WORKSHOP REPORT

Ultra-Deep Drilling Into Arc Crust

~Genesis of continental crust in volcanic arcs~

Date: 18th September, 2012 (Tue.) ~ 21st September, 2012 (Fri.)

Place: Waikoloa Beach Marriott Resort & Spa, Waikoloa Beach, Hawaii 96738 USA

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Participants

We had 58 participants from 9 countries around the world. All participants got involved in discussion and in writing this workshop report.

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Gazel	Esteban	Virginai Tech
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Glazner	Allen F.	University of North Carolina
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Country	Number of participants
US	34
Japan	13
UK	4
Switzerland	2
Mexico	1
Canada	1
Taipei	1
New Zealand	1
Australia	1
Total	58

Group photo of workshop participants at Waikoloa Beach Marriott Resort & Spa on September 21, 2012.

Introduction

This workshop aimed to gather a wide range of geophysicists, geologists, geochemists and petrologists who are interested in the nature of arc crust and how this is modified in collision zones and preserved in continental crust. Our goal has been to discuss the merits, methods and implications of “ULTRA-DEEP DRILLING INTO ARC CRUST” from both thematic (formation of continental crust) and regional (Izu-Bonin-Mariana) scope.

Overall scientific or technical objectives, and their relevance to the science being targeted by the new drilling program

The International Ocean Discovery Program (IODP) science plan highlights four main themes and 14 high-priority scientific challenges. One of the main themes is “Earth Connections: Deep Processes and Their Impact on Earth’s Surface Environment”. Challenge 11 is “How do subduction zones initiate, cycle volatiles, and generate continental crust?” The scientific and technical objectives of this workshop specifically address this Challenge 11 by studying the genesis of continental crust through ultra-deep drilling. D/V Chikyu (Fig. 1) has the ability to drill into the middle crust of intra-oceanic arcs where juvenile continental crust exists but has never been directly sampled. Our prime objectives are to explore the realm of the unknown and further elucidate the genesis of continental crust. Furthermore, if we can link processes active at specific levels in the arc crust with geophysical signals, then these signals can be used to infer processes in other active arcs.

Fig. 1. The riser-drilling platform D/V Chikyu.

The generation of continental crust on Earth is a unique process in our solar system. No other planet has developed such a sizeable volume of unsubductable crustal material. The consensus is that juvenile continental crust is created in arcs at subduction zones, but how does it form and evolve into mature continental crust? The continental crust we observe on the surface of the earth has been deformed, metamorphosed, and otherwise processed perhaps several times from its creation in subduction zones to the present. It’s impossible to imagine a wild tuna fish from opening a can of processed tuna; the same might be said about juvenile versus mature continental crust. Although there are many examples of accreted arc crust on the margins of continents, during- and/or post-collision geochemical changes are widespread (e.g., DeBari & Greene, 2011), and we don’t have the ability to observe active crust-forming processes in modern arcs except by what we can infer from eruptions at the surface, and by remote sensing of arc interiors. “ULTRA-DEEP DRILLING INTO ARC CRUST” is the best way to sample unprocessed juvenile continental-type crust, to observe these active processes that produce the nuclei of new continental crust, and to examine the nature of juvenile continental crust as first generated at intra-oceanic arcs.

How is continental crust created?

It is widely thought that continental crust has been created, or at least recycled, in subduction zones for the last ~3.5 Ga (e.g., Taylor, 1967; Rudnick, 1995). Although it is possible that some or most was originally created by obscure processes in the Hadean (e.g., Armstrong, 1968) and that some has been created from plume heads in Large Igneous Provinces (Bath *et al.,* 2000), neither of these hypotheses can be tested by drilling, so we will focus solely on the role of subduction in creating juvenile crust.

The presence of significant volume of middle crust with 6.0-6.8 km/s seismic velocities throughout the entire IBM arc (Calvert *et al.,* 2008; Kodaira *et al.,* 2007a,b; Kodaira *et al.,* 2008; Kodaira *et al.,* 2010; Takahashi *et al.,* 2007; Takahashi *et al.,* 2008; Takahashi *et al.,* 2009) is remarkable because these velocities are characteristic of a wide range of intermediate-felsic plutonic/metamorphic rocks (Christensen & Mooney, 1995; Behn & Kelemen, 2003, Behn & Kelemen, 2006) and are similar to the mean velocity of the continental crust. The density of these intermediate and felsic rocks makes them unsubductable, therefore, the IBM middle crust may be juvenile continental crust recently created in an oceanic subduction zone. However, this crust is presently thickest beneath basaltic, not rhyolitic, volcanoes (Kodaira *et al.,* 2007), which is another enigma.

Although the seismic velocity of the IBM middle and upper crust makes it an ideal candidate for juvenile crust, there have been questions about whether the overall composition of IBM curst has high enough concentrations of Mg, K, and light rare-earth elements (LREE) at a given silica concentrations to match the composition of typical continental crust (*e.g.* Kelemen *et al.,* 2003). The presence of significant volumes of boninites and LREE enriched high-Mg andesites in the IBM forearc (Ishizuka *et al.,* 2006; Ishiwatari *et al.,* 2006; Reagan *et al.,* 2010; Ishizuka *et al.,* 2011) opens the possibility that typical continental crust could be produced from the IBM arc with the appropriate mass balancing and processing of the various reservoirs making up its crust.

Ultra-deep drilling into this middle crust will constrain its petrologic and chronological relationship to the overlying upper crustal arc volcano and allow us to explore the active processes of continental crust growth below arc volcanoes. Such drilling will provide a unique perspective on how juvenile continental crust forms in the mid-crust of intra-oceanic arcs.

How is continental crust processed in subduction zones and collision zones?

The continental-crust-like middle crust in the IBM arc is underlain by thick high-velocity lower crust (e.g., Kodaira *et al.,* 2007). Occasional delamination may remove some of the dense mafic roots (e.g., Kay & Kay, 1991; Jull & Kelemen, 2001; Tatsumi *et al.,* 2008), but the bulk IBM arc crust is still basaltic or basaltic andesite (Calvert *et al.,* 2008; Taira *et al.,* 1998; Tatsumi *et al.,* 2008). In order to generate continental crust, mafic components of arc crust must be removed and felsic components must be concentrated. Hacker *et al.* (2011) propose that during arc-arc collisions, arc crust is subducted and buoyant felsic plutons in the mid-crust, together with felsic volcanic rocks, rise from the subducting plate and are "relaminated" at the base of the overlying arc crust. Alternatively, Tamura *et al.* (2010) suggested that the Miocene plutonic rocks in the Izu collision zone were derived from subducted and partially melted IBM middle crust of mostly Oligocene age. These ideas suggest that, once formed, felsic middle crust may be almost unsubductable, and represent permanent additions to continental crust. Studies of Hf and O isotopes and U/Pb ages of tens of thousands of zircons have led to nuanced studies of continuous crustal creation and periodic preservation during most of Earth history (Kemp *et al.,* 2006; Hawkesworth *et al.*, 2010) that need to be tested in juvenile arcs and collision zones. Thus, arc crust is somehow processed and refined through collisional orogeny to remove the most mafic lower crust and convert the remainder into continental crust, but the details remain vague because we have no samples of juvenile middle arc crust. These considerations make it imperative to understand what is the composition and origin of juvenile continental crust, such as that of the IBM middle crust. For the first time in human history, ultra-deep drilling can reach juvenile continental crust that has never been re-processed. The results of this ultra-deep drilling can then be used to characterize this crust and elucidate processes of crust formation. The results can also be used to create the very first correlation of rock type and depth to *in-situ* measurements of temperature, density, and seismic velocities. Applying this new framework to other active arcs can then give us the broadest view possible of crust formation.

Possible middle crustal rock types: what to expect from ultra-deep drilling.

Igneous and metamorphic rock types formed at depths of 5-20 km in arcs range in SiO_2 from 53-70 wt. % and in texture from dioritic and tonalitic plutons to metamorphic gneisses of mixed rock types (e.g. DeBari & Greene 2011; Gehrels *et al.* 2009; Hacker *et al.* 2008; Jagoutz *et al.* 2009; Saleeby *et al.* 2003, Busby *et al.* 2006). These rock types would be expected to have Vp=6.0-6.8 km/sec at those depths (Behn & Kelemen 2003; Hacker *et al.* 2003). The workshop brought together people experienced with the petrology, geochemistry, physical properties, and drill logging of such rocks from exhumed examples and deep continental drilling. We also invited people experienced with tonalitic plutons in current and former oceanic arcs. By combining this expertise with information about the middle crust of the modern IBM arc we will be able to develop and refine hypotheses that can be tested by drilling.

Destruction of continental crust by plate tectonics.

There are approximately 7 billion cubic kilometers of continental crust today (Cogley, 1984) and it is often assumed that this volume has grown over Earth history. However, it is clear from truncations of ancient orogenic belts, geochemical evidence for continental crustal components returned to the upper mantle, and the presence of >4.0 Ga zircons in younger sedimentary rocks that much continental crust has been destroyed, mostly by tectonic erosion at subduction zones. Lower crust foundering and “decratonization” might also be important destroyers of continental crust. The widely held view that the volume of continental crust has increased over time continues to be challenged (e.g., R. Stern & Scholl, 2010; Yoshida & Santosh, 2011; C. Stern, 2011). The question remains whether creation and destruction of continental crust is in balance or whether more crust is being destroyed than created.

Project IBM: Arc evolution and continental crust formation

Key questions for comprehending arc crust formation are: (1) What is the nature of the crust and mantle in the region prior to the beginning of subduction? (2) How does subduction initiate and initial arc crust form? (3) What are the spatial changes of arc magma and crust composition of the entire arc? (4) How does the middle arc crust evolve? The best possible strategy for answering these questions is drilling by IODP at the IBM arc system (Fig. 2). Four proposals to IODP to drill at the IBM, including three non-riser holes (IBM-1, IBM-2 and IBM-3 in Fig. 2) and one riser, ultra-deep hole (IBM-4) are focused on addressing these questions. The four drillings will result in comprehensive understanding of the arc evolution and continental crust formation. Ultra-deep drilling (IBM-4) will follow JR drilling at three sites (IBM-1, IBM-2 and IBM-3), which are scheduled for 2014.

IBM-1: Nature of the original crust and mantle

Pre-existing, non-arc oceanic crustal components should contribute to arc magma chemistry through assimilation and partial melting triggered during passage of arc magmas; oceanic crustal remnants could also make up an important part of the lower-arc crust. At the IBM, pre-existing oceanic crust is present west of the arc, under 1-1.5 km of sediments in the Amami Sankaku Basin adjacent to the Kyushu-Palau Ridge remnant arc (Fig. 2) (Taylor & Goodliffe, 2004).

IBM-2: Initial arc crust and subduction initiation

A section through the volcanic stratigraphy of the outer forearc of the IBM system will be drilled in order to trace the processes of magmatism, tectonics and crustal accretion associated with subduction initiation. The result of this drilling will be used to test hypotheses for subduction initiation and arc crust formation processes. This in turn has implications for understanding the origin of the many ophiolites that are now believed to form in this type of setting. The drilling will provide an opportunity to test the supra-subduction zone ophiolite model and involve the land-based geological community in IODP.

IBM-3: The rear arc: the missing half of the subduction factory

The spatial and temporal evolution of arc magmas within a single oceanic arc is fundamental to understanding the initiation and evolution of oceanic arcs and the genesis of continental crust, which is one key objective of the IODP ISP. The Izu-Bonin-Mariana arc has been a target for this task for many years, but previous drilling efforts have focused mainly on the IBM forearc, and thus the magmatic evolution of the volcanic front through 50 million years. Rear-arc IBM magmatic history has not been similarly well studied in spite of its importance in mass balance and flux calculations for crustal evolution, in establishing whether and why arc-related crust has inherent chemical asymmetry, in testing models of mantle flow and the history of mantle depletions and enrichments during arc evolution, and in testing models of intra-crustal differentiation.

IBM-4: Continental crust formation at intra-oceanic arc: ultra-deep drilling to the middle crust of the Izu-Bonin-Mariana arc

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.

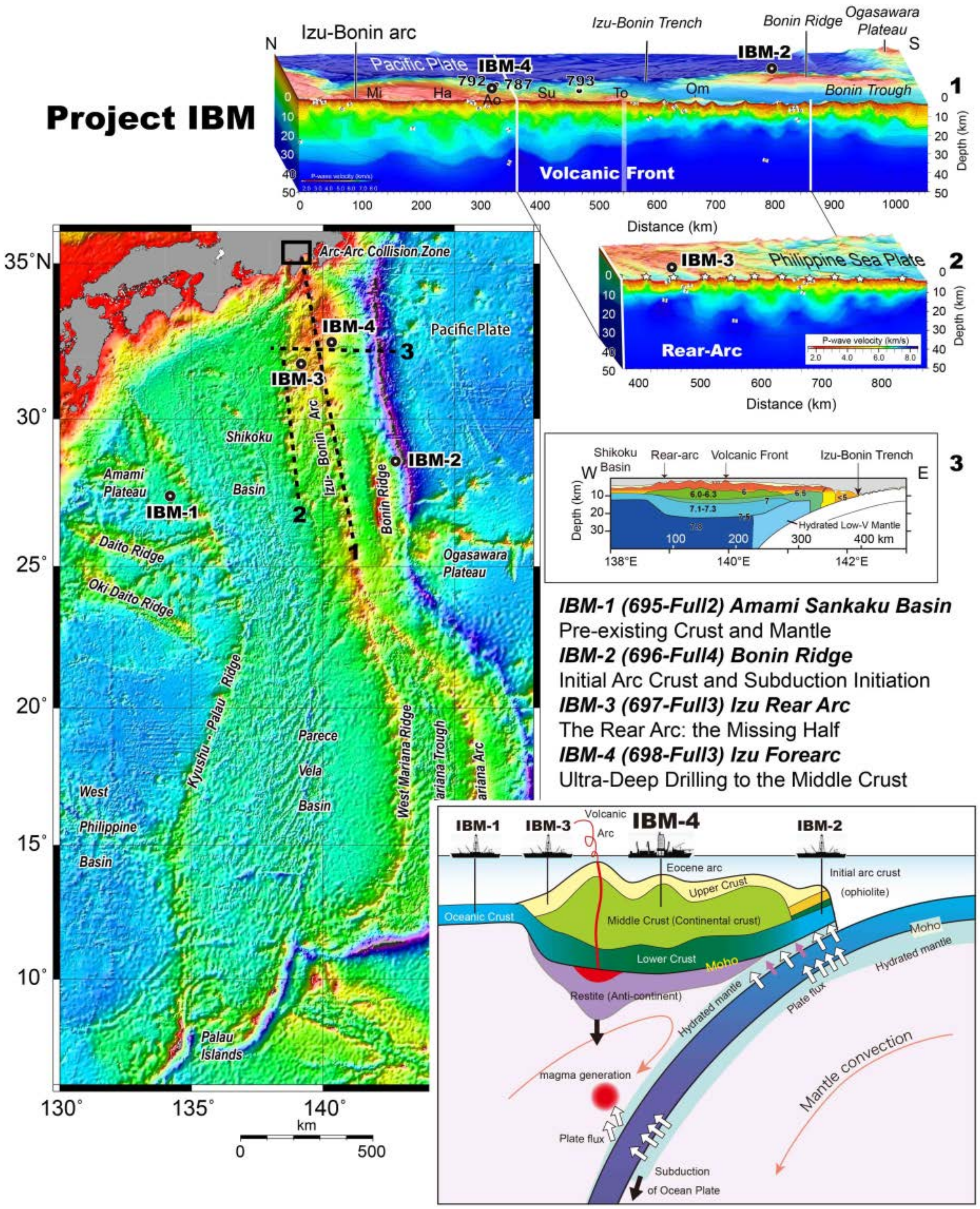

Fig. 2. Bathymetric features of the eastern Philippine Sea, including the Izu-Bonin-Mariana (IBM) arc system. Old seafloor (135-180 Ma) of the western Pacific plate subducts beneath the active IBM arc at the Izu-Bonin-Mariana trenches. Spreading centers active in the Mariana Trough (7-0 Ma) and relict in the Shikoku and Parece Vera Basins (30-15 Ma) and West Philippine Basin (50-35 Ma). The Ogasawara Plateau, Amami Plateau, Daito and Oki-Daito ridges are Cretaceous-Eocene features. The Kyushu-Palau Ridge (KPR) marks the rifted western edge of the initial IBM arc system (50-30 Ma), subsequently separated by the back-arc spreading into the Shikoku and Parece Vela Basins. The black dashed lines show the locations of the wide-angle seismic profiles (1) along the present day volcanic front (Kodaira et al., 2007), (2) along the rear-arc ~150 km west of the volcanic front (Kodaira et al., 2008) and (3) across the arc. IBM-1, IBM-2, IBM-3 and IBM-4 indicate proposed drill sites. Abbreviations show basalt-dominant Quaternary volcanoes (Mi, Miyakejima; Ha, Hachijojima; Ao, Aogashima; Su, Sumisu; To, Torishima) on the volcanic front and the andesite Oligocene volcano (Om, Omachi Seamount) east of the front. Numbered circles indicate sites drilled during ODP Legs 125 and 126.The 6.0-6.3 km/s, 7.1-7.3 km/s and 7.8 km/s layers correspond to parts of middle crust, lower crust and upper mantle, respectively.

Scope of topics covered by the workshop

Background information for all IBM drilling.

1. Evolution of IBM and its felsic rocks (Stern).
2. Geophysical overview of IBM arc (Calvert/Kodaira).
3. Kyushu-Palau Ridge (KPR) geophysics (Nishizawa).
4. Aleutian geophysics (Shillington).
5. IBM forearc geophysics (Kodaira)
6. IODP proposal 696-Full4 (IBM-2): Testing subduction initiation and ophiolite models by drilling the Bonin forearc (Pearce)
7. IODP proposal 695-Full2 (IBM-1): Continental crust formation at intra-oceanic arc: arc foundations, inception, and early evolution (Ishizuka)
8. IODP proposal 697-Full3 (IBM-3): The rear arc: the missing half of the subduction factory (Tamura/Gill)
9. IBM geochemical evolution (Straub)
10. Arc uppermost mantle: geophysical observations and processes (Wiens)
11. Chikyu drilling (Aoike)
12. Combining drill cores with in-situ geophysical measurements-reference model for other arcs (Saito)

What to expect in 698 (IBM-4)?

1. IODP proposal 698-Full3 (IBM-4): Continental crust formation at intra-oceanic arc: ultra-deep drilling to the middle crust of the Izu-Bonin-Mariana arc (Tamura)
2. Background; Review of Site 792 (Gill)
3. Field exposures of arc mid crust, Baja (Busby)
4. Field exposures of arc mid crust, Talkeetna (DeBari)
5. Field exposures of arc mid crust, Sierra Nevada (Coleman)
6. Possible continental basement beneath the northern Izu-Bonin arc (Tani)
7. Thermal modeling of lower crust melt generation (Bergantz)

8. Role of oceanic arcs and arc-related collisions in the evolution of continental crust (Draut)
9. Oceanic middle and lower curst (John)
10. Tatsumi model (Kimura)

    Produce science planning document outlines; refine proposal 698 scientific objectives and rationale; develop strategies for shipboard and land-based studies

1. What should be the scientific objectives for deep ocean drilling?
2. What at-sea drilling strategies and what shore-based studies are needed to achieve the scientific objectives? What expertise needs to be on the ship and to study the drill core afterward? How should drilling be staged over multiple legs?

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Geophysical overview of the Izu-Bonin-Mariana Arc-Back-arc System

1. Seismic Surveys

More seismic surveys have been acquired over the IBM arc-back-arc system than any other island arc setting on Earth. Consequently it is possible to contrast seismic velocity models across the arc representing different evolutionary histories, and to constrain them with strike lines where available. The Izu arc lies at the northern end of the IBM arc-back-arc system, and although affected by Oligocene arc rifting early in its history, the seafloor is shallower than 2000 m over a width of more than 150 km, in contrast to the more southerly elements of the IBM arc. A seismic survey of the Izu arc was acquired in 1992, and this survey is historically important, because of the first inference of a laterally extensive mid-crustal layer with a P wave velocity of 6.1-6.3 km s^{-1}, which was interpreted to be granitic (Suyehiro *et al.* 1996). The wide-angle line across the Izu arc (Fig. 1 and 2) was recorded using 26 OBS spaced every 15-30 km, and shot using a 3-airgun 2258 in^3 source, supplemented by 71 dynamite shots spaced every 2.5 km (Takahashi *et al.,* 1998).

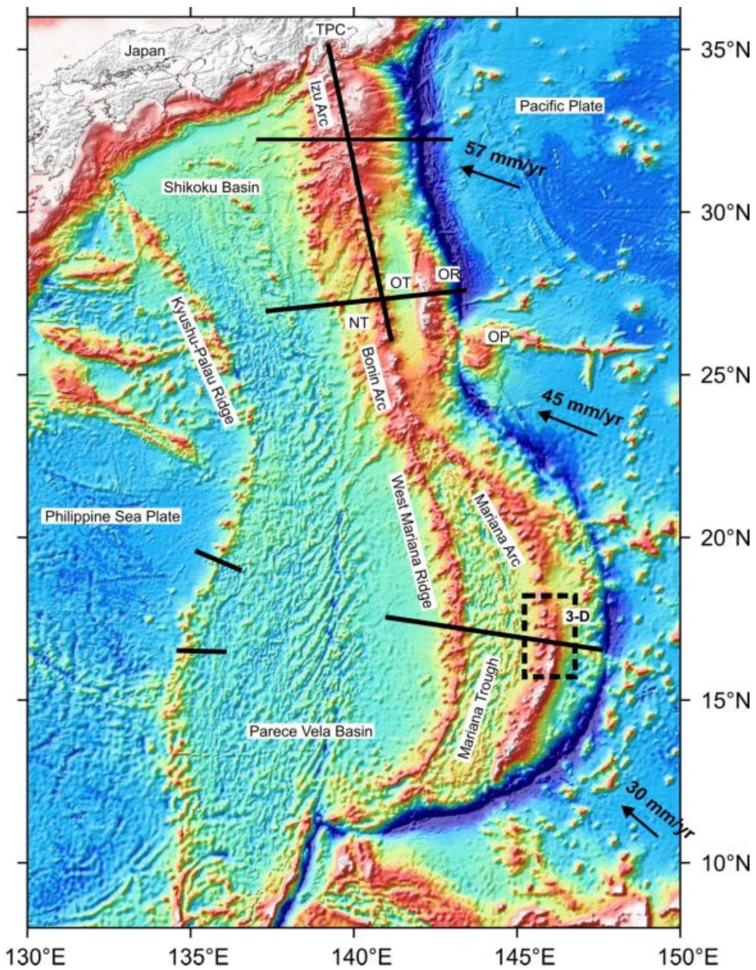

Fig. 1. *Bathymetry of Izu-Bonin-Mariana arc-back-arc system with the location of seismic lines. Seismic refraction lines are identified by solid black lines. The dashed black rectangle indicates the location of the 3-D survey of Calvert et al. (2008). The convergence of the Pacific plate at the trench is indicated by the arrows. OR, Ogasawara Ridge; OT, Ogasawara Trough; OP, Ogasawara Plateau; NT, Nishinoshima Trough; TPC, Tanzawa plutonic complex.*

Further south, the Bonin arc has been subject to a more complex history of rifting than the Izu arc, and the seismic line across the arc, which was acquired in 2005, crosses the Eocene Ogasawara forearc ridge and two failed rifts, the Nishinoshima trough and the Ogasawara trough, located respectively west and east of the present-day volcanic line. The wide-angle seismic survey employed 110 OBS spaced every 5 km to record shots from an airgun array with total volume 12,000 in^3 (Takahashi *et al.,* 2009). A 1060 km-long profile (Fig.1 and 3) was also acquired along the axis of the Izu-Bonin arc to show the along-strike variation in arc structure; shot in two phases this survey employed 103 OBS each time and the same 12,000 in^3 airgun array (Kodaira *et al.,* 2007a; Kodaira *et al.,* 2007b).

