODP Site 792) to the depth of 5500 mbsf
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
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: (e.g. ice, currents, cables)	None
9	Summary: What do you consider the major risks in drilling at this site?	Basement drilling with riser, but to ultra deep basement penetration (~4700m)

IODP Site Summary Forms:

Form 5 – Lithologic Summary

New *Revised*

Proposal #: 698	Site #:	Date Form Submitted: Sept. 30, 2010

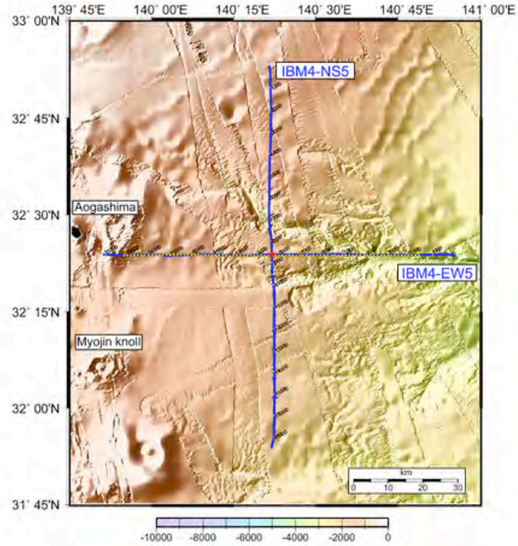
Sub-bottom depth (m)	*Key reflectors, Unconformities, faults, etc*	*Age (Ma)*	*Assumed velocity (km/sec)*	*Lithology*	*Paleo-environment*	*Avg. rate of sed. accum. (m/My)*	*Comments*
0-184	None	0-3.5	1.6	silty clay	forearc	100	
184-357	None	3.5-13	1.8	vitric siltstone	forearc	30	
357-429	None	13-25	1.9	claystone	forearc	14	
429-783	None	25-30	2.4	vitric sandstone and volcanic sandy congromerate	forearc to volcanic front	300	
783-804	None	?	2.2	altered volcanic standstone	forearc to volcanic front		
804-2400	volcanics	37	4.0-5.0	andesite lava	volcanic front		
2400-3500	upper crust	>37	5.0-6.0	andesite-basalt lava and intrusive	volcanic front		
3500-5500	middle crust	?	6.0-6.2	tonalite to gabbro	volcanic front		

Form 6 Site Summary

Proposal 698Full
Site IBM-4

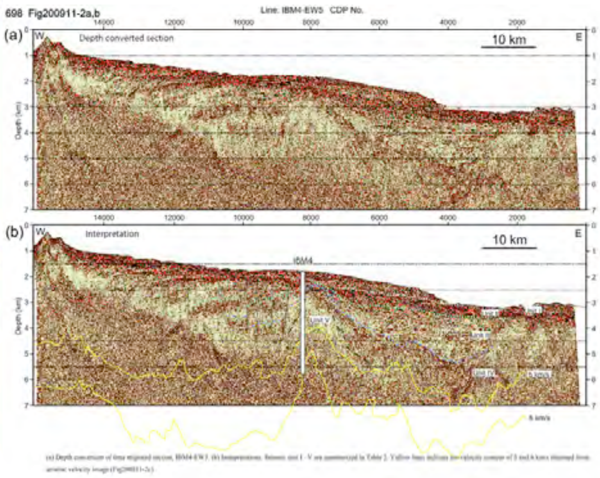
All images are from IODP-SSD.

698 Fig200911-1

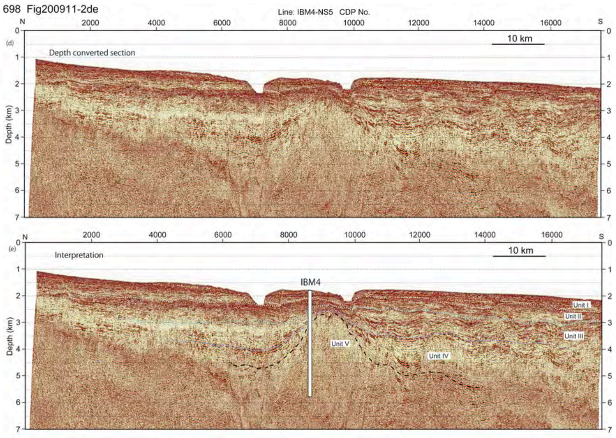


Location map of seismic profiles. Blue lines, yellow circles and white dot with numbers indicate seismic lines, OBSs and CDP numbers respectively. Seismic images are shown in Fig200911-2 and Fig200911-3. Red star indicates the proposed site, IBM4

698 Fig200911-2a,b

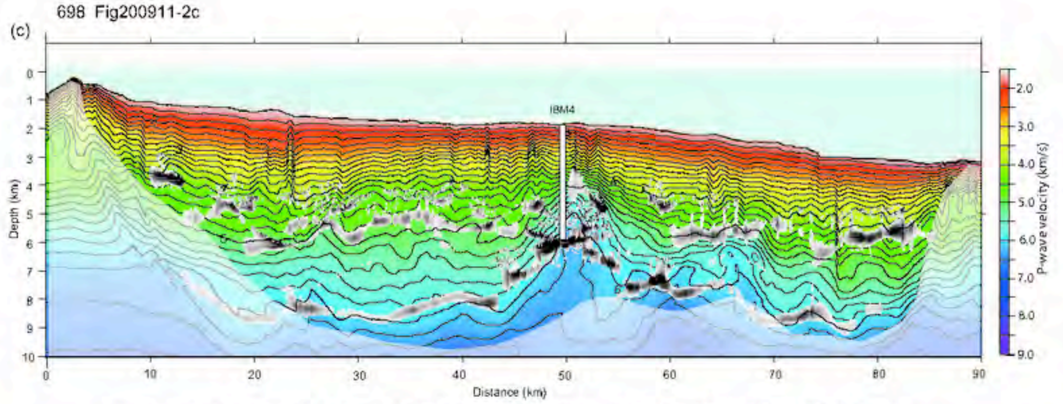


698 Fig200911-2de



(d) Depth conversion of time migrated section, IBM4-NS5. (e) Interpretations. Seismic unit I –V are summarized in Table 2.

698 Fig200911-2c



Seismic velocity and reflectivity images obtained from wide-angle OBS data. OBSs used are deployed at every 1 km along IBM4-EW5 (Fig200911-1). Refraction tomography (Zhang and Toksöz, 1998) and diffraction stack migration of picked travel times (Fujie et al., 2006) are applied for obtaining the seismic velocity and the reflectivity images (Fig200911-2c), respectively.The shaded area indicates the poorly resolved area.