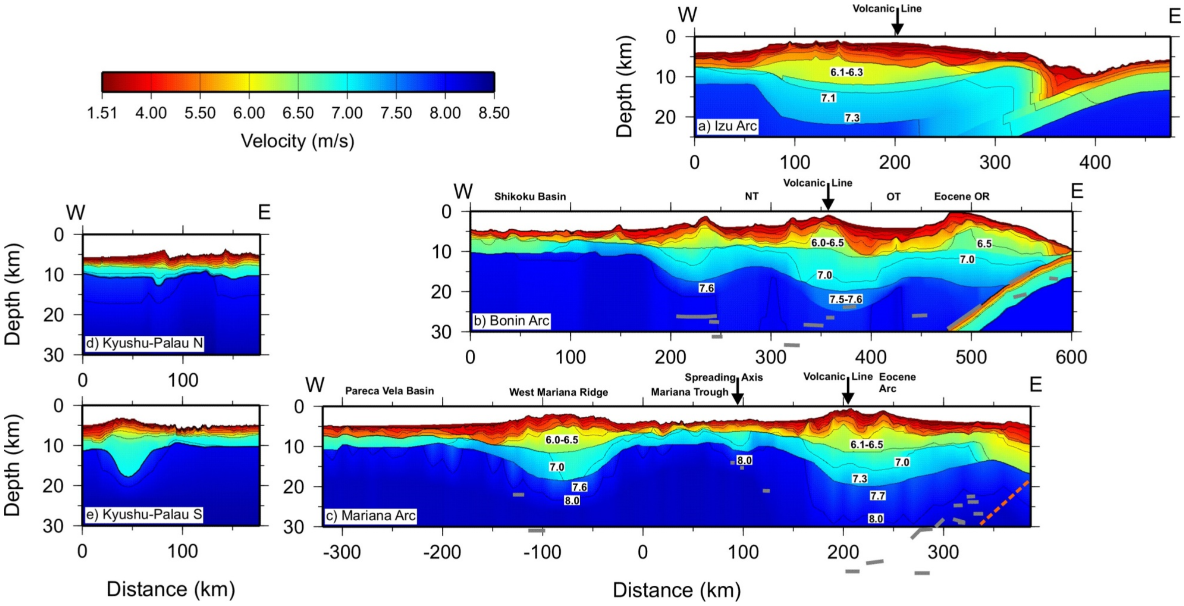

Fig. 2. Seismic velocity models across the Izu-Bonin-Mariana arc-back-arc system. a) Line across the Izu arc (Suyehiro et al. 1996); b) Line across the Bonin arc (Takahashi et al. 2009); c) Line across the Mariana arc and remnant West Mariana ridge (Takahashi et al 2007); d) Northern line across the Kyushu-Palau ridge (Nishizawa et al. 2007); e) Southern line across the Kyushu-Palau ridge (Nishizawa et al. 2007). The velocity models across the modern arc are aligned at the location of the trench. The lines across the Kyushu-Palau ridge are separated from the western end of the Mariana line by over 300 km of the Parece Vela basin, which is not shown here. The location of the top and bottom of the subducting oceanic crust beneath the Bonin forearc are constrained by wide-angle reflections. Beneath the Mariana forearc, the more steeply dipping oceanic crust is not resolved in this survey, but its approximate position is indicated by the dashed orange line. Grey line segments, some of which are at >30 km depth, indicate sub-Moho reflectors. Vertical exaggeration is 4:1.

Unlike the Izu-Bonin arc, the Mariana arc has undergone two episodes of rifting that developed to full back-arc spreading: initially in the Oligocene and later in the late Miocene. A seismic profile was acquired from the forearc, across the arc, the present-day back-arc spreading center and the West Mariana ridge, which is the Miocene remnant arc. This line used 106 OBS spaced at 5-10 km intervals and an airgun array with total volume 12,000 in^3 (Takahashi *et al.,* 2007; Takahashi *et al.,* 2008). The Kyushu-Palau ridge, which is the older remnant arc, has a narrower expression in the seafloor bathymetry than the West Mariana ridge. The variation in crustal structure along the Kyushu-Palau ridge has been revealed by four profiles that were acquired across this remnant arc in 2004 using up to 200 OBS spaced at 5 km intervals, and a 8040 in^3 airgun array (Nishizawa *et al.,* 2007); two representative velocity models derived from this survey (Fig. 1) are included here. A 3-D refraction survey, which involves an areal distribution of sources and receivers, has also been acquired over the central section of the Mariana arc (Calvert *et al.,* 2008); 53 OBS were laid along three north-south lines and four north-south and 7 east-west airgun lines were shot with a 10,810 in^3 airgun array.

2. Seismic Velocity Models

2.1. Cross-arc Lines

The seismic velocity models across the arc are aligned at the trench and presented in Fig. 2 north to south with the Izu arc at the top. The two included seismic profiles from the Kyushu-Palau ridge lie at approximately the same latitude as the line across the Mariana arc and are shown on the left in Fig. 2, but these parts of the remnant arc actually originated further to the north, because the Parece Vela basin opened obliquely.

The crust of the Izu arc is inferred to be 18-21 km thick over at least 130 km of the east-west oriented profile (Fig. 2), but the limited number of PmP reflections suggest that this thickness is not well constrained and the Moho is not identified at all under the forearc (Suyehiro *et al.,* 1996; Takahashi *et al.,* 1998). The midcrustal layer with velocities of 6.1-6.3 km s^{-1}, which reaches a maximum thickness of 7 km, also extends laterally over more than 100 km. This layer was introduced into the velocity model to reproduce the observed intracrustal reflections, and is also included, albeit in a less continuous form, in the velocity models across the Bonin and Mariana arcs. Although similar velocities are observed in the profile along-strike, the different tomographic approach used for inversion of the travel times of the strike line produces a velocity model with greater lateral heterogeneity (Fig. 3), suggesting that greater compositional variation may be present in the middle crust of the Izu arc than implied by the first survey.

The velocity model across the Bonin arc shows the variation in crustal thickness caused by the two episodes of failed rifting here; the crust under the forearc Ogasawara ridge and the modern arc is as thick as 20 km, and the rear part of the arc reaches 15 km, but in the rift zones the crust thins to 9-12 km (Fig. 2) with 2-3 km of this thickness comprising sedimentary rocks (Takahashi et al. 2009). The greater thicknesses of arc crust include mid-crustal regions with velocities of 6.0-6.5 km s^{-1} that are absent from the rift zones. In addition, Pn arrivals and some reflections from the upper mantle constrain velocities immediately below the inferred, laterally continuous (top)-Moho interface to be 7.5-7.6 km s^{-1}, leading to the interpretation of a crust-mantle transition zone up to 5 km thick beneath the thickest sections of arc crust. Under the rift zones, the Moho is inferred to be a sharp boundary.

In the Mariana arc, the initial Eocene arc lies 40 km east of the modern arc, but the crust, which is approximately 20-22 km thick (Takahashi *et al.,* 2007; Calvert *et al.,* 2008), does not appear to thin significantly between the two arcs (Fig. 2) unlike the Bonin arc where the separation due to rifting is greater at 150 km. However, the thickness of the mid-crustal region with velocities of 6.1-6.5 km s^{-1}, is reduced by half between the Mariana modern and Eocene arcs. The crust of the 120 km-wide West Mariana ridge is up to 17 km thick, including a mid-crustal layer with velocities of 5.6-6.5 km s^{-1}. The smaller, 50 km-wide Kyushu-Palau ridge is 7-14 km thick (Figs. 2d and 2e), and lacks a significant region with velocities of 6.0-6.5 km s^{-1}, presumably due to its removal from the rear part of the arc massif. Velocities of 7.6-7.7 km s^{-1} inferred immediately below the top-Moho interface beneath the West Mariana ridge and the Mariana arc suggest crust-mantle transition zones are present beneath both the active arc and the remnant arc.

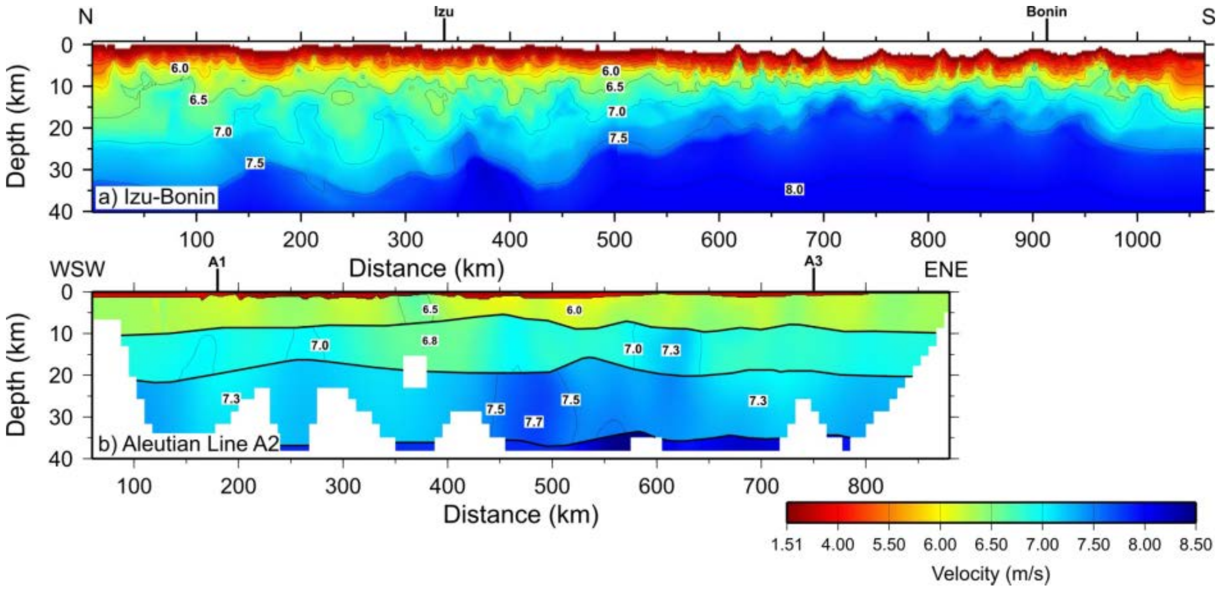

Fig. 3. (Top) Combined seismic velocity models along the modern volcanic line of the Izu and Bonin arcs (Kodaira et al. 2007b). Velocities are displayed with the same scale as Fig. 2. Vertical exaggeration is 4:1. (Bottom) The along-strike P-wave velocity structure of the Aleutian island arc (Shillington et al., 2004).

2.2. Along-strike Variation

The velocity models obtained from the along-strike surveys reveal the variation in crustal structure of the Izu-Bonin arc from the collision zone with Japan in the north to the extended Bonin arc in the south (Kodaira *et al.,* 2007b) (Fig. 3). The seismic surveys were acquired along the modern volcanic line, and did not extend onto the failed rifts of the Bonin arc: the Nishinoshima trough and the Ogasawara trough. Velocity models were derived independently using a multi-step procedure for each of the two ~500 km-long surveys, and then combined. In the first stage, a velocity model was derived using tomographic inversion of first arrivals, and this model was then locally updated to reproduce the arrival times of the wide-angle intracrustal reflections with these locations determined through migration of these second arrival picks (Kodaira *et al.,* 2007a). This latter approach results in a model that lacks intracrustal interfaces that are continuous over large distances, e.g. more than 100 km, and variations in crustal velocity and thickness that occur over less than 50 km are quite apparent (Fig. 3). The most striking feature of the velocity model, however, is the change in crustal thickness from 35 km to 10 km, which is inferred from the 7.6 km s^{-1} velocity contour, and occurs over a distance of ~300 km. The thickness of the northern Izu arc is 26-35 km, but the Bonin arc is only 9-22 km thick. Lower average crustal velocities, more representative of an intermediate crustal composition, are inferred beneath the basaltic volcanoes of both the Izu and Bonin arcs, but higher velocities implying a more mafic crustal composition are found beneath rhyolitic arc volcanoes (Kodaira *et al.,* 2007a).

3. Structure of sub-arc mantle

Large-scale passive seismic tomography of the Mariana volcanic arc using data from land stations and ocean bottom seismographs shows a prominent low velocity anomaly centered beneath the arc at a depth of 50-70 km (Barklage *et al.,* 2012). Very high P and S wave attenuation is also found at this depth from attenuation tomography (Pozgay *et al.,* 2009). Interestingly, by using chemical composition of primitive basalt lavas of the Northwest Rota-1 volcano, Mariana arc, Tamura *et al.* (2011) estimated segregation pressure of 1.5-2 GPa (equivalent of 50-65 km depth) for primary basalt magmas from their mantle source region. These depths are also similar to the 34-87 km estimated for the equilibration depths of hydrous melts beneath the Mariana volcanic arc using thermobarometry (Kelley *et al.,* 2010), indicating that the low velocity and high attenuation region represents the mantle source region for arc magmas.

Low velocities and high attenuation are also found in a separate region at shallower depths (10-50 km) beneath the Mariana backarc spreading center. This is also similar to the 21-37 km equilibration depths of backarc magmas (Kelley *et al.,* 2010), consistent with the shallower decompression melting depths of backarc basin basalts. The arc and backarc magma production systems are separated by cold, high velocity lithosphere just to the west of the arc at depths shallower than 50 km, but may be connected by hot, possibly hydrous asthenosphere at greater depths.

Some models for the generation of more evolved arc magmas propose processes that involve the generation of mafic restites and cumulates with seismic velocities in the range of 7.5 km/s, which may lie below the conventionally defined seismic Moho (e.g. Tatsumi *et al.,* 2008). Thus the velocity structure of the uppermost mantle has significant implications for the generation of arc middle crust. In the IBM system, detailed active source studies show Moho velocities of 7.6-7.9 km/s (Kodaira *et al.,* 2007; Takahashi *et al.,* 2008; Calvert *et al.,* 2008), well below the global average Moho velocity of 8.1 km/s. Wide angle reflections may define a higher velocity layer at a depth of about 40 km (Takahashi *et al.,* 2008). Lower resolution P wave tomography results show P velocities of about 7.5 km/s in this region, decreasing to 7.3-7.4 km/s in the magma production region around a depth of 50 km. However, these results may be relatively insensitive to a thin higher velocity layer in the uppermost mantle.

4. Comparison with the Aleutian arc

Drilling the middle crust in the IBM can provide insights into the magmatic evolution of not just this arc but other island arcs around the world by linking ground-truth information on the composition of the middle crust and possible genetic relationship between different levels of the arc with its geophysical characteristics. A notable attribute of the crust of the IBM arc is a middle crust with velocities of 6-6.5 km/s, which are interpreted to represent the presence of intermediate material. Interestingly, along-strike changes in the thickness of this layer correlate with the composition of volcanoes at the surface (Kodaira et al., 2007). Although comparably dense datasets on velocity structure are not available for any other intraoceanic island arcs, existing constraints from other island arcs provide useful comparisons.

Wide-angle reflection/refraction data from the Aleutian island arc reveal some similarities and differences with the IBM arc. Perhaps most importantly, this arc appears to lack a comparable mid-crustal layer with velocities of 6-6.5 km/s (e.g., Holbrook *et al.,* 1999; Shillington *et al.,* 2004) (Fig. 3). Although such velocities are present in the upper crust, they do not appear to constitute a thick layer, but are instead within the upper crust and interpreted to represent volcanics and shallow plutons. The middle crust has velocities of 6.5-7.3 km/s and is thought to comprise either remnants of the Kula plate (on which the arc is built) or new mafic arc crust (Holbrook *et al.,* 1999; Shillington *et al.,* 2004). Similar to the IBM arc, velocity models of the Aleutians contain an interval with high velocities (7.3-7.5 km/s) in the lower crust/upper mantle, whose composition and relationship to the middle and upper crust is uncertain. As in IBM, sparse data also hint at a correlation between along-strike changes in lava composition at the surface and variations in average crustal velocity and lower crustal velocity (Shillington *et al.,* 2004). However, existing data are too sparse to determine whether or not variations in crustal thickness and velocity similar to the IBM are present. Limited data on other island arcs globally suggest a range of velocity structures that mostly fall between the IBM and Aleutians.

Although there are differences in the velocity structure and other subduction parameters of the Aleutian, IBM and other arcs worldwide, many of the same overarching questions on how seismic attributes can be used to discern information on arc magmatic evolution apply: 1) What are the bulk compositions of the middle and lower crust, and how are these manifest in velocity structure? 2) How do variations in velocity with depth relate to the magmatic evolution of arc crust? 3) Can along-strike variations in average crustal velocity and the velocity and thickness of arc layers be used to understand arc magmatic processes? The deep drill hole in the IBM arc offers the opportunity to examine the important relationship between magmatic processes and the resulting geophysical structure. The linkages established here can also be used to determine the evolution of other arcs from geophysical surveys.

5. Seismic image of the ultra-deep drilling site

A multi-channel seismic reflection (MCS) survey was acquired in 2008 around the proposed drilling site of the ultra-deep drill-hole, IBM-4. The MCS data, which comprise a grid of 2-D lines (Fig.4), were acquired using *R/V Kairei* of JAMSTEC which has a tuned air-gun array with a total volume of 7800 cu.in and a 6000 m long solid streamer cable (444 ch with 12.5 m group interval). A time-migrated MCS sections along EW and NS profiles through the proposed site clearly images a domal basement high beneath the IBM-4 site (Fig. 5. Comparison of the MCS data with the core recovered from Site 792 indicates the section above the basement high comprises silt, clay, pumiceous sand/sandstone and pumiceous gravel, with ages from Quaternary to the upper Eocene. At the top of the basement high, andesitic lavas were sampled at 886 mbsf (Fig. 5).

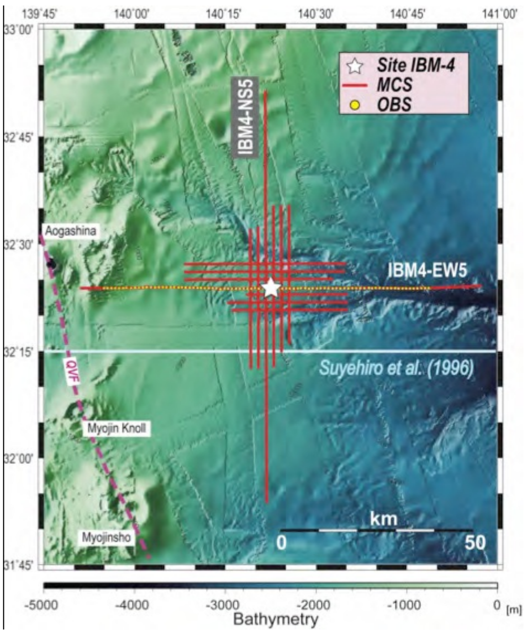

Fig. 4. Location of the proposed Site IBM-4 (open star) and MCS-OBS seismic lines surveyed in 2008 and Suyehiro et al. (1996). QVF, Quaternary volcanic front of the IBM arc.

A seismic refraction survey using densely deployed ocean bottom seismographs (OBSs) was also conducted along the MCS profile across the proposed site in order to clarify the detailed seismic velocity structure of the middle crust (Fig. 6), which is mostly transparent in the MCS reflection images. The seismic velocity structure derived from the OBS data clearly show a domal structure in the 6 km/s Vp iso-velocity contour. These Vp values, which are critical to identification of the middle crust, are located 3.5 km below sea floor at Site IBM-4.

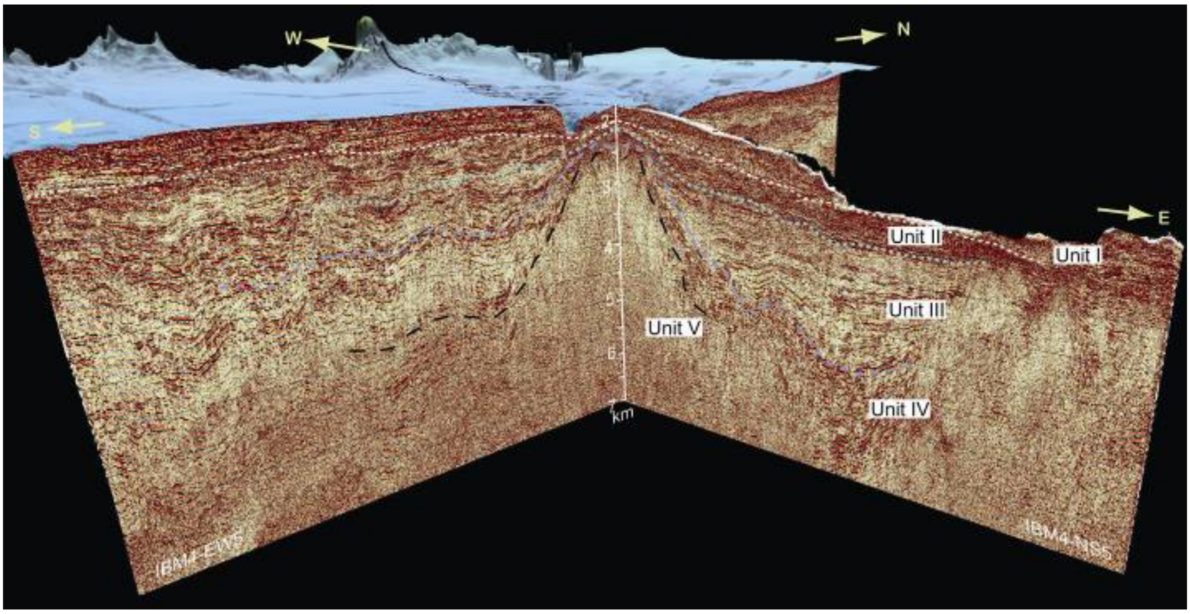

Fig. 5. 3D view of the seismic reflection sections crossing the IBM-4 Site. A conical basement high, which is likely to be composed of lavas and volcaniclastics, is well documented, suggesting the presence of an Eocene volcanic body beneath the IBM-4 Site.

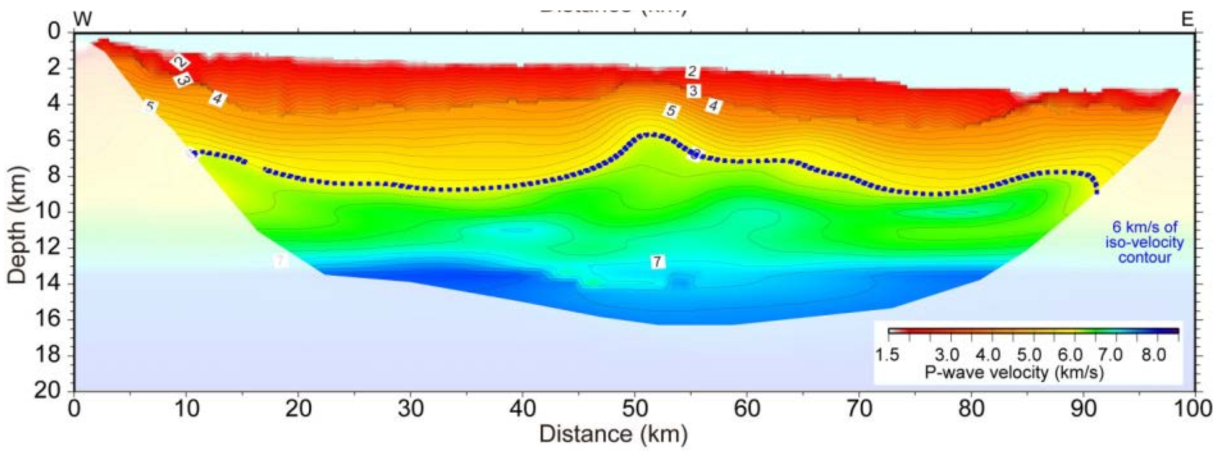

Fig. 6 Seismic velocity image of the E-W profile at the proposed site.

6. Pre- During- Post-drilling geophysical studies

Ultra-deep drilling to the middle crust is a unique opportunity to carry out many important pre-, during- and post-drilling studies, which can extrapolate 1-D drilling results to three dimensions. Here, we list the possible studies below;

Pre-drilling studies

1. S-wave velocity imaging. Although it is difficult to observe a converted S-wave phase in the existing wide-angle OBS data, it is believed that S-wave velocity combined with P-wave velocity results (i.e., a Vp/Vs image) is essential to identify a felsic-to-intermediate crustal layer. Receiver function study and noise tomography study may be possible techniques to obtain the S-wave structure.

2. Waveform inversion. As shown in the seismic velocity image obtained by travel time tomography, fine-scale velocity perturbations, which may reflect structural complexity at the top of the middle crust, are not imaged. Waveform tomography of wide-angle OBS data is one possible approach to obtaining a higher resolution image.

During- and Post-drilling studies

1. Sonic-logging. Sonic-logging is essential in order to obtain in-situ geophysical parameters, such as Vp, Vs, density, Qp, Qs.

2. Vertical seismic profile (VSP). Zero-offset VSP, walk-away VSP and 3D VSP can improve the seismic structural image around the borehole and extend the drilling results into three dimensions.

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New ages of IBM basement and its implications for subduction initiation

Evidence of pre-Eocene oceanic basement

The recent discovery of Mesozoic basement in the Izu-Bonin forearc (Ishizuka *et al.,* 2011a) illustrates that pre-existing crust might have played an important role in the early development of the IBM arc. Two pillow basalts recovered trenchward and beneath 51-52 Ma gabbros produced identical Ar-Ar plateau ages of 159.4 ± 0.9 Ma, indicating that these basalts resulted from Mesozoic magmatic activity (Ishizuka *et al.,* 2011a). These basalts have MORB-like compositions, and could be ocean crust created in a mid-ocean ridge, back-arc, or fore-arc (cf. Reagan *et al.,* 2010) setting. Pb isotope compositions of these basalts are similar to those Indian Ocean MORB and other lavas from the Philippine Sea Plate, and are clearly dissimilar to basalts from the Pacific plate. Thus, these basalts are not accreted Pacific crust, but in situ Mesozoic basement (Ishizuka *et al.,* 2011a). Gabbros and diabase from the Huatung Basin, west of West Philippine Basin were dated at 199-133 Ma illustrating that other areas of the Philippine Sea plate also consist of Mesozoic ocean crust (Deschamps *et al.,* 2000; Hickey-Vargas *et al.,* 2008).

Evidence of Mesozoic arc terrane

1) Daito Ridge group

The northern segments of the Kyushu-Palau Ridge (KPR) form the eastern boundary of a complex array of Cretaceous to Eocene ridges and basins. This region includes three remnant arcs: Amami Plateau, Daito Ridge, and Oki-Daito Ridge; and three rift basins: Kita-Daito, Minami-Daito and Amami-Sankaku Basins (Fig. 1; The Daito Ridge group: e.g., Mizuno, *et al.,* 1978; Hickey-Vargas, unpublished).

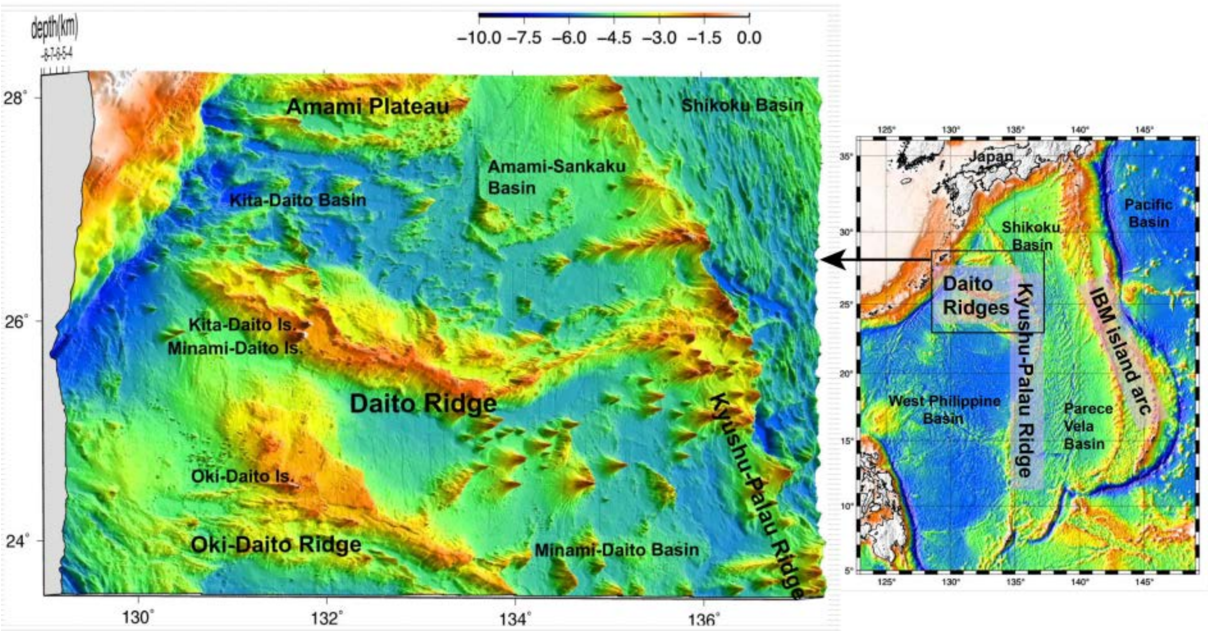

Fig. 1. The Daito Ridge Group. Figures by courtesy of A. Nishizawa.

Amami Plateau exposes granites and arc volcanics of Cretaceous age (e.g., Matsuda *et al.,* 1975; Hickey-Vargas, 2005), and has crustal thicknesses of up to 19 km (Nishizawa *et al.,* 2011). Geochemical characteristics of the volcanic rocks imply that the plateau was formed in an oceanic island arc setting (Hickey-Vargas, 2005).

The Daito Ridge trends E-W and intersects with KPR at its eastern end. Sedimentary, igneous, and low grade metamorphic rocks were recovered by dredging, and underlie Eocene sedimentary rocks (Mizuno *et al.,* 1975, 1978; Yuasa & Watanabe, 1975). Recent drilling and Shinkai diving recovered fresh volcanic rocks from the eastern part of the ridge. Andesites and basalts gave $^{40}Ar/^{39}Ar$ ages of 113-123 Ma (Ishizuka *et al.,* 2011b, unpubl. data). U-Pb zircon ages of gabbro and tonalites are dominantly Cretaceous, with one gabbro from Daito Ridge with arc-like geochemical affinities, expanding the age range to as old as 159 Ma (Tani *et al.,* unpublished). These samples have the geochemical signatures of arc magma (Ishizuka *et al.,* 2011b), illustrating that the Daito Ridge is a Mesozoic arc terrane. The existence of this terrane adjacent to the KPR implies that the IBM arc has Mesozoic basement at least in its northern section.

2) Izu forearc

Recent submersible surveys in the lowermost section of the northern Izu forearc found andesite and diorite samples that could be a possible counterpart of the Mesozoic remnant-arc terranes exposed in the Daito Ridge group. These rocks have geochemical signatures typical of arc magmas, and one of the diorite sample contains abundant Proterozoic detrital zircon grains as well as ~105 Ma magmatic zircons. (Tani *et al.,* unpublished). The sources of the old detrital zircons are not well constrained, but may have been derived from terrigenous sediments deposited adjacent to the Mesozoic arc terranes. The discovery of the pre-existing Mesozoic arc basement beneath the northern Izu arc suggests pre-Eocene Philippine Sea Plate had a complex crustal history that may have contributed to the development of the along-strike crustal structure observed beneath the present northern Izu-Bonin arc (Kodaira *et al.,* 2007).

Possibility of post-Eocene basement

Whereas the northern part of the IBM arc could have a basement consisting of Mesozoic arc terranes and ocean basins, other parts of the IBM arc might lack pre-Eocene basement. It is notable that Eocene ages only have been obtained from northern segments of the KPR (Fig. 2, Ishizuka *et al.,* 2011b). Even though the majority of the samples marked the last stage of magmatism along the KPR, lack of older ages (older than 32.5 Ma) in southern part of KPR implies that these southern segments might not have Eocene or older crustal rocks. This is consistent with the geographic relationship between the West Philippine Basin and KPR, and tectonic model deduced from this relationship (Casey & Dewey, unpublished). Much of the southern part of the KPR, and corresponding parts of the IBM arc, might have been established on the growing West Philippine Basin ocean crust (see Deschamps & Lallemand, 2002; Okino & Fujioka, 2003). This result opens the possibility that basement of the central IBM arc could be younger than the 51-52 Ma ages found in the forearc basement to the north and south (e.g., Ishizuka *et al.,* 2006; Casey & Dewey, unpublished; Ishizuka *et al.,* 2011a).

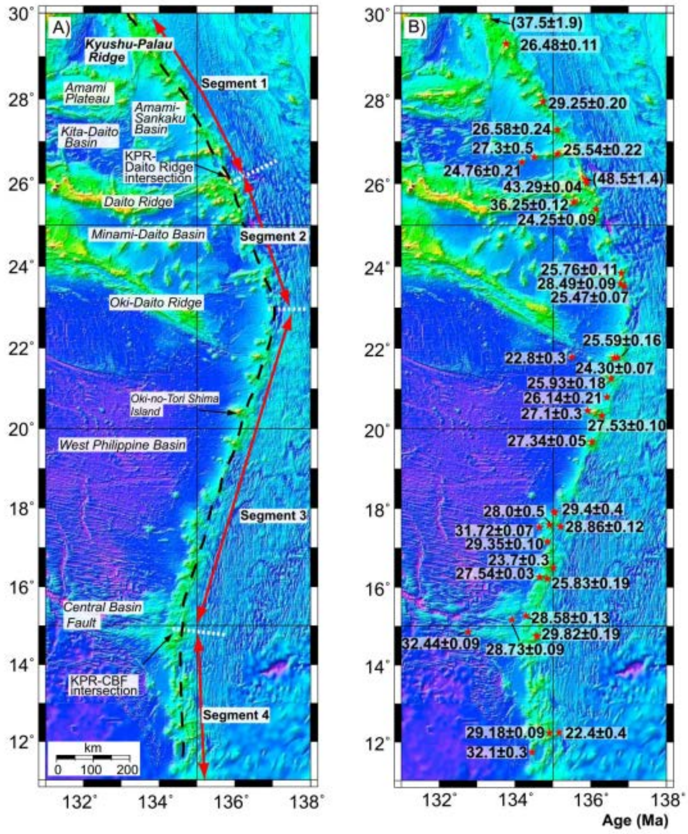

Fig. 2. (a) Bathymetric features and their names of the Kyushu-Palau Ridge. (b) Distribution of 40Ar/39Ar ages (in Ma) obtained for volcanic rocks from the Kyushu-Palau Ridge area. (Ishizuka et al., 2011).

Implication for heterogeneity of the arc basement

The crustal structures and variations in lava compositions in the IBM arc and KPR might be linked to the variability in the nature of the basement crust and lithospheric mantle beneath it. For example, high-K andesite only occurs in the northern KPR, especially near its intersection with the Daito Ridge (Ishizuka *et al.,* 2011b). These andesites from KPR-Daito Ridge intersection have a distinctively enriched trace element and isotopic character relative to the surrounding KPR samples. In particular, they have higher $^{206}Pb/^{204}Pb$ and LREE/HREE in combination with low Δ8/4 relative to KPR (Ishizuka *et al.,* 2011b). These distinct geochemical characteristics of KPR-Daito Ridge intersection are likely related to the involvement of sub-Daito Ridge crust or lithospheric mantle. This hypothesis will be tested when we obtain more comprehensive information about Daito Ridge crust and underlying lithospheric mantle based on study of Jurassic to Cretaceous arc magma from this region.

The thickest crust in the present IBM arc is north of the Sofugan Tectonic line at ca. 29°N (Kodaira *et al.,* 2007). Closing the Shikoku back-arc basin places this section of crust adjacent to the Mesozoic Daito Ridge Group terrane. This opens the intriguing possibility that this older crust played a role in thickening this crust. In contrast with the northern KPR, however, lavas from the Izu arc do not have compositions that are obviously affected by the presence of an older crust or lithospheric mantle. Geochemical characteristics of arc lavas from the Amami Plateau, especially their Nd isotopic composition (Hickey-Vargas, 2005), imply that Mesozoic arcs preserved in the Daito Ridge Group were juvenile arcs. This implication might explain lack of Nd isotopic evidence of involvement of continental root to the IBM arc magmas (e.g., Straub *et al.,* 2010; Tollstrup *et al.,* 2010; Taylor & Nesbitt, 1998).

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The generation of intermediate (andesitic) magmas and their relevance to growth of continental crust

Introduction

The workshop presentations and discussions reinforced that the Izu Bonin arc was the ideal place worldwide to study the mid-crust formation, as there is minimal sediment recycling and minimal pre-existing continental crust. Hence, the net flux from the mantle/subduction zone to the crust is visible with the greatest possible clarity. While the low-Vp mid-crust (6.0-6.8 km/s) of the Izu-Bonin arc resembles seismic continental crust, it still differs in several ways (*e.g.,* K_2O content, thickness, etc.) from average continental crust, which was probably formed largely in the Archean (hotter slab and mantle). The Izu example, however, may be more typical of current crustal growth (i.e., the composition of new continent may shift through earth history as slab and mantle continue to cool; Terry Plank, this workshop). All the same, it is important to note that the primary products of Archean crustal growth (e.g., TTG magmas) are still produced in modern arc environments, including IBM.

Possible Mechanisms of Andesite Formation and Arc Crustal Growth

Although there is widespread agreement regarding the key role of andesite formation in convergent margins with regards to the formation and evolution of continental crust, there is no consensus regarding the relative roles of melting of mantle and crustal lithologies, fractional crystallization, and/or magma mixing in the genesis of andesitic and other rocks of intermediate silica contents, and implicitly in the formation of the mid-crust low Vp layer. The following hypotheses are considered:

(i) Fractional crystallization in the lower crust that produces intermediate magmas which segregate in the mid-crust ('lower crustal hot zone model' by, Annen et al., 2006).

(ii) Silicic melt generation by partial melting of pre-existing (mafic) crust instigated by emplacement of new, hot mafic melts. Continuous upwards segregation of silicic melts (mid-crust) and periodic delamination of mafic residues can produce an average andesitic crust (Tatsumi et al., 2008, Tatsumi this workshop).

(iii) A range of primary basaltic to dacitic, high-Mg# magmas much of which may be emplaced intrusively and that seldom erupt (Tamura & Tatsumi, 2002; Straub et al., 2011; Yogodzinski et al., 2011) (Fig. 1). Crustal differentiation to low-Mg# compositions is then more rapid and less complicated.

(iv) Assimilation/contamination of mafic magmas by pre-existing intermediate crust (Ken Tani, this workshop). Blocks of Cretaceous continental crust, believed to be remnants of the proto-Philippine Sea Plate, have been found west of the Shikoku Basin. Did the Izu Bonin –Mariana arc form at a pre-existing discontinuity that was a Mesozoic arc? Is the thicker crust at the northern end of the Izu-Bonin Arc a remnant of this Cretaceous continental basement, separated from the others by the back-arc spreading? If so, this might also suggest a role for enriched, Mesozoic or older, sub-arc mantle lithosphere.

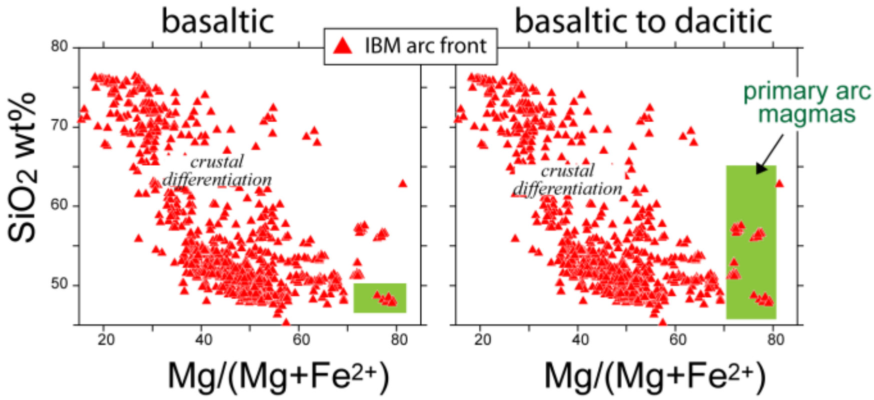

Fig. 1: Contrasting composition of primary arc magmas. Note that in either scenario substantial crustal differentiation is required to produce the composition of the erupted melts.

Deep Drilling to Test Models of Andesite Petrogenesis

Much of the continental crust is constructed by intrusive magmatism, yet most genetic models are based on the volcanic series. Thus, in order to decipher the mechanisms of crust formation, the genetic links must be established between the intrusive and extrusive magma series. Deep drilling into oceanic arc crust provides the only opportunity to probe in-situ the subvolcanic environment, much of which may control the composition of erupted magmas (Kent, this workshop). Drilling through an andesitic edifice (as shown to exist by ODP Site 792) into the subvolcanic realm below will help test hypotheses regarding the compositional equivalence of subvolcanic plutons and volcanic rocks. The mobility of magmas (primarily controlled by viscosity and density) are a strong function of composition, and as a result it is likely that the erupted compositions in many volcanic systems differ substantially from those present within the subvolcanic plutonic section – an effect referred to as eruption filtering. Thus we might expect significant compositional differences between erupted volcanic and unerupted plutonic rocks.

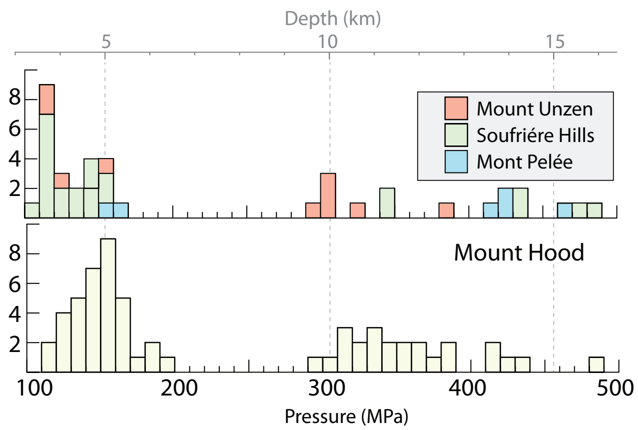

Fig. 2: Crystallization pressures calculated for amphibole from andesites from Mount Hood, Mount Unzen, Soufriére Hills and Mont Peleé using the method of Ridolfi et al. (2010). Amphiboles formed at pressures ~300 MPa (~10 km) crystallized from mafic magmas. Amphiboles formed at shallower pressures (< ~200 MPa) formed from more evolved magmas (see Koleszar and Kent, in review for more details). Significant amphibole growth, interpreted to occur in shallow crustal magma chambers where magma mixing creates andesitic magmas, occurred within the range of pressures that will be sampled by the proposed IBM-4 drill hole.

As an example, Kent *et al.* (2010) argue that many andesitic magmas are preferentially erupted relative to more mafic and felsic magmas within the subvolcanic environment due to their formation during energetic recharge and mixing events. Andesites, then, would form in relatively shallow crustal settings by magma mixing immediately prior to eruption. Existing mineral barometry suggests that mixing and assembly of many andesitic magmas occurs within the upper 5 km of crust – within the region that will be sampled by this deep drill hole (Fig. 2). This region plays an important role in andesite genesis (s.l.), but is difficult to access in most volcanic systems, thus this drill hole represents a unique opportunity to link the petrological study of erupted magmas directly to samples and data obtained from within the subvolcanic environment.

Complementary Case Studies in Support of Chikyu Drilling

Obtaining a complete rock record of basement rocks from ODP Site 792

Deep drilling to the low-Vp mid-crust will cut through ~3.5 km of magmatic upper crust. If full coring is not feasible owing to limits in time and resources, much of the data will have to be interpreted from the intermittent record of seismic logging, rock chippings and side cores to allow a reconstruction of the full sequence and the processes of crustal differentiation. Some critical sections in proximity to seismic boundary layers, or a preferred 'stalling levels of magma' (aka 'magma chamber', see also below), may be preferentially cored at the expense of other sections. Another problem – in an unlucky scenario – is that drilling on the center of the conical high formed by the basement may hit a central conduit, or possibly a single intrusive body all the way to the final depth reached. Thus, in order to maximize the scientific outcome of Chikyu drilling, complementary sources of information must be fully explored.

An important issue is to re-investigate the 82 m of volcanic basement (porphyritic andesite with minor basaltic andesite and dacite) drilled at ODP Site 792 (Leg 126), which is located right next to the planned deep hole IBM 4. While some whole rock and mineral data and Ar-Ar chronological data have been obtained (Lapierre et al., 1992; Taylor et al., 1992; Ishizuka et al., 2011b), studies dedicated to deciphering the processes of melt differentiation are still lacking. Because of the much higher core recovery (4-24%) from the riser-less drilling, a detailed investigation of this section likely spares coring the uppermost 82 m at IBM 4, provides valuable complementary scientific data, and serves as a guide on how to optimize the deep drilling strategy.

Do all arc magmas stall at mid-crust levels?

In recent years, it has become clear that melt inclusion work points to major magma stalling at 6-12 km in the modern Mariana Arc (Terry Plank, this workshop). This is also concluded from a case study on West Zealandia Seamount, also within the Mariana Arc (Alex Nichols, this workshop). H_2O-CO_2 contents within melt inclusions hosted in olivines from wehrlite and dunite crustal xenoliths, and the phenocryst population suggest final equilibration at ~300 MPa, equivalent to depths of ~11 kmbsl (wehrlites), and ~180 MPa, equivalent to depths of ~6 kmbsl (dunites and phenocrysts) (Figs. 3,4). Beneath West Zealandia these depths correspond to the lower-middle crust and middle-upper crust boundaries, respectively. Importantly, apparent stalling of magma at these depths is not unique to the Marianas, but is a typical feature of arcs worldwide (e.g. Ruscitto et al., 2012). Seismic/geodetic arrays on some of the islands would be good to test this. Vs would be really useful. If so, why are magmas stalling at this depth? Is this due to an intrinsic magmatic H_2O content of 4±2 wt% that compel the magma to first degas H_2O at these levels? Or is there a fundamental cause related to the crustal structure/density/stress that imposes stalling here? This observation points to a fundamental relationship between magma stalling and differentiation, and generation of middle crust, such as formed in the broader IBM and other volcanic arcs.

Further case studies could be conducted on favorable locations in the IBM where the depth of magma chamber(s) can be constrained, such as where crustal xenoliths have been found. Possibly, Anatahan volcano (Mariana arc island) may be a type example of this although no one has constrained the depths of fractionation.

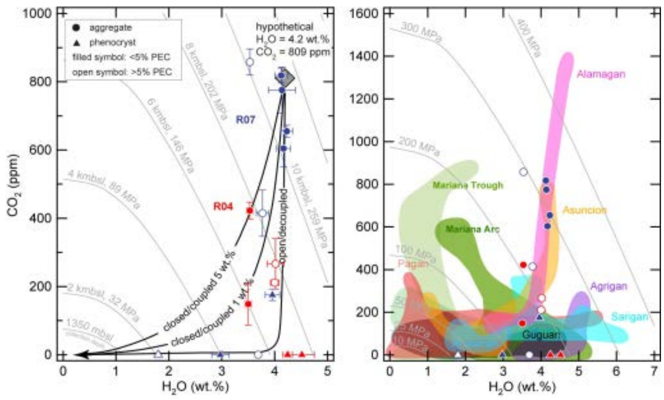

Fig. 3: H_2O-CO_2 relationships for West Zealandia melt inclusions found in aggregates and phenocrysts with degassing paths. West Zealandia inclusions compared to other inclusion data from the Mariana Arc. Note that many of the individual volcanoes from the volcanic front have maximum H_2O-CO_2 contents that suggest final equilibration at 200 – 300 MPa.

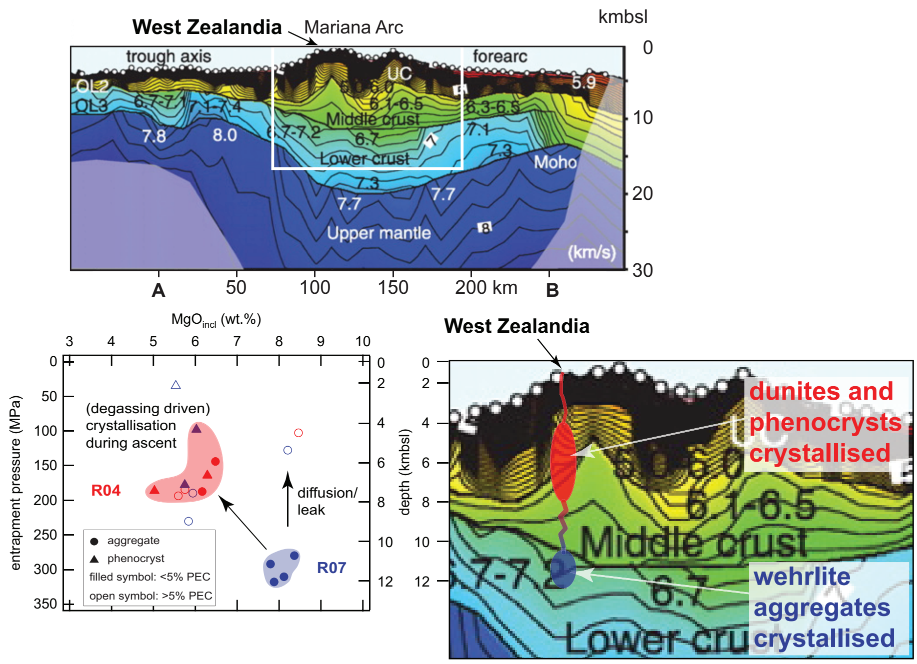

Fig. 4: Relationship between entrapment pressure and MgO content of West Zealandia inclusions compared to velocity model and crustal structure beneath West Zealandia.

Conceptual Approaches

Participants also discussed several conceptual approaches on how to obtain the maximum information from the rock series recovered during deep drilling of IBM 4.

How fast to magmas ascent from mantle to crust?

As mantle melts are added to the crust, one major question is whether those primitive melts take a prolonged path through the crust or whether they occasionally transit the entire crustal column rapidly within months to years (Philipp Ruprecht, this workshop). Thus different modes of mantle-melt addition and crust assembly may occur at any given time during arc maturation. Primitive phenocrysts (high magnesium olivines and pyroxenes) may provide insights into these modes and the timing of magma ascent through the crust. In particular, elemental diffusion modeling of Ni zonations (Fig. 5) in primitive olivines can track ascent times from the Moho to the surface (Ruprecht and Plank, manuscript in revision). The Ni zonations are thought to reflect growth in compositionally distinct mantle melts as they arrive and stall at the Moho and other depths.

While primitive magmas often carry olivine as the first liquidus phase (i.e., highest Mg# number minerals), magmas exposed in arc sections rarely contain extensive cumulates of olivine crystals (e.g. DeBari & Sleep, 1991; Jagoutz *et al.,* 2007). This dichotomy can mostly be explained by the fact that the olivine liquidus field expands with decreasing pressure, and pyroxene may replace olivine as the liquidus phase at higher pressure (Weaver *et al.,* 2011; Melekhova, this workshop).

Drilling into the middle crust will reveal the relative importance of olivine and pyroxene cumulates in-situ, and thus help to connect the plutonic and the volcanic records in primitive arc sections. Furthermore, using olivine phenocrysts as time capsules to track Moho-to-surface ascent rates assumes that such primitive olivines are crystals growing from the ascending melt and not simply picked up as xenocrysts within the crustal column. Thus, even in the limited material recovered in rock chippings and side cores during the middle crust drilling project, it is likely that in-situ mineral compositions and the origin of crystals carried up by magmas in volcanic eruptions will be able to be constrained.

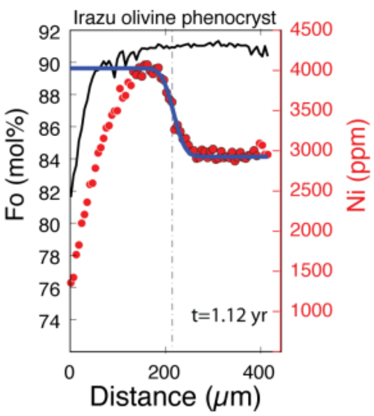

Fig. 5: Representative zonation profiles for a magnesian olivine phenocryst from Irazu volcano, Costa Rica (Ruprecht and Plank, in revision). The olivine shows a reversal that is modeled (blue line) using the analytical equation for a planar confined source in an infinite medium. Model curve and calculated mixing timescale (t=1.12 yr) are from a best fit calculation (lowest RMS).

Tracing different origin of magmas by Hf isotopes of zircons

Hf isotopes of individual zircons of zircon-bearing samples (e.g. gabbroic rocks, veins) could be used to determine to which extent magmas had different origins or represent mixtures of magmas from distinct sources (Paul Mueller, this workshop). It is common to see considerable variation in continental felsic rocks, but substantial variations have been observed in mid-ocean ridge rocks as well (e.g. at the now extinct proto-Macquarie, slow-spreading, mid-ocean ridge, Jeffcoat et al., 2011). This may be one way to detect to what extent older crust/lithosphere may have been involved in petrogenesis while avoiding the homogenizing effects of single measurements of Nd, Sr, and Pb.

Mafic magma reservoirs – long-lived evolving bodies or rapidly solidifying small plutons?

Magmatic minerals also contain direct information on melt differentiation (Georg Zellmer, this workshop). Minerals of mafic rocks from the southwestern Japan arc have been studied to deduce their origin (Zellmer et al., 2013a). Two-pyroxene thermobarometry of magmas from several volcanoes yields constant temperatures and variable pressures. MELTS fractional crystallization modeling show that such "pseudo-decompression paths" (PDPs) are artifacts that derive from uptake of pyroxene antecrysts formed at a range of crustal levels by isobaric cooling of previously intruded mafic melts. Similar PDPs are found in other arc volcanic products (Andes, New Zealand, N. Taiwan, Zellmer et al., Moebis et al., and Iizuka et al., unpublished data). The ultra-deep drilling project may be used to test this hypothesis by (i) studying the size of mafic crustal reservoirs beneath the volcanic sequence, and (ii) comparing the chemistry of crystals in the plutonic sections with those in the eruptive pile.

Computational approaches to understanding the origin of mid-crustal magmas

There is abundant evidence from whole-rock, mineral and melt inclusion data to suggest that many magmas undergo processing in crustal transport and storage systems (Wendy Bohrson, this workshop). Computational models afford the opportunity to use this wealth of data to quantify processes such as recharge/magma mixing, crustal assimilation and crystallization (RAFC). Application of such models allows quantitative estimates to be made of mantle vs. crustal and mafic vs. silicic contributions to magma composition and lead to mass balance models for the formation of upper and middle crust. A number of computational approaches are available, but one approach in particular couples mass and energy constraints (EC-RAFC, e.g. Bohrson and Spera, 2001; Spera and Bohrson, 2001; Spera and Bohrson, 2002; Bohrson and Spera, 2003) to provide trace element and isotopic information about magmas undergoing coupled RAFC. An extension of EC-RAFC utilizes capabilities of MELTS (Ghiorso and Sack, 1995; Gualda et al., 2012) by applying energy and mass conservation to track the state of a coupled magma-wallrock composite system. This computational tool, called the Magma Chamber Simulator, tracks phase equilibria, major and trace element chemistry, radiogenic isotope signatures and dynamical characteristics of crystals and melt in magma and wallrock as magma cools and wallrock heats up. Both tools can be equally well applied to plutonic and volcanic rocks. Drill samples that represent the temporal and compositional diversity of crust at the Izu Bonin site will allow quantification of the components that play critical roles in the development of mafic to silicic compositions thus addressing the critical question of how compositional diversity occurs, including the formation of intermediate-composition middle crust.

Preliminary Magma Chamber Simulator results of cases in which MORB is emplaced into ultramafic to silicic crust of appropriate thermo-mechanical characteristics illustrate the impact AFC has on magma composition and phase equilibria. In the case of intermediate to silicic wallrock compositions, melting can produce a large mass of anatectic melt over a small temperature interval, and consequently can change magma SiO_2 dramatically (Fig. 6); other oxides respond variably, with some higher than the FC only case, and others lower. A key observation is once intermediate to silicic material is available as wallrock and if thermo-mechanical conditions are appropriate to allow anatectic melt transport into the magma, then intermediate composition magmas are produced by AFC. A second observation of importance is that addition of silicic anatectic melts to evolving basalt suppresses crystallization of plagioclase, clinopyroxene and olivine. This result has implications for studies that address the origin and evolution of crystal populations in volcanic rocks. The crystal information provided by the Magma Chamber Simulator also allows hypotheses regarding the origin of plutonic crystals to be tested. Thus, the drilling project provides a unique opportunity to apply energy-constrained computational models to questions that address the origin and evolution of magmas, and thus of the crust.

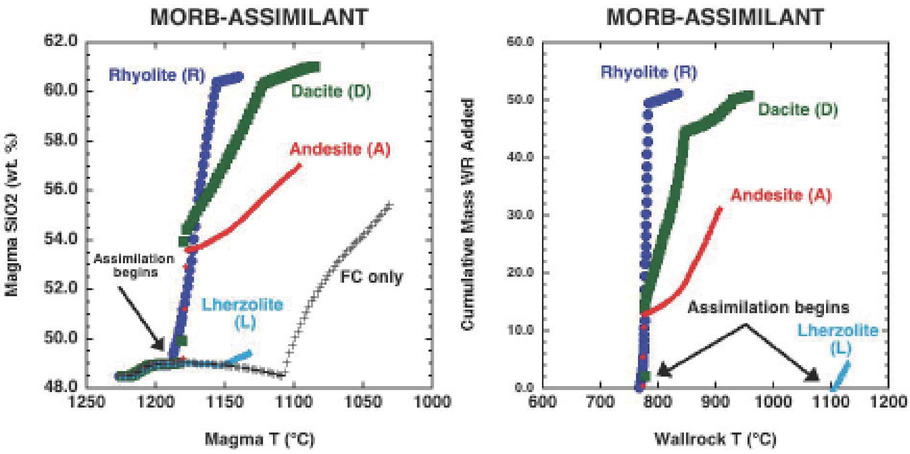

Fig. 6: MORB-Assimilant simulations, with assimilant labeled and shown as different color symbols. FC is fractional crystallization only case shown for comparison. More silicic wallrock melts over a small T interval, and thus magma SiO_2 changes over a small T interval. Simulations run at ~0.1 GPa.

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Using exposed arc sections in conjunction with IBM deep crustal drilling to understand the generation and growth of arc crust, and transferability to other active arc settings

Introduction

Investigation of arc crustal sections exposed on land provide an important companion study for any deep crustal drilling program. Although altered by syn- or post-accretion modifications, the study of paleo-arcs provides a larger, more volumetrically abundant record of both the intrusive and extrusive record of the processes that generate continental crust from mantle-derived magmas. In turn, deep crustal drilling can answer many questions that remain unanswered after examination of exposed sections, the activity of which ended long before they were amassed in their current locations. For example, through the direct petrological, geochemical, and geophysical characterization of the crust at site IBM-4, a reference section of intraoceanic arc crust can be generated. The cored rocks and borehole properties can be directly linked to the seismic velocity structure of the crust, providing the first in situ test of seismic velocity models against known rock types and structures within the deep arc crust. The IBM-4 site will provide an essential reference both for active arc crust and for accreted arc crustal terranes.

Many active arcs (except the Aleutians) have a middle crust with seismic velocities (V_p) of 6.0-6.5 (Fig. 1), which are interpreted to be intermediate to felsic plutonic rocks. Exposed arc crustal sections (e.g., the Talkeetna arc crustal section in the last panel of Fig. 1) typically include middle crust composed of diorite to tonalite to granodiorite. These rock types have seismic velocities predicted to be ~6.3 based on models such as in Hacker & Abers (2004). The potential to drill into active arc crust at IBM provides an unparalleled opportunity to provide linked geophysical and lithological data that can then be transferred to other active arcs that are missing the lithologic data and to exposed crustal sections that are missing the *in situ* geophysical data. The results can be used to create the very first correlation of rock type and depth to *in-situ* measurements of temperature, density, and seismic velocities. Applying this new framework to other active arcs and crustal sections can then give us the broadest view possible of the evolution of juvenile arc crust and its subsequent transformation to continental crust.

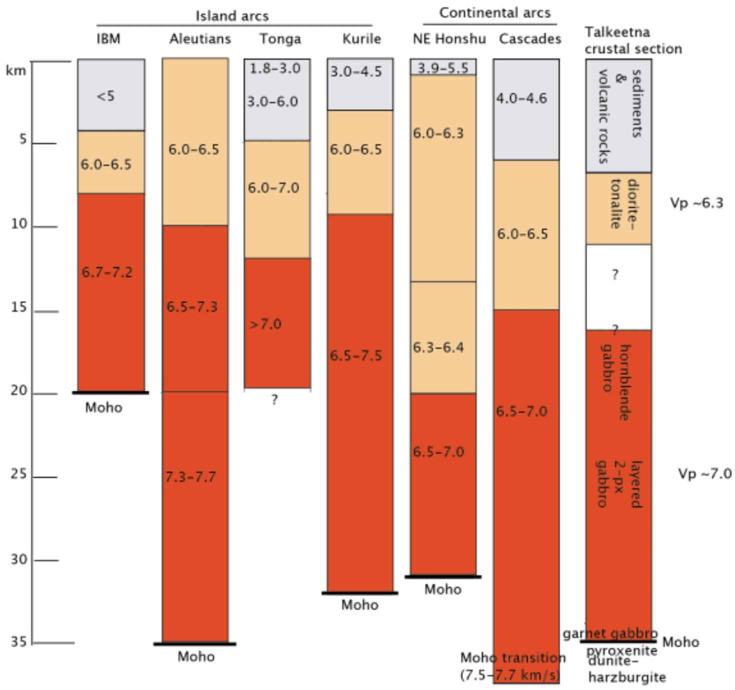

Figure 1. Seismic velocity profiles of various modern island arcs and continental arcs compared to the

Talkeetna crustal section. The Izu-Bonin arc is from Suyehiro et al. (1996), the Aleutian arc is from Shillington et al. (2004), the Tonga arc is from Crawford et al. (2003), the Kurile arc is from Nakanishi et al. (2009), NE Honshu is from Iwasaki et al (2001), and the Cascade arc is from Parsons et al. (1998).

Accreted arc sections: Lithologic variations with depth

Exposed arc sections show that: 1) shallow arc crust is lithologically heterogeneous, and 2) arc crust is, on a gross scale, vertically stratified in composition due to differentiation processes active within the crust. The discussion below summarizes this information.

One of the goals of the proposed drilling at IBM-4 is to examine the transition from upper to middle crust, and to better understand the pluton-volcano connection. The Cretaceous Alisitos arc in Baja California (Fig. 2) is an outstanding analog for what might be expected during drilling of the Izu Bonin arc. Its upper crustal section is lithologically heterogeneous, and the section "captures" the upper- to middle-crust transition. The view shown in Figure 2 is not a reconstruction; it is a down-dip cross section made directly from a 60-km long segment mapped in detail (Busby *et al.,* 2006). The section is structurally intact, unmetamorphosed, and very well exposed, permitting detailed examination of the pluton-volcanic connection. The mapped segment has a central subaerial edifice,

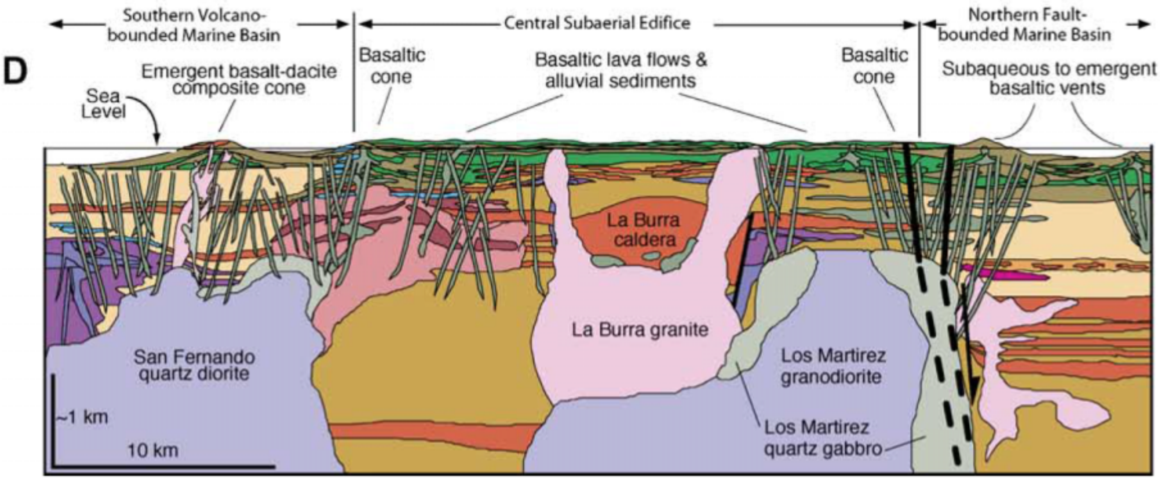

Figure 2: Down-dip cross-sectional view of a 60 km-long segment of the Cretaceous Alisitos extensional oceanic arc in Baja California, Mexico (Busby et al., 2006). This segment was mapped and dated in detail because it has superior exposure, and is undisrupted by post-depositional faults (the normal faults shown at right are synvolcanic)

made largely of andesite and dacite lava flows; these are capped by a silicic caldera and related granites that formed in response to extension (Busby *et al.,* 2006). This central edifice was flanked by a down-faulted deep-water marine basin to the north, and a volcano-bounded shallow-water marine basin to the south. Basins around the central subaerial edifice preserve products of mass wasting, subaqueous pyroclastic flow activity, and deep-water silicic caldera collapse (Fig. 2). Extension and silicic caldera magmatism was immediately followed by widespread emplacement of mafic dikes and associated mafic dikes and plutons (except where they were occluded by the sub caldera granite, which must have still been hot); this is interpreted to record arc rifting (Busby et al., 2006). U-Pb zircon dates indicate that the entire 5 km-thick crustal section shown in Figure 2 was created in less than 1.5 myr. The original crustal thickness is not known, because the top is covered, and the base passes downward into unmapped deformed rocks. However, the exposed top of the section is probably not far from the original top, since strata at the base of the 5 km-thick section are zeolite grade (except for local contact hornfels).

Another example of the relatively intact uppermost few kilometers of arc crust is provided by the early Jurassic Talkeetna arc, also formed in an extensional arc setting (Clift *et al.,* 2005). The Talkeetna Formation forms the upper 7 km of the Talkeetna arc (Figs. 3 and 4) and includes a series of lavas, tuffs, and volcaniclastic debris-flow and turbidite deposits described by Clift *et al.* (2005). There is a general trend toward more volcaniclastic sediment at the top of the section and more lavas and tuff breccias toward the base. Where exposed, the base of the volcanic section is intruded by mid-crustal plutonic rocks. In this arc, the volcanic section totals 7 km in thickness, which is about 20% of the entire arc section from the paleo Moho to the surface (Fig. 3). This gives a plutonic:volcanic ratio of 5:1. Maximum metamorphic grade of these volcanic rocks, even where intruded by plutons at the base of the section, is lower greenschist facies.

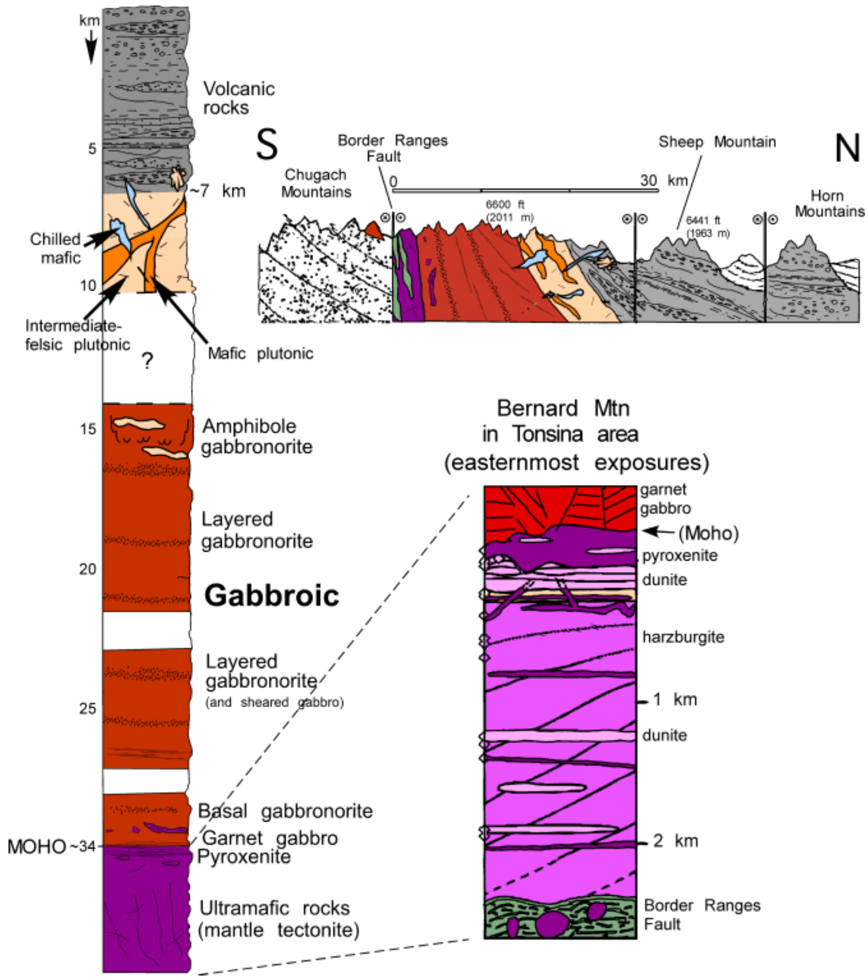

Figure 3. Detailed crustal section for the Talkeetna arc based on stratigraphic thickness of the volcanic section (Clift et al. 2005) and geobarometry of Hacker et al. (2008). From DeBari and Greene (2011).

The transition to plutonic rock in these sections, as well as many others (e.g., Lapierre *et al.,* 1992; DeBari *et al.,* 1999; Jagoutz, 2010) is generally an intrusive relationship so that the transition within a narrow vertical profile is sharp (volcanic facies above, plutons below). Laterally, however, the transition depth is variable depending on how far upsection the shallowest plutons intruded. For example, in the Alisitos arc (Fig. 2), at some locations the shallowest plutons are at ~1 km depth and at others, the shallowest plutons are deeper than ~3 km. In some arcs, these shallowest level plutons tend to be the most felsic compositions.

Arc sections that expose rock from upper mid-crustal depths contain a range of felsic to intermediate composition plutons that are dominated by granodiorite to tonalite to quartz diorite, with rare granite and gabbro (Lapierre *et al.,* 1992; Coleman *et al.,* 1997; DeBari *et al.,* 1999; Ducea, 2001; Hacker *et al.,* 2008, Otamendi *et al.,* 2009) (tan colored rock types in Figure 4). In almost all cases, felsic to intermediate plutons at these depths are heterogeneous and are composed of intrusions of multiple magma types. In arc sections where magma flux was very high for short periods of time (e.g. the Coast Plutonic Complex, the Sierran arc, Famatinian arc, western Talkeetna arc), these felsic to intermediate plutonic lithologies make up a much larger share of the crustal section, and indicate that large amounts of "continental" crust may be generated in a short amount of time (see mid crust production rate section below). Lower middle crust in the Talkeetna and Kohistan arcs is more mafic than upper middle crust (hornblende-bearing gabbros to diorites).

The presence or absence of pre-existing oceanic crust upon which the arc was built appears to be arc-specific. Only small scraps of previous oceanic crust basement are preserved in the Talkeetna arc crustal section and have not played a role in arc evolution. The same appears to be true of the Sierran arc (Kistler 1990; Coleman *et al.,* 1992). The Kohistan arc section (Jagoutz, 2010), the Bonanza arc section (DeBari *et al.,* 1999), and the Famatinian arc section (Otamendi *et al.,* 2009) do have clear remnants of pre-existing oceanic crust that have undergone crustal melting, but their role in middle crust production varies from minor (Kohistan) to major (Bonanza & Famatina).

The deepest levels of an arc (lower crust to upper mantle) are exposed in the Talkeetna and Kohistan arc sections (DeBari & Greene (2011) and references therein). These expose pyroxene and plagioclase rich rocks, with garnet appearing near the crust-mantle boundary (see Figures 3 & 4). The IBM-4 drill core will not reach these depths; however, given the age, depth, and compositional control on the Talkeetna and Kohistan arcs, and the modeled similarity in Vp profile between Talkeetna and IBM (see Fig. 1), these arc sections may be a valuable complement to the results of the proposed Izu Bonin drilling. If the upper crustal section in the IBM arc is similar to that of Talkeetna, then the deeper Talkeetna section can be used as a model for reconstruction of the complete crustal sequence of mature IBM crust.

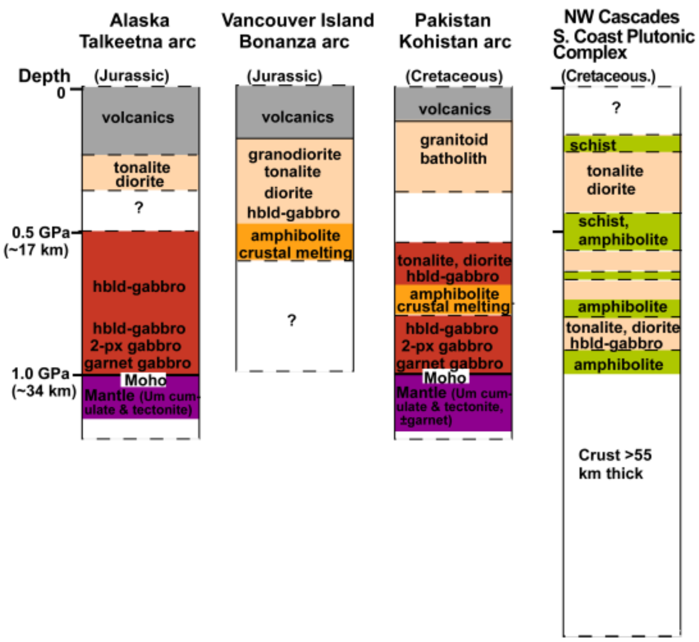

Figure 4. Schematic lithologic sections of four accreted arcs. Colors are meant to be broad generalizations of lithologic types. Grey is volcanic rock (all compositions), tan is intermediate to felsic plutonic rock (53–72 wt% SiO_2), red is gabbroic rock (typically cumulate) (45–52 wt% SiO_2), purple is ultramafic rock (pyroxenite, wehrlite, dunite and harzburgite) (<52 wt% SiO_2). Orange regions show crustal

levels where partial melting has taken place. Green areas represent abundant metamorphic country rock that has not melted. The paleo-Moho is defined as the transition between ultramafic rock (plagioclase absent) and gabbroic rock (plagioclase present). From DeBari & Greene (2011).

Interpreting seismic velocities

Exposed reference sections of deep crust and upper mantle (Talkeetna and Kohistan) will also be important for interpreting seismic data collected beneath the level of IBM-4 drilling. For example, Figure 5 shows a correlation of seismic measurements for rocks present at the paleo Moho of the Kohistan arc (Kono et al. 2009).

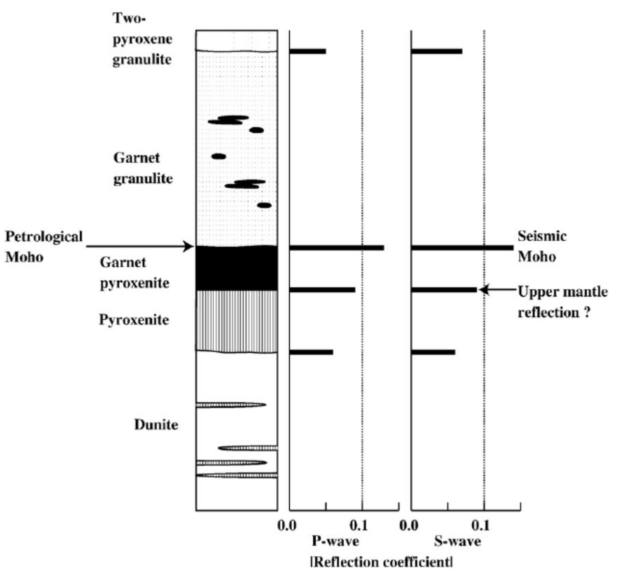

Figure 5. Schematic illustration for the lowermost crust and upper mantle of the Kohistan arc section and absolute values of the maximum reflection coefficents for P- and S-waves at each lithological boundary. From Kono et al. (2009)

Rates of middle crust (and continental crust) production

One of the key questions that can be answered by the IBM-4 drill core is magma production rates for both plutonic and volcanic processes in this juvenile arc. Are formation of volcanic and plutonic rocks coupled? In the Cretaceous Sierran arc, Barth *et al.* (2012) showed that explosive volcanism began before and continued throughout emplacement of granodioritic to granitic plutons. The same is true for the Kohistan, Talkeetna, and Bonanza arc sections.

Many arc sections show discrete 15-20 million-year flareups in production of intermediate-felsic rock production in the middle crust, with values as high as 100 cubic kilometers per kilometer of arc length per million years (km^3 km^{-1} Ma^{-1}) in the Famatinian arc (Ducea *et al.,* 2010), 85 km^3 km^{-1} Ma^{-1} in the Sierran arc (Ducea, 2001), and 35-50 km^3 km^{-1} Ma^{-1} in the Coast Mountains (Gehrels *et al.,* 2009), separated by periods of lower flux. By definition, these are important periods of continental crust growth. Cores from IBM drilling will establish whether these episodic flare-ups are also present in modern arc middle crust production rates.

Models for formation of modern arc crust

Studies of exposed arc sections and modern intra-oceanic arcs indicate that the creation of middle crust may happen in different ways depending on the specifics of the arc system. In some arcs, middle crust develops dominantly by fractional crystallization of mantle-derived magmas (e.g. Talkeetna, Kohistan) or partial melting of juvenile lower crust (e.g., the Cretaceous Sierran arc; Coleman *et al.,* 1992; Ratajeski *et al.,* 2005; Sisson *et al.,* 2005), whereas others include a component of recycled crust (e.g. Bonanza arc, Famatinian arc). In all cases however, a simple model can provide a generalized framework.

The middle crust can originate in three main ways: 1) Deeply buried former arc upper crust, modified by diagenesis, burial (grading to regional) metamorphism and contact metamorphism. 2) partial melting of deeply buried arc upper crust; these magmas will be emplaced in the middle and upper crust, and probably also erupt. 3) Magmas from deeper sources such as the mantle wedge, the slab, or the lower crust (former 1, modified by metamorphism). The creation of middle crust may involve a combination of processes or else one process may be dominant. Drilling and recovery of samples from a young ocean arc will allow direct evaluation of the relative importance of these processes.

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Models of crustal evolution in the oceanic arc and its collision: Key observations and questions for the future IBM research

NOTE: This report aims to summarize the discussions and questions, which are relevant specifically to the subject "juvenile oceanic arc crust formation" during the IBM Kona workshop. Construction of this report follows the order of presentations performed on the Day 1 and 2. Content of presentation irrelevant to the "crustal formation" will be summarized in the separate reports and thus are not included here. Texts with underlines are the highlights for the key observations and questions.

Formation history of felsic rocks and crustal formation (Bob Stern)

(1) Early felsic rocks (45 Ma) exist in Bird Island, Saipan (low-K tholeiite) and Chichijima, Bonin (boninitic rhyolite) indicating that the mid crust was formed at very early stage (Fig. 1). Calvert *et al.* (2008)'s seismic imaging also shows thickest middle crust exists in the forearc (Fig. 2). The production rate of the middle crust in the early stage of arc activity should be re-examined.

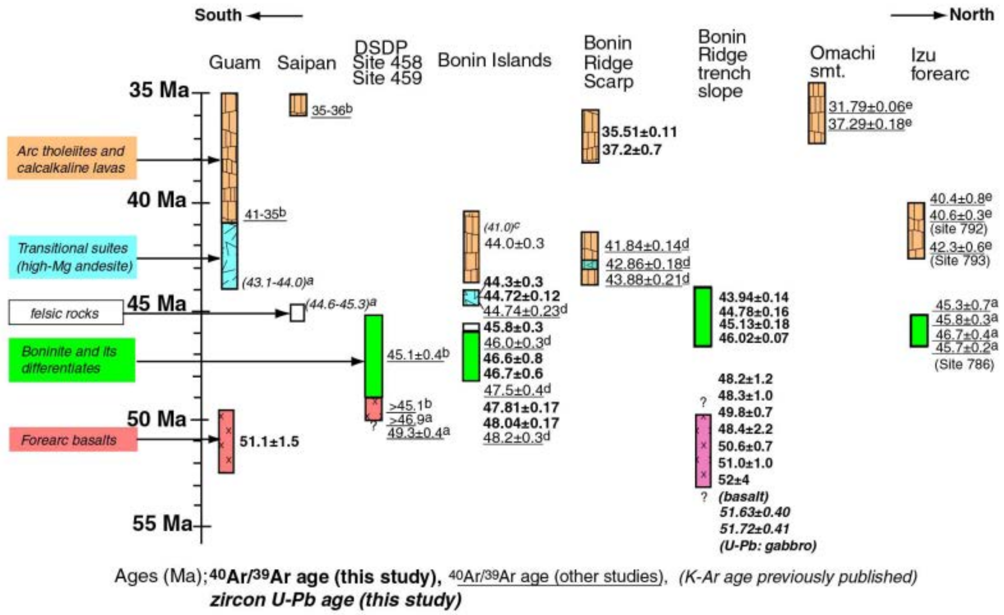


Fig. 1. Compilation of $^{40}Ar/^{39}Ar$, K/Ar and U-Pb zircon dating results for igneous rocks from the IBM forearc (Ishizuka et al., 2011).

(2) Tephra records indicate that substantial intermediate to felsic volcanics erupted throughout the arc growth history. Along with the early felsics, this suggests mis-conception of basaltic arc scheme, although mafic magmas are still major eruptives and seismic structure of the arc suggest mafic crust in bulk. Such the problem should be reconciled by tephra records and deep crustal drilling.

(3) Why is the surface manifestation of the felsic rocks limited? Sampling bias is one of the reasons. But felsic middle crustal melts can reach to the surface when extension (to neutral) tectonics was dominant. This should also be taken into account for the analysis of genesis history of the middle arc crust.

(4) Existence of adakite and high-Mg# andesite in Oligocene-Eocene early arc raise a question on how mantle derived felsic magmas affected formation of felsic arc crust and how this affected the formation of the middle crust? If such the mantle derived felsics underplated the crust, is this related to the slow-seismic-velocity "uppermost mantle" beneath IBM? This can be tested by observation of hidden (un-erupted) felsics via deep drilling.

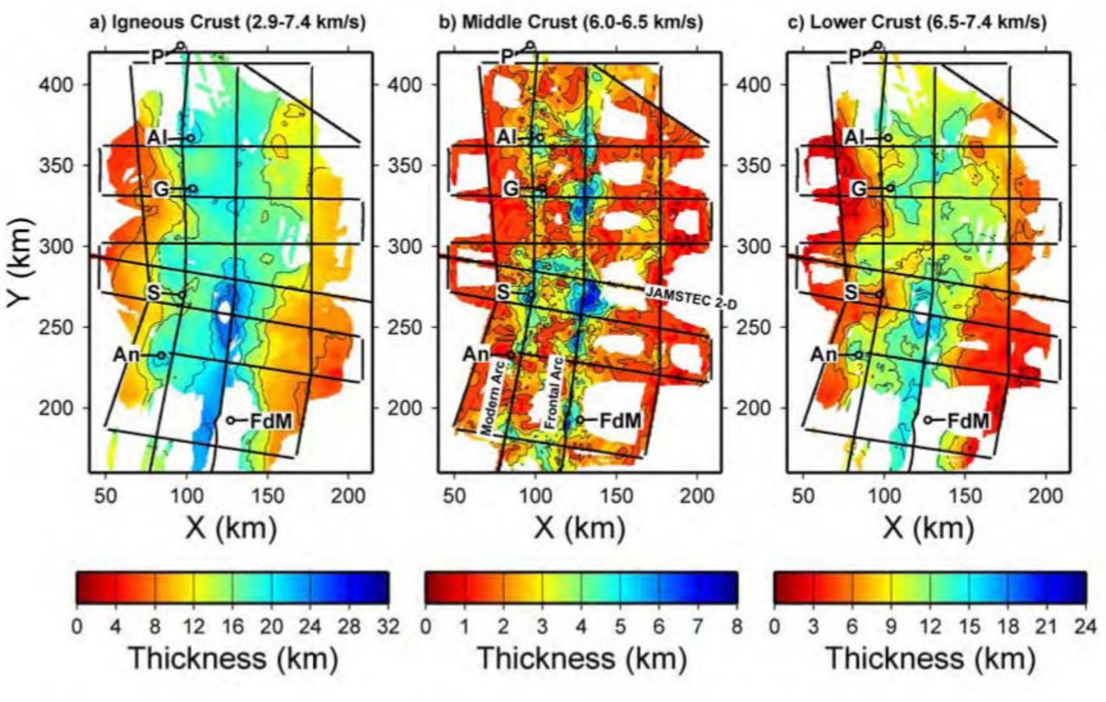


Fig. 2. Isopachs calculated from 3-D velocity model for (a) igneous crust (2.9-7.4 km/s), (b) middle crust (6.0-6.5 km/s) and (c) lower crust (6.5-7.4 km/s). P, Al, G, S and An are the active volcanic islands of Pagan, Alamagan, Guguan, Sarigan, and Anatahan, respectively. FdM is Ferdinand de Medinilla on the frontal arc (Calvert et al., 2008).

Crustal structure and felsic crust formation (Calvert/ Kodaira)

(1) Seismic velocity 7.5–7.7 km/s occurs in the uppermost upper mantle below the "Moho". Slower velocities (6.0–6.5 km/s) indicating intermediate/felsic composition commonly exist over a wide range of thick arc crust but are not present in the Bonin forearc and spreading regions such as Mariana Trough. Such slow upper mantle may be composed of mafic-ultramafic rock composite. How the slow uppermost upper mantle (potentially mafic lower crust) and slower-velocity middle crust were formed is the key to understanding the vertical differentiation of the arc crust. Is Tatsumi *et al.* (2008) model correct?

(2) The Kohistan ophiolite shows the existence of garnet at the bottom of arc crust. If garnet bearing deep lower crust (up to 45 km deep) exists in the Izu-Bonin arc, why does garnet signature not appear in any of the tonalites (e.g., flat REE) in IBM and KPR (Kyushu-Palau Ridge)? This should be tested by obtaining middle crustal felsic rocks.

(3) Thickness of the middle crust is highly variable in 3D, and the thicker parts correspond to the distributions of the Quaternary basaltic arc volcanoes (Fig. 3). How this happens is not known. How can we test this? Why is there slower seismic velocity beneath basaltic volcanic centers,

counter-intuitively?

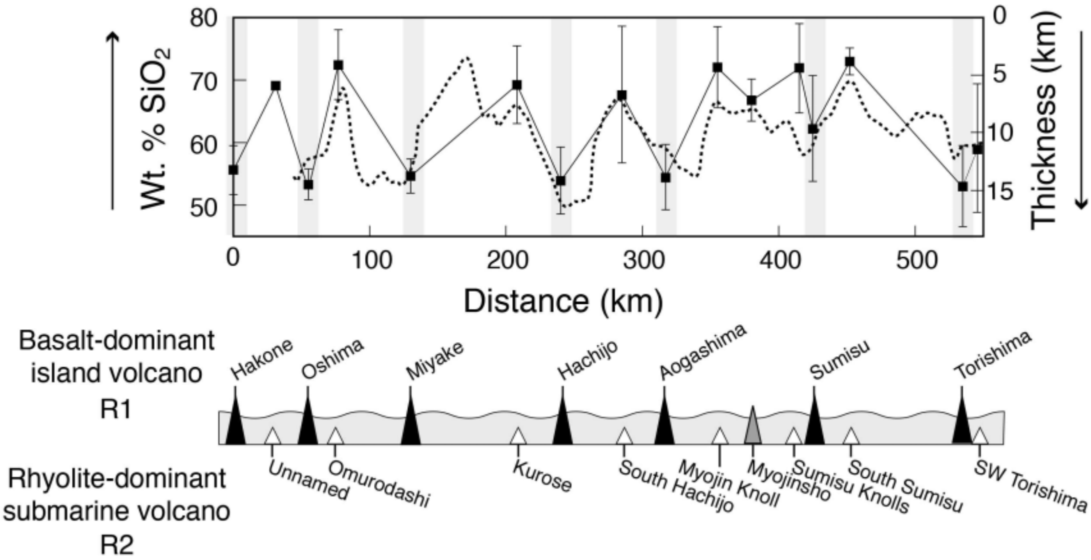


Fig. 3. Along-arc crustal structure (dotted line; thickness of middle crust) and average wt % SiO2 of volcanic rocks (solid squares) sampled and dredged from the 16 Quaternary volcanoes of the Izu-Bonin arc (Tamura et al., 2009).

(4) A 3D modeling of crustal volume (Calvert *et al.,* 2008) indicates that the most voluminous middle crust develops beneath the frontal (old) arc (Fig. 2). If real, what does this mean? Crustal delamination thins the lower crust, sending high-velocity crust foundering into the mantle? Or were more felsic magmas formed in the early arc stage? Is this because of the slab melting? Early magmatic activity should be reconciled.

(5) How do the 3D distributions of the mid and the lower crusts correlate? Do they have any relations to the mid-crust and intra-mantle reflectors and the seismic velocity distributions beneath Moho? Analysis on their spatial distributions would help to solve the intra-crustal differentiation problem.

Kyushu-Palau Ridge (Nishizawa)

(1) Middle crusts of KPR tend to be thinner than those of IBM arc. The thickest KPR crust (18-20 km) is in the north beneath Komanashi-Daini Seamount. Exposure of low-K tonalite with flat REE patterns has been reported (Haraguchi *et al.,* 2003). Amami Plateau has 20 km thick crust with exposed 6km mid crust layer, similar to KPR. The exposure may have formed by the rifting during opening of the ocean basing. How the exposed middle crust of these old (<25 Ma) arcs look like is the key to understand the tonalitic middle crust formation. Comparison to the middle crustal rocks from the thicker IBM crust will provide the key to understand the mid crust formation. What is the difference between 54-25 Ma rear-arc middle crust (KPR) and 54-35 Ma frontal arc middle crust (IBM)?

(2) Reflectors beneath KPR locate at 30-40 km depth (in the mantle?) near the Amami Sankaku Basin. Mantle Vp beneath KPR is also low at ~7.8 km /s and slowness relate to the thickness of the crust.

Slow upper mantle with intra-mantle reflectors is common over the IBM and KPR.

Aleutian geophysics (Shillington)

(1) Aleutians is different from the IBM arc in having faster seismic velocities in (mafic) middle crust velocity but with similar 7.x km/s velocities in the lower crust to upper mantle. What makes the difference from IBM? Is middle crust tonalite absent? Clinopyroxenite exists in the lower crust from the observations of xenoliths. This fits in Vp/Vs ratios observed from the lower crust. But there is much more data covering the IBM arc, and relatively little data (seismic or sampling) from the Aleutians that would allow a full comparison.

(2) One controversy is that the primary magmas are more felsic (high-Mg# andesite) at least in the western Aleutians. This should make the difference from the eastern Aleutians and IBM. Relation between primary arc magmas and arc crust structure should be examined.

IBM forearc (Kodaira)

(1) Two characteristic early arc crustal structures were found in Bonin forearc (Fig. 4). One is in off Chichijima (boninite island) having oceanic crust profile and the other off Hahajima (boninite + tholeiite island) having arc crust structure. This means that magmatic accretion of tholeiite forms arc crust including the middle crust. Questions arise whether or not boninite did nothing to arc crust formation and only tholeiite could do.

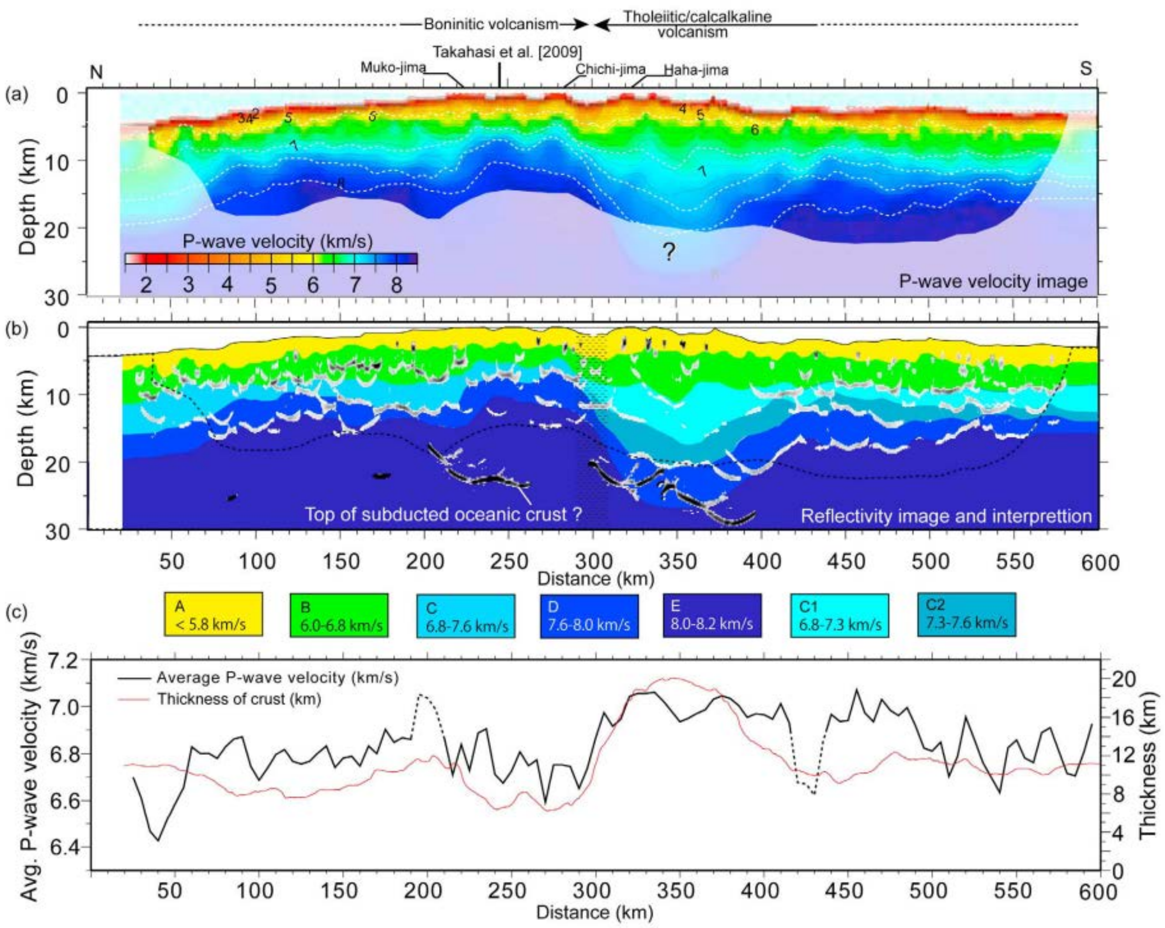


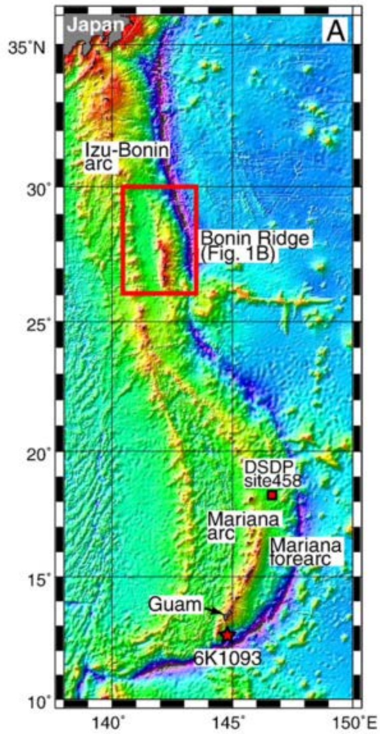
Fig. 4. (a) P-wave velocity image along the Bonin ridge, 100-150 km east of the present-day volcanic

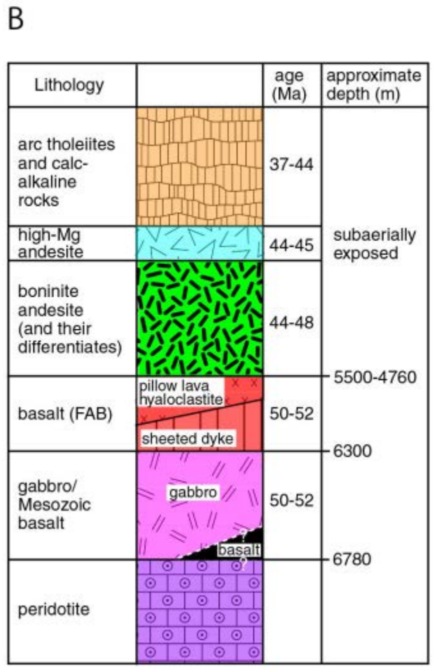
front. (b) Reflectivity image superimposed on a layered structure constructed from the velocity and reflectivity images. Petrological interpretations are as follows. Unit A, sediment, volcaniclastics and volcanic rocks; Unit B, felsic-to-intermediate component; Unit C, mafic component; Unit D and E, ultra-mafic component. (c) Black line indicates lateral variations of average P-wave velocity of the crust (Unit B and C). Upper crust (Unit A) was excluded. Red line indicates lateral variation of the crustal thickness which is calculated as the total thickness of unit A, B and C (Kodaira et al., 2010).

IBM-2; 696-Full4 Forearc drilling proposal (Pearce)

(1) Site 696 indicates coeval boninite and tholeiite magmas. How do these observations correlate with Kodaira's fore-arc seismic section? Being able to ground-truth observed seismic velocities (by deep drilling) will be a major, fundamental advance made by the proposed drilling objectives.

(2) Forearc drilling will also confirm whether or not the forearc basalt (FAB) was the fundamental volcanism prior to the initiation of subduction (Fig. 5). If the model is real, <u>foundation of the new "FAB arc crust" would affect the formation history of the middle crust.</u>





Lithology		age (Ma)	approximate depth (m)
arc tholeiites and calc-alkaline rocks		37-44	
high-Mg andesite		44-45	subaerially exposed
boninite andesite (and their differentiates)		44-48	
basalt (FAB)	pillow lava hyaloclastite; sheeted dyke	50-52	5500-4760
gabbro/ Mesozoic basalt	gabbro; basalt	50-52	6300
peridotite			6780

Fig. 5. A. Location of the Bonin Ridge in the Izu-Bonin-Mariana arc. The location of Shinkai 6500 Dive 6K1093 in the Mariana forearc is also shown. B. Schematic columnar section as a summary of observed Bonin Ridge forearc section. 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 (Ishizuka et al., 2011).

IBM-1; 695 Full-2 Amami drilling proposal (Ishizuka)

(1) Amami Sankaku Basin (ASB, Fig. 6) drilling will provide ideas on the transformation of pre-existing oceanic crust to the arc crust by answering what was (were) the source materials for the middle crustal felsic rocks (i.e., pre-existing oceanic crust, FAB crust, or underplated tholeiitic basalt during arc growth)?

(2) Mesozoic basement (160-100 Ma, remnant of neo-Tethys) exists around ASB and these can be extended towards east and hidden beneath the N-Izu arc.

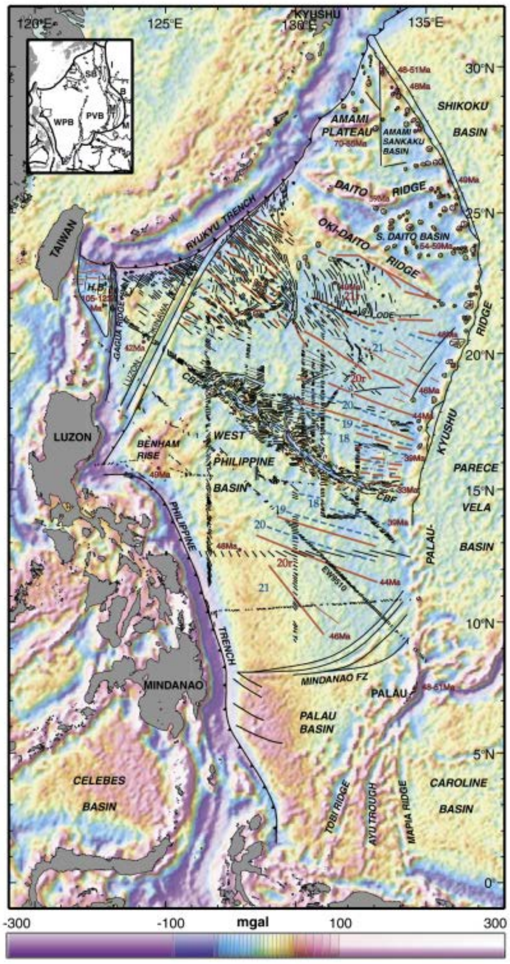


Fig. 6. Map of seafloor fabric (black) and magnetic anomaly lineations (red, positive; blue negative) superimposed on sunlit marine gravity data (Taylor & Goodliffe, 2004). Amami Sankaku Basin is located in the east of Amami Plateau, and the west of the northern end of the Kyushu-Palau ridge.

697 Rear arc proposal (Tamura)

(1) Across arc geochemical variations exists perhaps due to the contributions of slab fluid (VF, volcanicfront) and melt (RA, rear-arc) (Fig. 7). How the mantle derived basalt signatures in the rear arc affect the formation of the arc middle crust?

(2) Are the rear-arc magmas more felsic than in VF? If so, why? Is this due to more involvement of slab melts?

(3) Is there any spatial variation in the middle crustal tonalites (and its eruptive equivalents)? If exists, which is dominant: low-K tholeiite or medium- to high-K magmas in contributing juvenile arc crust?

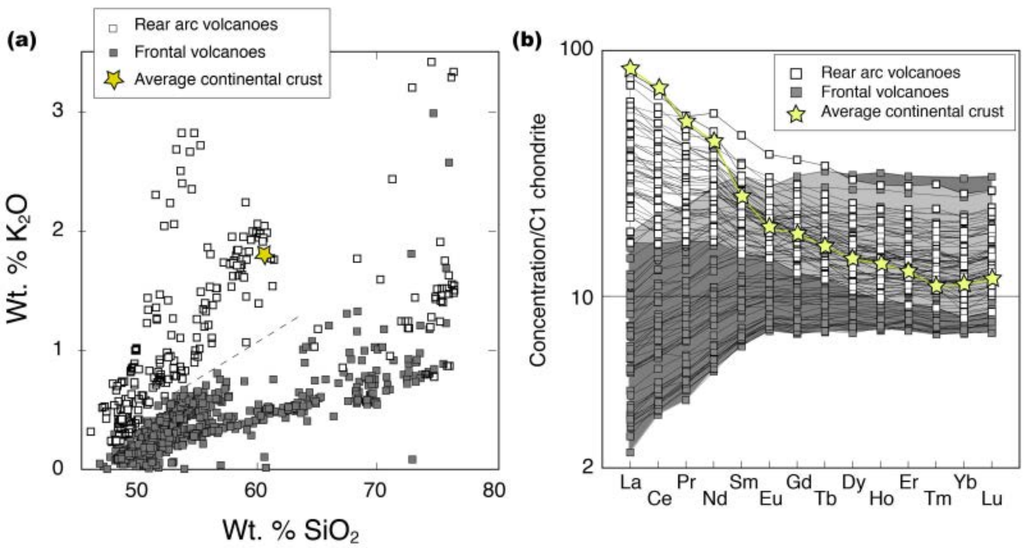


Fig. 7. (a) K_2O vs SiO_2 (wt %) of lavas of the volcanic front and the rear arc of the Izu-Bonin arc and average continental crust. (b) Chondrite-normalized rare earth element (REE) abundances in the Izu-Bonin volcanic front and the rear-arc basalts and andesites and average continental crust (Tamura et al., 2007).

IBM geochemical evolution from tephra studies (Straub)

(1) Early- versus mature-arc geochemical variations exist particularly in isotopes. Mantle ingrowth signals are found in the tephra records in Nd and Hf isotopes for Izu over 50 Ma (not for Marianas). Input slab sediment signals (Pb isotopes) change with time reflecting the changes in input materials. Questions are (a) whether these changes reflect the chemistry of the middle crustal rocks, and if so, (b) how much.

Pop-ups

(1) **Martin Jutzeler**: IBM-4 deep drill site will provide a comprehensive sequence of a volcano-plutonic complex. Whether or not it is true can be tested. The drilling of Hole 792E of ODP expedition 126 successfully retrieved an Oligocene-Recent turbiditic sequence, but failed in recovering a complete sequence of the basement (from ~800 mbsf). The current proposal 698 aims to recover rocks from the upper and middle crust. It is obvious for me that a complete study of the system - from top to bottom - is necessary to understand the formation of evolved crust in a volcanic island arc. In addition, this project would be the first to drill through a complete sequence of a large andesitic submarine volcano. Therefore, we propose to get the maximum recovery where it is easy and quick to drill, i.e. in the lesser indurated rocks, near the surface. To spend a bit more time (hours to days) drilling the entire upper basement is realistic considering the relative softness of the rocks, and the great potential of recovery. To core the upper basement with XCB would give important insights on the volcanic facies, petrology and geochemistry of rocks generated from the underling crust (which will be drilled and cored). To get well-preserved lithological contacts would help constraining whether lavas and breccias are extrusive or intrusive, thus how the volcano was formed. In addition, interbedded layers of hemipelagic mud may be fossiliferous, giving an age to the formation.

(2) **Gene Yogodzinski**: West in the Aleutians are calc-alkaline volcanic centers producing fairly LREE-enriched lavas with high silica content from this oceanic arc (Fig. 8), produced from melting of the basaltic part of the Pacific plate (downgoing slab). "Generating continental crust by immaculate conception, without the seed of recycling continental crust."

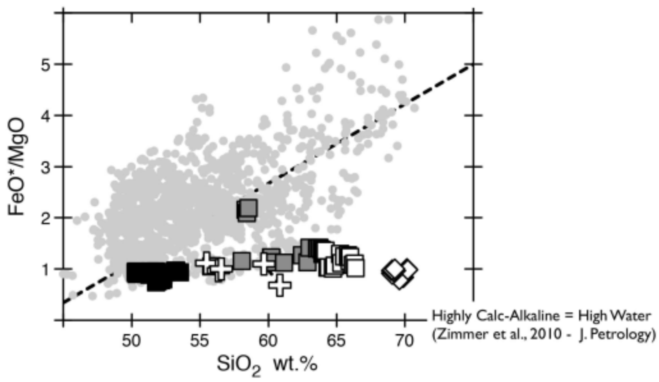


Fig. 8. Western Aleutian Seafloor lavas.

(3) **Alan Glazner:** Magma production vs. erosion should be examined with respect to tectonic history of the arc.

(4) **Michael Brown**: Anatectic reworking and differentiation in the lower crust at active plate margins is the principal process by which new crust becomes stabilized as part of the continents. Residual migmatitic gneisses and

associated granites in the Pacific-style accretionary margin convergence are common and should be considered even in the genesis of the intra-oceanic juvenile arc.

(5) **Brian Taylor**: Update on evolution of West Philippine Basin (Taylor and Chandler). What is IBM arc getting built on should be fundamental question for arc crust genesis.

IODP Proposal 698 Deep drilling (Tamura on behalf of Tatsumi and Kelley)

(1) Sampling new 'continental root, juvenile continental crust' beneath young oceanic arcs by IODP will be tremendous step toward understanding origin of andesitic continental crust.

(2) How do subduction zones initiate, cycle volatiles and generate continental crust? IODP Challenge 11 in the work plan, Project IBM: toward comprehensive understanding of arc evolution and continental crust formation.

(3) Total penetration expected at IBM-4 is 5500 m at 1800 m water depth. Close to ODP site 792 consisting of andesite lavas. Therefore, IBM-4 would hit an Eocene andesitic mid-crustal pluton beneath an andesitic volcanic dome.

Overview of ODP site 792 (Gill)

(1) Oligocene lavas are andesite>dacite>rhyolite containing plag, opx, cpx, mt, qz with CA geochemical signatures. LREE are depleted in all the andesite with slight Eu negative anomalies. These are in CA field but not boninite fractionates because of low MgO. Some HREE depleted dacites and rhyolites present. Available data are limited and need some more geochemical analyses on site ODP 792 samples before CHIKYU drilling. *Adam Kent responded to this after the workshop and accessed by NSF about the possibilities of funding when CHIKYU drilling is scheduled.*

(2) Question1: How the "juvenile" crust looks like in the cold subduction zone endmember? How the "juvenile" arc crust is converted to the "continental crust"? These are important scientific objectives to strengthen the drilling proposal.

Field exposures of middle crust = Baja: Alisitos arc as an analog to IBM ultra-deep drill site. Growth of North American continent by accretion of extensional, fringing intra-oceanic arcs. (Busby)

(1) Plutonic-volcanic connections: mid-upper crustal plutonic bodies are usually associated with voluminous volcanism.

(2) Arcs in extensional setting arc are the silicic material factory (caldera formation and felsic extrusions). Does it happen in IBM? IBM has been extensional over quite long time. Consider tephra records.

(3) Collision of arcs with continents can be (but are not necessarily) associated with subduction of the lower crust and obduction of upper crust.

Field exposures of middle crust = Talkeetna: Exposed arc crustal sections as a framework for drilling of active arc middle crust. (DeBari)

(1) Talkeetna section consists of ultramafic (harzburgite, pyroxinite increase upwards), garnet gabbro, 2-px gabbro (no olivine), (amphibolite crustal melting), hornblende gabbro, "intrusive gap", tonalite diorite, and volcanics, in ascending order. No garnet-bearing restite unlike Kohistan arc.

(2) Lower crust formation is explained by crystal fractionation process of LREE depleted magma. Mafic parent was fractionated to form andesitic then to tonalitic intermediate magmas. A 25% crystallization of cpx to form the most mafic lavas in the lower crust but no pyroxenite bodies. Such a pyroxnite should have been delaminated.

(3) Intermediate middle crust is heterogeneous. Pluton intruded by mafic intrusions with chilled margins.

Field exposures of middle crust = Sierra Nevada (Coleman)

(1) All the crustal rocks have 6-6.5 km middle crust component (Fig. 9) with 115-60 My ages.

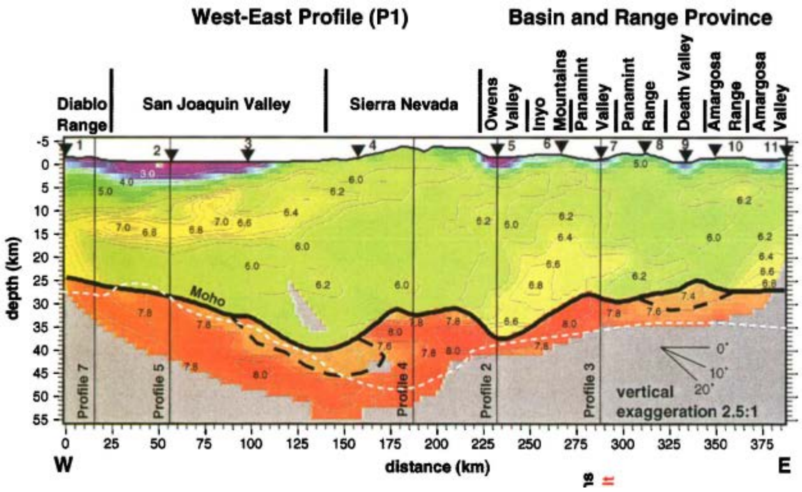


Fig. 9. Low seismic velocities (Vp=6.0±0.2 km/s) through most of the Sierran crust (Fliedner et al., 2000).

(2) Although the whole rock compositions represent arc magmas, although this was a continental active margin, not an intraoceanic subduction zone like IBM, so some differences are expected with IBM; crystals in the plutons do not tell us about magmatic history but metamorphic sub-solidus history.

(3) Sharp contact between leuco-melano granitoids (SiO_2 = 65–75 wt% range). One cycle is thought to correspond to an upward melt migration in one cooling cycle.

(4) Aplite melt paths are in very late magmatic stage? U-shaped REE patterns show minor mineral phase fractionation, such as apatite?

Possible continental basement beneath the N Izu (Tani)

(1) Cretaceous U-Pb zircon and Ar-Ar ages of 110-120 Ma are reported from proto-PSP in Oki-Daito, Daito Ridge areas.

(2) A sandstone sample from Shin-Kurose Bank showed 2226 Ma to 15.3 Ma U-Pb ages of zircons.

(3) Diorite samples collected from forearc near the 698 deep drill site contains 100Ma igneous zircon with >2Ga detrital zircons. Pre IBM arc basement may consist of some continental crust beneath the N-Izu arc and Site 698 may encounter Cretaceous crust.

(4) Stern: Faintly possible (?) that these old zircons came from mantle. In Indian Ocean, there's evidence for a delaminated continental slab that returned old continental material (including zircons?) back into the mantle. Could same thing be happening under Izu? This is an important problem that the proposed drilling could test.

Thermal-mechanical ("TM") modeling – a framework for transferability (Berganz)

(1) Modeling should be vetted against real geologic examples. Melt migration in the crust should be multiple phase flow and it is still hard to model this.

Role of oceanic arc collision (Draut)

(1) Collision of oceanic arcs with continents generates high-silica melt and high degrees of trace-element enrichment of the upper crust by melting and crystal fractionation, which can drive the bulk composition of accreted crust toward the andesitic average for continental crust. Collision geometry (whether the arc collides with the continent forearc-first or backarc-first) matters greatly: highly enriched, high-silica melt is only documented in "forward-facing" collision (such as the Ordovician Caledonide suture zone), but not for "backward-facing" collisions (Talkeetna or Kohistan).

(2) Involvement of collided continental materials or sediments in the melting-remobilization process should also be examined for formation of continents through collision. Drilling the deep crust of Izu will inform as to whether the role of arc-continent collision in forming andesitic continental crust may have been overemphasized in the past.

Oceanic middle and lower crust (Barbara John)

(1) In considering the possible source of the infant arc crust, the nature of the oceanic crust can be generalized as (a) shallow middle crust = isotropic gabbro, (b) lower crust = igneous fabric gabbros for fast spreading ridges (FSR). Slow spreading ridges (SSR) would be composed of (a) shallow/middle to lower crust = isotropic gabbro, and (b) peridotite heavily impregnated by melts. There should be variations between FSR and SSR; there is less alteration in FSR, whereas >200m severe alteration by cracks in SSR.

The Tatsumi model (Kimura on behalf of Tatsumi)

(1) A brief summary of Tatsumi model. A question to the model is that the presence of garnet in the entire lower crust after magmatic fractionation by anatexis. Why garnet signatures are not recorded in any middle to upper crustal rocks in IBM?

(2) Tanzawa pluton, ~5 Ma at Honshu – post-collisional tonalite formed by remelting of crust at Honshu collision zone Tani *et al.* (2010) showed it is NOT an exposure of IBM middle crust but rather a post-collisional pluton, but still provides information on anatexis of middle (?) crust. This scheme may also work for remobilized ancient (Cretaceous) crust, if igneous processes are the main factor of material fractionation in the crust.

(3) Even though the 692 site is possibly underlain by the 100-120 Ma oceanic arc crust with continental materials involved, this may be still juvenile oceanic arc crust abandoned before 50 Ma (and maybe superimposed by arc crust formation after 50 Ma). Such multiple processes are resolvable by chronology and petrology/geochemistry.

Pop-ups

(1) Bob Stern: What we might find drilling deeply at IBM-4. Oligocene and younger volcanics, Eocene volcanics and sediments (that's as far as ODP 792 got) and then into tonalite mid-crustal pluton. Evidence for Eocene hydrothermal cells – how deep was circulation? Sulfide mineralization, degassing magma, metamorphism and migmatization. Behavior of Eocene section

depends on abundance of sills/lavas (drier) vs. volcaniclastics (wetter). Wet volcaniclastics will be more reactive than massive igneous rocks.

(6) Yoshi Tamura – Arc crust to continental crust: Izu-Honshu collision at Tanzawa region (Fig. 10). During the collision, the down-dragged slab (to about 100 km depth) includes pre-heated middle crust of IBM arc partially melted. Melt fraction of 20-40% at 900-1000 °C. But mafic lower crust did not melt, resulting in delamination and separation of middle crust from lower crust. The remobilized middle crust then rose buoyantly to form KGC (Kofu Granitic Complex) and Tanzawa tonalites. <u>Partial melting during collision erased the Eocene-Oligocene age of this remobilized crust and explains the Miocene age of these intrusive complexes seen today</u>.

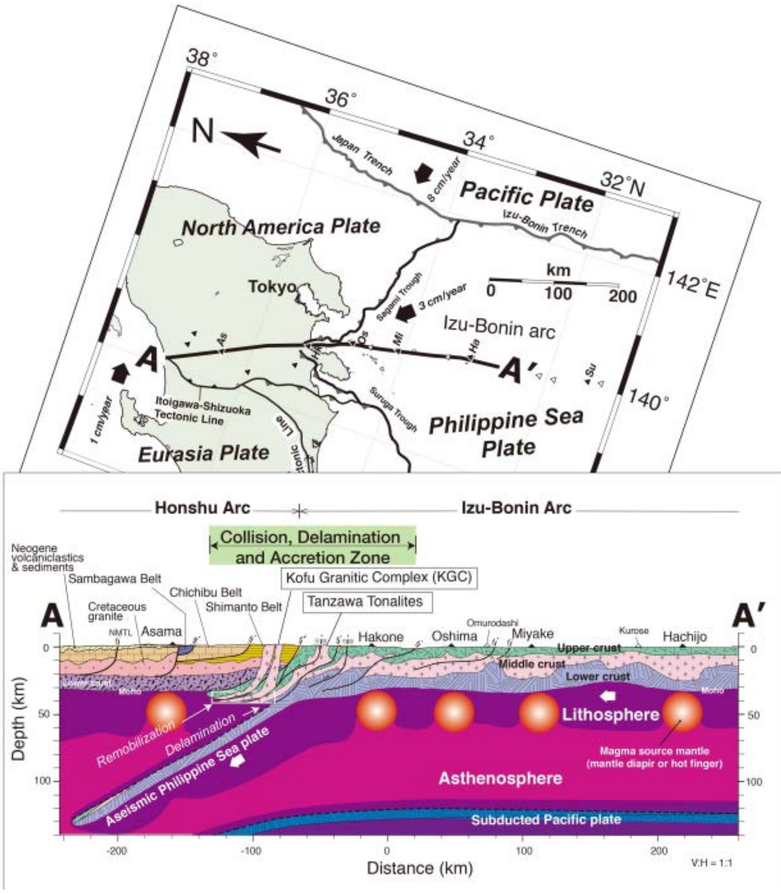


Fig. 10. Schematic cross-section of the Honshu arc, the collision zone and the Izu-Bonin arc along the A-A' profile, based on Aoike (2001), Kodaira et al. (2007) and Tamura et al. (2009). (Tamura et al., 2010). Abbreviations of upper diagram show Quaternary volcano of Honshu (As, Asama) and basalt-dominant Quaternary volcanoes of the Izu-Bonin arc (Hk, Hakone; Os, Oshima; Mi, Miyake; Ha, Hachijo; Su, Sumisu). A seismic velocity study of the Tanzawa tonalites (Kitamura et al., 2003) suggests that most of the lower crust is missing beneath the Tanzawa tonalites, consistent with delamination of the Izu-Bonin middle and lower crusts below the Honshu arc. Confirmation of these interpretations might be provided by drilling into the Eocene middle crust of the Izu-Bonin arc (IBM-4).

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Reasonable Estimates of IBM4 temperature at proposed TD = 5.5 km mbsf (Brian Taylor)

Heat Flow at IBM forearc site 792 (30°24'N, 140° 22.8'E, 1788m): = 54.6 mW/m^2 = 1.3 HFU

The full geothermal and conductivity information is contained in the Leg126 Initial Report, Chapt. 8 Site 792. At Site 792, four depth vs temperature measurements define a particularly precise linear thermal gradient of 0.054°C/m to 110 mbsf: (0 mbsf, 2.02°C; 47.2 mbsf, 4.5°C; 67 mbsf, 5.6°C; 110 mbsf, 7.92°C) The linearity indicates that no convection is occurring and thus heat flow (Q) may be calculated as Q = k dT/dz where k = the average thermal conductivity and dT/dz = the geothermal gradient. Using the average thermal conductivity of 1.012 W/m·K measured for the upper 110 mbsf and this geothermal gradient, yields an average heat flow of 0.0546 W/m^2 (54.6 mW/m^2=1.3 heat flow units). Given the precise linear vertical heat flow, the only variable affecting the temperature vs depth profile is thermal conductivity. Many measurements of thermal conductivity were made within Units I, II, and III (to 429 mbsf). They are highly variable, with averages that increase slightly with depth from 1.010, 1.018, to 1.047, respectively. Two well-lithified sedimentary rocks from the lower parts of Unit IV (771.80 mbsf) and Unit V (798.20 mbsf) yielded thermal conductivity values of 1.172 and 1.038 W/m·K, respectively. Thermal conductivity (TC) values within the top of andesitic "basement" (Unit VI) average 1.565±0.11 W/m·K (5 measurements from 813-850 mbsf). The deepest measurement at 878 mbsf is 1.838 W/m·K. Therefore, a depth vs temperature profile may be constructed from the heat flow of 54.6 mW/m^2 and TC measurements, as follows:

0 mbsf 2°C - seafloor measurement
110 mbsf 7.9°C - direct measurement
429 mbsf 24.9°C - avg. TC = 1.023 W/m·K of interval 110-429 mbsf
804 mbsf 43.4°C - avg. TC = 1.105 W/m·K of interval 429-804 mbsf
850 mbsf 45°C - avg. TC = 1.565 W/m·K of interval 804-850 mbsf
5500 mbsf 183°C - avg. TC = 1.838 W/m·K of interval 850-5500 mbsf
(5500 mbsf 166°C - avg. TC = 2.1 W/m·K of interval 850-5500 mbsf)
(5500 mbsf 150°C - avg. TC = 2.42 W/m·K of interval 850-5500 mbsf)

A temperature of 45°C at 850 mbsf can be calculated based on existing heat flow and thermal conductivity measurements (and consistent with the downhole logging results of <30°C unequilibrated temperatures). As long as average thermal conductivity in the basement below 850 mbsf equals or exceeds 2.1 W/m·K (highly likely - see attached and refs therein) then the in-situ static temperature at the IBM4 T.D. of 5500 mbsf should not exceed 170°C (and will not exceed 150°C if the avg. TC below 850 mbsf equals 2.42 W/m·K or greater). Furthermore, given the heat flow refraction effect (Site 792 was drilled over a local buried basement high = volcano) then the measured heat flow could be overestimating that at deeper levels, in which case the TD temperatures would be even lower. [Sclater et al., 1970 (Tectonophysics V. 10 p 283-300)]

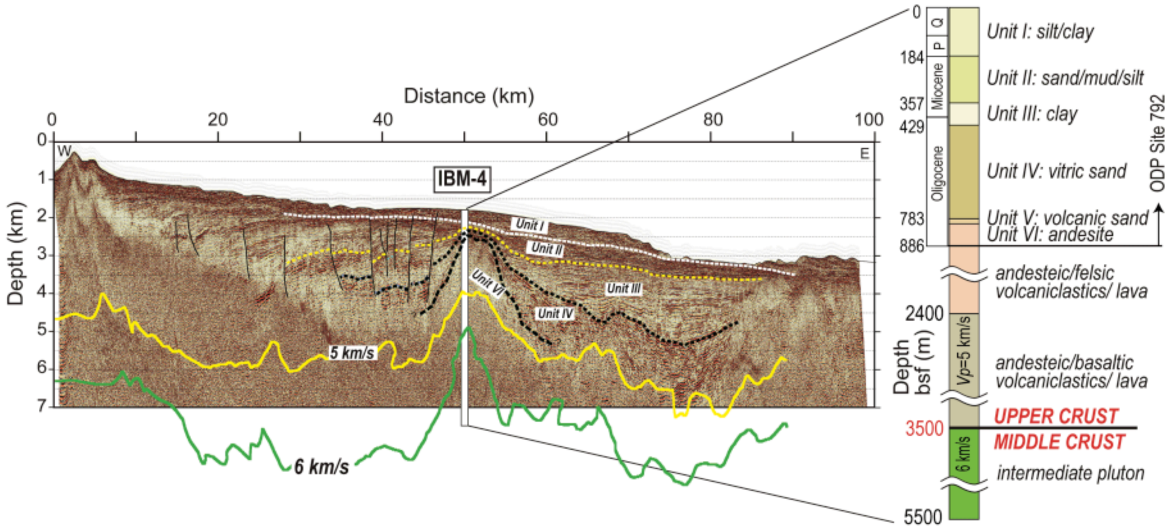

Fig. 1. Lithological interpretation of the seismic image along the IBM-4-EW5 section based on the results of ODP792 (Taylor et al., *1992). Iso-Vp contours of 5 km/s and 6 km/s obtained by wide-angle OBS data are also shown.*

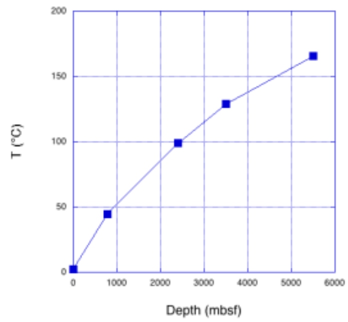

Fig. 2. One possible temperature estimate, assuming that thermal conductivity between 0-783 m, 783-2400 m, 2400-3500m, and 3500-5500m are 1.012, 1.610, 2 and 3, respectively.

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Utilization of Downhole Logging for Deep Drilling into Arc Crust (Sanny Saito)

To drill into deeper crust down to >5,500 m below seafloor, all coring throughout the whole section is not a realistic scenario due to time and budgetary constrains. Therefore, utilizations of cuttings samples and downhole logging data/samples are critical to characterize uncored intervals between limited spot coring intervals.

Downhole logging acquires in-situ parameters such as borehole diameter/shape, natural gamma ray, resistivity, density, porosity, sonic velocity, magnetic properties, etc along the borehole wall continuously to characterize rock properties. Logging data can be applied for a wide range of research such as lithostratigraphy, sedimentology, petrology, structural geology, rock mechanics, hydrogeology, geochemistry and borehole geophysics. Wireline logging tools measure borehole wall while reeling tools up in the borehole after coring, whereas logging while drilling (LWD) measures borehole with sensors equipped above the drill bit while drilling just after the borehole was cut. Although no cores can be recovered from an LWD hole, real-time decision can be made by LWD for drilling strategy such as switching from LWD to coring.

Borehole imaging technology is a key to reconstruct geological succession in arc crust such as volcaniclastic, volcanic, and plutonic rocks, especially when core recovery is poor or nothing. Electric microimaging tool consists of four pads each contains 16-32 microelectrodes, which are in direct contact with the borehole wall during the reeling up. The tool works by emitting a focused current from the pads into the formation. The current intensity variations on microelectrodes provide high-resolution (2-3 mm) electrical images of the borehole. Another useful wireline logging tool features a rotating ultrasonic transducer that provides high-resolution acoustic images (amplitude and travel time) of the borehole. One of the LWD tool scan borehole wall while drilling and create 360° resistivity images of the borehole.

Plenty of excellent images from ODP/IODP boreholes exhibit variety of lithology such as sandstone, breccia, lava flow (pillow, massive, fractured, vesicular) and identify transition of sediments to volcanic and volcanic to plutonic from high-resolution images (Fig. 1).

Sidewall coring is an alternative strategy to sample a certain amount of rock from uncored intervals of the drilled borehole. Current technology of the sidewall coring tool allows retrieving up to 50 samples by single wireline run into a borehole. Size of core sample is 3.75 cm in diameter and 6.35 cm in length. Sampling depth can be chosen from borehole images beforehand and sample depth and orientation will be confirmed by microresistivity images afterwards (Fig. 2). As such, combination of borehole imaging and sidewall coring provide significant contribution to lithostratigraphy and petrology.

Check shot and vertical seismic profile (VSP) are also important operations to conduct depth calibration of seismic profiles. Hydrophone built in a tool receives first arrivals of seismic wave shoot from the ship at regular interval (~10 m) in the borehole and determine relationship between depth and interval velocity (check shot). This operation also identifies seismic events at greater depth below the bottom of borehole to improve the depth accuracy of deeper seismic horizons (VSP), such as seismic reflectors around transition to the middle crust (~6 km/sec; ~3,500 mbsf).

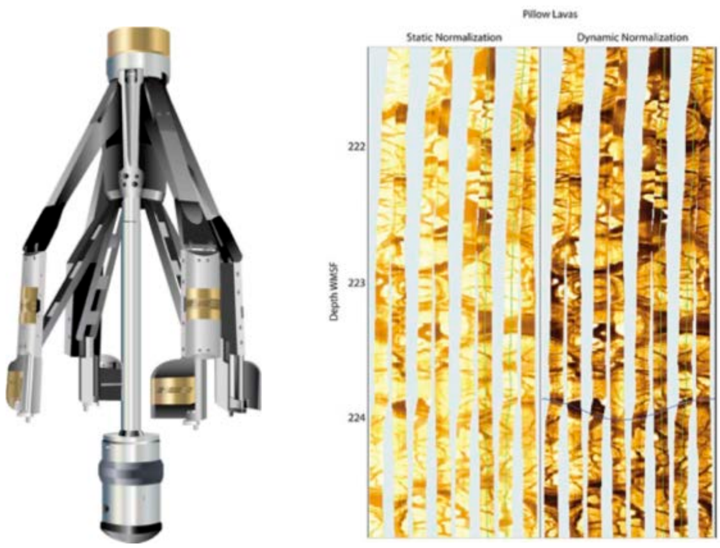

Figure 1. Left: Formation MicroImager (FMI), an electric microimaging wireline tool. Right: Formation MicroScanner (FMS) image from Hole 1347A, IODP Expedition 324, Shaysky Rise. Fractured pillows and dip direction of lava flow plane are well imaged.

Figure 2. Left: Sidewall coring tool (XL-Rocks). Center: Samples taken by XL-Rock. Right: FMI images after sidewall samples were taken. Figures are taken from
http://www.slb.com/services/characterization/wireline_open_hole/rotary_sidewall_coring/xl_rock.aspx

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Ultra-deep drilling options (Kan Aoike/CDEX)

General cost of riser drilling

Among the IODP drilling platforms, riser drilling with D/V Chikyu is indeed the only way to enable to reach the target of IBM-4, an oceanic island arc's middle crust. As the middle crust beneath IBM-4 seems to be upheaved to a relatively shallow depth compared with its surroundings, this site was selected as a location beneath which a reasonably achievable target by riser drilling lies. Riser drilling, however, requires much higher cost and quite long operation time compared with riserless drilling. A total operation cost is in fact a function of time, generally estimated at 1 million dollars per day in offshore oil industry rigs. In case of scientific drilling by D/V Chikyu, it is roughly estimated at a number where the industry daily cost is multiplied by 0.6-0.7, including all relevant costs such as those for the drilling contractor, logistics, fuel, insurance and so on.

We have two examples of IODP riser drilling projects implemented by D/V Chikyu: NanTroSEIZE (Nankai Trough Seismogenic Zone Experiments) and Deep Coalbed Biosphere off Shimokita. In NanTroSEIZE, the planned total depth (TD) of the deep riser hole (Hole C0002F) until 2013 is 5.2 km below seafloor, aiming at penetrating through a mega-spray fault, requiring totally about 9 months to get it through three expeditions, Exp. 326 (2010), Exp. 338 (2012) and Exp. 348 (2013). Among the three expeditions, Exp. 326 was an engineering cruise that was dedicatedly carried out for constructing the riser top hole. In Exp. 338, which is in operation as of writing, the hole will be deepened with measurement-while-drilling/logging-while-drilling (MWD/LWD). Coring will be performed only in a section of 100 m just below the first casing shoe in the middle of the TD. In the Shimokita project, which was carried out as Exp. 337, operations with mud logging, spot coring and wire line logging (WL) including formation fluid sampling were performed down to 2466 mbsf from 647 mbsf for about 2 months. The total length of cored intervals was 263.5 m. For reaching the TD of 2466 mbsf, about 4 months were totally spent, including duration of the shakedown cruise during which construction of the riser top hole and tests of riser drilling were conducted.

The two examples above suggest that it requires roughly 1 month to proceed 600 m in average for a riser drilling project if the TD is down to 5 km, even though it depends on what kinds of sampling, logging and measurement programs are involved. Accordingly it will take roughly more than 9 months on calculation to reach 5500 mbsf, the TD of IBM-4, suggesting also that it may cost close up to 200 million dollars in total.

Deep riser drilling in an inactive marine volcanic terrane

The formations to be drilled in IBM-4 are expected to be marine volcanics and volcaniclastics for the most part back to the Eocene down to 3.5 km below the seafloor and then be replaced presumably with intermediate plutonic rocks. The lowest part of the former formations, corresponding to the upper crust, is potentially metamorphosed into hornfels and/or greenschist facies. The formation temperature can be estimated at up to 170°C as indicated by B.Tayor in this report.

As the formations of IBM-4 are quite different from those of NanTroSEIZE and Shimokita, we should understand about general practicalities of drilling into formations of an inactive submarine volcanic terrane. For example, industry oil exploration drilling in the so-called “Green Tuff” area along the Japan Sea coast will provide helpful information. In the Green Tuff area, where marine volcanics and volcaniclastics associated with plutonic rocks bearing oil formed during the early to middle Miocene are distributed, there are many deep oil exploration wells of which penetration depths are averagely 3000-5000 m and the bottom hole static temperatures are up to 200 °C (personal communication). According to the results of oil industry, very low ROP up to 1 m/hour (in case of a 4” industry conventional coring system) is recorded for coring. Even in drill down without core, ROP is still low, 3-5 m/hour for volcaniclastics and 2 m/hour for lava/intrusive. Core recovery, however, is very good, more than 90 % in average, even in case of fractured granite and under high temperature. These results of deep drilling in the formations similar to those of IBM-4 suggest situations with which we will encounter while drilling IBM-4.

Temperature limit

Circulation temperature of drilling mud changes closely along with the geothermal gradient, cooled down several tens degree C less than the static temperature at the bottom depending on the circulation rates in general. Drilling mud for high-temperature holes with heat resistance up to 260°C is available in the oil industry. Thus, we have no serious concern about drilling tools themselves in terms of high-temperature resistance, because formation temperature of IBM-4 probably never exceed 170°C as estimated by B.Taylor.

With regard to logging tools, however, allowable operation temperature needs to be considered with special attention. In the ODP/IODP history, only Schlumberger’s logging tools have been used. They presently provide ordinary MWD/LWD tools and WL tools of which the upper operation limit temperature is up to 150°C and 260°C, respectively. In addition they can provide optionally special high-temperature MWD/LWD tools with heat resistance is up to 175°C. Besides there is a logging company who can provide high-temperature tools which are able to withstand 230°C (Halliburton). Therefore, MWD/LWD and WL are feasible even by using tools which are presently available under formation temperature up to 170°C.

Operational options

For scientific drilling full coring is ideal, however, it is unrealistic to take continuously core samples down to 5500 mbsf due to tripping time of drill string and wire line getting progressively longer and very low ROP in hard formations. If ROP is 1 m/hour while coring, for example, 13 hours or more may be required to take only a 9.5 m core including tripping time. Low ROP increases operation time and exerts directly impacts on the cost.

In order to maximize sufficiently scientific outcomes while intending persistently to reach the target down to the proposed TD, 5.5 km below seafloor, within a limited budget; it is inevitable to plan a drilling project with combining various survey programs instead of full coring. Survey programs may include MWD/LWD, cuttings survey, mud (gas) logging, WL with sidewall coring and spot coring. MWD/LWD and WL can provide continuous in-situ measurement data of a borehole, including properties of natural gamma-ray, electrical resistivity, borehole resistivity image, sonic velocity, porosity, nuclear magnetic resonance, etc. Cuttings and formation gas are another formation materials that can be continuously taken from a borehole only available in riser drilling. Schlumberger's latest sidewall coring tool can take mini core samples of 2.5 inch long with 1.5 inch diameter up to 50 samples per run (note that the temperature rating is 177°C). In a LWD hole, spot coring may be limited in short intervals, for instance, below casing shoe depths in terms of operation efficiency. Spot coring, however, can be technically performed in a sidetrack hole(s), which is deviated actively away from the main hole at a certain depth(s), after MWD/LWD operations.

Several options in which these survey programs are combined can be on the table, for example, given as follows:

- MWD/LWD + spot core (limited) + WL with sidewall core
- MWD/LWD + WL with sidewall core + spot core from sidetrack hole
- Drill down + spot core + WL with sidewall core
- MWD/LWD
- Drill down + WL with sidewall core
- Drill down + spot core

Every riser drilling program, of course, includes cuttings survey and gas monitoring. The actual drilling program will be created in accordance with scientific objectives and priority, technological and operational feasibility, logistics, cost and budget through in-depth discussions among operators and scientists.

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http://www.slb.com/services/characterization/wireline_open_hole.aspx

http://www.halliburton.com/ps/default.aspx?navid=1496&pageid=3913&prodgrpid=PRG%3a%3aKQQZ7AKG4

What should be the scientific objectives for deep ocean drilling?

The over-arching science objective for ultradeep drilling into the middle crust of the IBM arc is to understand how juvenile arc crust forms and differentiates. This objective directly supports the International Ocean Discovery Program Theme 4: Earth Connections: Deep Processes and their Impact on Earth's Surface environment, specifically Challenge 11: How do subduction zones initiate, cycle volatiles, and generate continental crust? The proposed drilling of intact upper to middle oceanic arc crust - without the structural complications accompanying collision - to penetrate an entire crustal-scale volcanic-plutonic connection has never been done before. Consequently ultradeep drilling in the Izu forearc can be expected to result in a quantum advance in our understanding of the solid Earth system. This research program promises to transform our understanding of the solid Earth at the same time that it will lead to advances in techniques and strategies that must be met if we are to successfully meet the challenges of other deep crustal drilling projects such as Project Moho. In turn, answering the challenges of ultradeep drilling will surely stimulate new technological advances that will further advance studies of the deep Earth.

It is widely recognized that continental crust today forms at convergent plate margins, where it is mostly extracted from the mantle as mafic magma. This is further refined by crystal fractionation, anatectic remelting, and delamination (foundering) to yield andesitic material approximating the bulk composition of continental crust (Tatsumi 2005; Tatsumi *et al.,* 2008). This is not mature continental crust, which further requires multiple arc collisions, metamorphism, mafic underplating, anatectic processing, delamination, and perhaps processes unrelated to subduction earlier in Earth history in order to become true continental crust (Rudnick & Gao, 2003). Nevertheless, we need to understand the composition of Phanerozoic juvenile arc crust as a first step towards understanding the materials that form mature continental crust, and relating in situ measurements to the more disrupted character of exhumed arc terranes (e.g., Talkeetna, Kohistan, Fjordland NZ, Pennisular Ranges in Mexico, Ordovician Famatina arc in Argentina). This "transferability" of drilling results to terrestrial geology is an essential scientific objective.

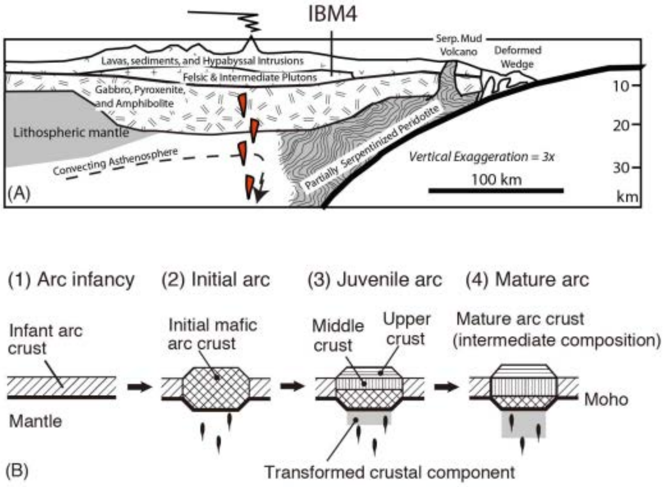

Figure 1. Structure of the Izu forearc (A) and how it might have formed (B). A shows inferred lithologic structure of Izu forearc after Suyehiro et al. (1996) and Debari et al. (1999). B shows the model of arc crust evolution from Tatsumi et al. (2008). Incipient arc magmatism replaces the pre-existing oceanic crust to create the initial mafic arc crust. Continuing arc magmatism causes anatexis and differentiation of the arc crust, along with transformation of mafic crustal component into the mantle through the Moho, finally creating mature arc crust with an intermediate composition similar to the average continental crust.

The Izu-Bonin-Mariana arc system is unsurpassed for the above purposes. As a result of focused studies by the US MARGINS program and especially because of geophysical imaging by JAMSTEC/IFREE and other geoscientists (e.g., Suyehiro *et al.* 1996; Kodaira *et al.* 2007; Takahashi *et al.,* 2007; Calvert *et al.,* 2008), we understand the structure of this arc better than any other intra-oceanic arc (Fig. 1A). This unsurpassed intellectual foundation has led to increasingly sophisticated models for how this distinctive structure formed, as summarized in Fig. 1B. This understanding needs to be tested by deep drilling into the middle crust, particularly to sample the 6.0-6.7 km/sec "tonalite" mid-crustal layer first identified by Suyehiro *et al.* (1996). In reaching the middle crust, we hope to image, sample, and thus understand the composition, chronology, and fine structure of the mid-crustal layer and implications for its origin. We also plan to link the existing geophysical models to rock types in order to better understand the rock compositions, mineralogy, structural fabric, and physical properties such as alteration and porosity, that produce the ~6.5 km/sec seismic velocity.

Reaching and studying the IBM middle crust is the primary scientific objective driving the proposed ultra-deep drilling to 5.5 km beneath the seafloor, the depth that have to drill to answer the question what is the 6.0 – 6.5 seismic velocity material made of? In addition, ten other important additional science objectives are outlined below; please note that the list is not in order of priority.

Ten other important Science Objectives

1. What is the tempo of constructing arc juvenile continental crust?

ODP hole 792, very near the proposed drillsite, penetrated 886m bsf, bottoming in porphyritic andesite of Middle Eocene (41 Ma) age (Shipboard Scientific Party, 1990; Ishizuka *et al.,* 2011). Ultradeep drilling will penetrate into older lavas before reaching the presumed tonalitic layer. Subduction began ~51 Ma (Ishizuka *et al.,* 2011), so most of the rocks above the tonalitic middle crust will be this age and younger, up to 41 Ma. Ultradeep drilling combined with modern U-Pb zircon and $^{40}Ar/^{39}Ar$ dating techniques will allow us to determine the rate at which this crust formed – did it grow at a steady rate over this 12 Ma period, or did most growth occur at the very beginning or very end? How far has this crust gone on the path toward becoming continental crust? Determining this will allow us to evaluate how much of that process must take place later, during or after arc and other collisions.

2. How does arc crust composition change with time?

Ultradeep drilling will sample a thick section of arc upper and middle crust, which will allow us to assess how magma compositions changed with time during the early stages of an intra-oceanic arc. Geochemical and radiogenic isotopic analyses will allow us to assess how the source regions of these magmas changed with time. Will this chemostratigraphy be similar to what has been sampled in the IBM inner trench wall (Reagan *et al.,* 2010; Ishizuka *et al.,* 2011)? These studies show that the earliest magmas are MORB-like asthenospheric melts that formed by decompression with negligible slab components, but that younger magmas are progressively affected by slab components. Or will a different chemotemporal variation be found by ultradeep drilling of the thicker forearc section?

3. Is there older (pre-51 Ma) crust that makes up significant parts of the Izu arc?

Recent geochronological investigations suggest that there may be some remnants of older crust that formed before the current phase of subduction began ~51 Ma preserved as parts of IBM crust (Fig. 2). Some evidence is in the form of old zircons in young rocks (K. Tani, unpublished) or Re-Os model ages, and it is not always clear if old components represent intact crust or were delivered by turbidites from a nearby continent. Ultradeep drilling will allow us to examine IBM crust with deep drilling to see if there is direct evidence for significant amounts of older crust. If this exists, we will examine what are the relations of this material to juvenile crustal components, and how such material contributed to the creation of juvenile arc crust.

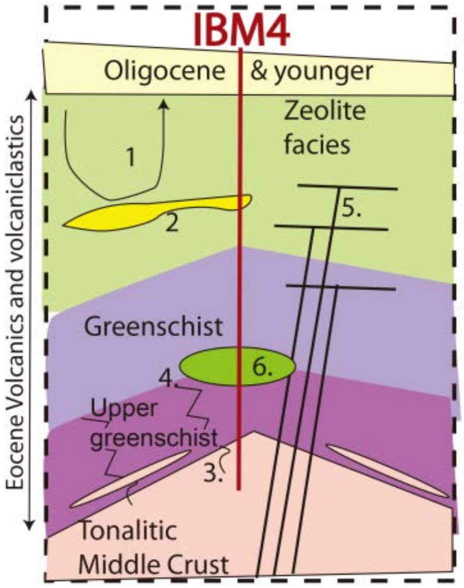

Fig. 2. Cartoon summary of what ultradeep drilling (IBM-4) may encounter above tonalitic middle crust. 1: Evidence of Eocene hydrothermal activity; 2: sulfide mineralization; 3: Evidence of degassing from tonalitic plutonic rocks in middle crust; 4: Metamorphism and possible migmatization, from low-grade near surface (zeolite facies) increasing to greenschist and upper greenschist facies with depth; 5: dikes and sills; 6: older (pre-52 Ma) crust.

4. How do the results of ultradeep drilling into the Izu forearc fit with perspectives gained from other drill sites?

Ultradeep drilling will follow JR drilling at three other sites in 2014. Drilling near Izu rear arc cross chain (IBM-3) to sample the enriched (continental crust-like) component is scheduled for 31 March – 2 June. This will be followed by drilling to sample sediments and crust of the Amami Basin (IBM-1) that were produced before subduction began ~51 Ma, which is scheduled 2 June -4 Aug. Finally, the igneous rocks of the Bonin forearc that formed when subduction began (IBM-2) will be drilled 4 Aug-23 Sept. These drilling results and those of previous drilling expeditions (DSDP Leg 60; IODP Leg 125; IODP Leg 126) will provide context and so inform interpretations of ultradeep drilling. In turn, the results of ultradeep drilling will provide context and inform interpretation of 2014 JR drilling results.

5. What is the relationship and proportion between volcanic and plutonic rocks in ultradeep juvenile arc crust?

The proposed drilling will provide the first chance to see how volcanic cover changes downward in an island arc. Given that much of the upper arc crust will be volcanic rocks and that fossil arc sections in Talkeetna and Kohistan show that plutonic rocks are increasingly common with depth, the drillhole will allow us to examine in detail how the transition between overlying extrusives and underlying plutonic rocks occurs. Will there be a transitional zone of dikes and sills, as is typical for oceanic crust and ophiolites? Or will it be marked by a metamorphic transition, from low grade (zeolite-facies) alteration at the top, changing downwards into greenschist and higher facies with depth? This information will also inform our understanding of how gradational or abrupt are changes in seismic velocity in the transition from overlying sequences down into the tonalitic middle crust and how these relate to rock type. In addition, drilling into the middle crust will allow us to obtain robust estimates for the relative proportions of extrusive to intrusive igneous rocks in arcs and how this proportion changes with depth. At present we only have the volcanic record preserved at active arcs and intrusive rocks preserved in fossil arcs that have been deeply eroded. Consequently, this proportion is poorly constrained (for example White *et al.* (2006) estimate that the proportions of intrusive and extrusive igneous rocks in arcs range from 1:1 to 16:1).

6. What was the role of fluids in the evolution of the rocks that we will penetrate?

In particular, what evidence is there that igneous activity was accompanied by hydrothermal circulation? The depth of the 6.0-6.7 km/sec crust is also the depth at which arc magmas with their typical 4 wt.% H_2O degas. Is there evidence in veins and fracture fillings that tonalitic plutons in the middle crust degassed, releasing fluids that interacted with overlying rock sequences as they rose through them (Fig. 2)? What is the nature of fluids trapped between rock fragments (pore water) and that trapped in fluid inclusions and what is the role of this water for alteration of associated rocks? Are these fluids in thermodynamic equilibrium with secondary minerals? Beyond fluids trapped in pores or inclusions, what is the steady-state flux and composition of fluids rising from the shallow subduction zone beneath the drillsite? How does the composition of pore water and fluid inclusions compare with fluids rising today from greater depth, out of the active subduction zone? Installing a CORK when the hole is completed would allow us to monitor these fluids for several years in the future.

7. What is the nature of the ultradeep biosphere?

Ultradeep drilling will penetrate into regions where temperatures are likely to be as high as 175°C. This is beyond the acknowledged temperature limits to microbial life at ~100°C (Jørgenson & Boetius, 2007). What will the biosphere consist of as we drill down to and across this inferred temperature limit? What does the ultradeep biosphere look like, what does it feed on, how does it reflect the compositions of ambient fluids, how do microbes affect fluid compositions, and how do microbes interact with (alter) the surrounding rocks?

8. What can we learn about convergent margin mineralization by ultradeep drilling into arc crust?

Convergent margins have been important sites of mineralization through much of Earth history. Submarine arc volcanoes are important sites of mineralization (de Ronde et al., 2003) and mineralization is also associated with arc plutons (Kessler, 1997). Ultradeep drilling will almost certainly encounter mineralized zones: as stratabound hydrothermal (Kuroko-type) exhalative deposits associated with volcanic (especially felsic) lavas and pyroclastic deposits; as disseminated porphyry ores associated with plutonic cupolas and intrusive contacts; and associated with veins. What mineralizing processes can be recognized and how do these relate to the formation of the arc crust and its chemotemporal evolution? What was the timing of mineralization and how was this related to circulation fluids? What is the relationship between the agents of metallogenesis and microbial activity?

9. What is the paleomagnetic record preserved in Izu arc crust?

As noted above, we should penetrate about 10 million years of Eocene igneous rocks, which will contain important primary or secondary paleomagnetic information. The Eocene was a time of frequent magnetic reversals, including seafloor anomalies 14-24 (Walker & Geissman, 2009). Rapid reversals should be easily captured in this high magmatic flux setting. After we distinguish primary vs. secondary magnetization or demagnetization events, we should be able to refine this chronology. Similarly, the Philippine Sea plate is thought to have rotated ~90° since it formed, with about 50% of the total rotation occurring during Eocene time (Hall, 2002). Finally, what was the depth of the Curie T (remagnetization T) when tonalitic middle crust formed? The paleomagnetic record encountered by ultradeep drilling can be expected to reflect the interplay between primary magnetizations preserved in lavas and remagnetization due to intrusion of tonalitic middle crust and associated metamorphism. Recovering and interpreting this record is an important scientific objective of this project.

10. How well can we use surface geophysical measurements such as heat flow and seismic velocity to infer properties at depth?

We need to be able to check our seismic velocity models by *in situ* (borehole) measurements; this will allow us to refine seismic processing techniques and so lead to increased confidence in interpreting seismic structures elsewhere. This is especially important for predicting what will be encountered when Project Moho drilling gets underway. Just as important is the ability to predict downhole temperatures. Given that deep drilling is limited by high temperatures (< 175°C?), it is critical that we be able to use surface measurements such as heat flow to predict what will be encountered at depth. It is especially important that we predict downhole temperatures and test them with borehole measurements. Did we get it right or are there additional considerations such as advective heat transport by hydrothermal circulation or magmatic intrusion, failure to reach thermal equilibrium, etc. that we need to consider?

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WHAT AT-SEA DRILLING STRATEGIES AND WHAT SHORE-BASED STUDIES ARE NEEDED TO ACHIEVE THE SCIENTIFIC OBJECTIVES?

At-sea drilling strategies and shipboard personnel

Drilling to the middle crust differs fundamentally from NanTroSEIZE or CRISP in that achieving the scientific objectives for the middle crust requires substantial core recovery. Consequently, high priority should be given to in-depth planning with CDEX engineers about how much, where, and by what methods coring can be done within a realistic budget. If, for example, only about a hundred meters of core below each depth of casing is possible, and the rest of the hole involves Logging While Drilling, Wireline Logging, and Sidewall Sampling, then that determines most other strategic decisions. Specifically, the depth of casing levels, the size and volume of cuttings per core length, and the total number of sidewall samples become crucial. If, instead, it is also possible to do spot coring and/or secondary slant hole coring, at depths other than just below casing, then this needs to be understood and its costs estimated. There may be a fundamental trade-off between total depth drilled and amount of core returned. Unless middle crust samples are lithologically homogeneous, the amount of core from the middle crust may be more important than the depth of penetration into the middle crust.

Four depth intervals were considered most essential for coring: (a) the sediment to volcanic transition previously cored at ~800 mbsf at Site 792; (b) the transition from mostly volcanic to mostly plutonic rocks; (c) the depth at which site survey work places the transition to ~6 km/sec (~3500 mbsf); and (d) the bottom of the hole (<5500 mbsf). Intervals (b) and (c) two may or may not be at the same depth, and either could be smeared out over hundreds of meters. However, they are the most crucial part of the section for models of crustal genesis and for transferability to exhumed rock sections.

Other parts of the section that are especially high priority for core samples are:

1. the most mafic rocks (basalt, diabase, gabbro) because these most closely reflect mantle conditions and processes;
2. the most felsic rocks, because these contain zircons useful for U-Pb geochronology and Hf and O isotope geochemistry;
3. boninitic rocks, for their significance in models for subduction initiation processes
4. levels of metallic mineralization and associated alteration
5. metamorphic rocks associated with plutons.
6. rocks that host life.

In light of the above, the shipboard party should include the standard IODP specialists and others at different stages of drilling. For example, experts on the first leg should include a benthic paleontologist, a pore water geochemist, a geomicrobiologist, a submarine process volcanologist, a volcanic igneous petrologist, and a sedimentary stratigrapher. Later legs should have experts in hydrothermal alteration and sulfide mineralization, deep geomicrobiology, structural analysis, batholith petrogenesis, and metamorphic petrology. Because of the importance of mud logging and cuttings, it may be valuable for some shipboard scientists to be trained in those skills by mining industry personnel prior to sailing and/or to have such personnel on board.

There is interest in geobiology, especially the microbial colonization of different lithologies at high temperatures, but there is concern about the scarcity of core from key intervals. If some cuttings or core could be identified at sea as "having life", then those intervals could be given higher priority for geobiological study.

It may also be important to add specific micro-analytical equipment for these legs such as a handheld XRF or equivalent (cf. NASA Curiosity analytical package) or even a microprobe or SEM. Mineral separation facilities optimized for zircon are important. Reflected as well as transmitted light microscopy will be needed. Finally, it may be necessary to adjust the on-board analytical approach to facilitate as close to real-time (at least same-day) chemical and mineralogical data flow, and to allow the scientific party to participate actively in analyses and methods.

It is essential to establish sample management protocols and priorities prior to drilling. For example, effects of drilling mud must be removed quickly. Searching for zircon and monazite must be a high priority because U/Pb geochronology is so important to the scientific objectives. After crushing and sieving, the majority of the sample can be retained for other studies but a thin section must be taken beforehand.

Regarding shore-based studies:

Standard igneous and metamorphic mineralogy, petrology, and geochemistry (including major and trace elements, and Sr-Nd-Hf-Pb-O isotopes) are essential. U-Pb, O and Hf isotopic work on zircons from silicic pyroclastic rocks is also essential.

High-precision U/Pb and Ar-Ar geochronology are essential and, therefore, searching for suitable minerals must have high priority.

A walk-away VSP experiment, perhaps after completion of drilling, is essential in order to generalize the ground-truthed velocity structure of the site at scales applicable to exhumed terranes.

Other desirable studies include: (a) hydrothermal alteration, contact metamorphism, and ore deposit petrology and geochemistry; (b) experimental mineral physics to determine the effect of water and temperature on the sound velocity of the primary minerals in the middle crust section; (c) structural analysis; (d) pore water chemistry and its relation to observed rock alteration; (e) melt inclusion analyses; (f) paleomagnetic determination of site paleo-latitude and the intensity and direction of rock magnetism in different lithologies, (g) thermochronology of apatite and zircon as a function of depth and temperature, and (h) microbial geobiology as appropriate.

Micro-analytical methods (e.g., SEM, electron microprobe, LA-ICPMS, SIMS) will be essential.