International Ocean Discovery Program
Expedition 350 Scientific Prospectus

Izu-Bonin-Mariana Rear Arc

The missing half of the subduction factory

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Abstract

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 International Ocean Discovery Program *Initial Science Plan*. The Izu-Bonin-Mariana (IBM) arc has been a target for this task for many years, but previous drilling efforts have focused mainly on the IBM fore arc and the magmatic evolution of the volcanic front through 50 Ma. 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 intracrustal differentiation.

Expedition 350 will contribute to the understanding of intraoceanic arc evolution and continental crust formation by drilling in the IBM rear arc to examine three phenomena:

1. Crust develops that is "continental" in velocity structure and seismically similar beneath both the volcanic front and rear arc but is heterogeneous in chemical composition.
2. Magmas at the volcanic front are rich in fluid-mobile recycled slab components that swamp the mantle, yet these magmas are so depleted in mantle-derived fluid-immobile elements that they are dissimilar to "average continental crust" in detail. This is less true in the rear arc where the diminished slab signature and lower degrees of mantle melting create crust that is more typical of the continents and allows the temporal history of the mantle source to be tracked more easily.
3. The crust beneath the rear arc is volumetrically more abundant than beneath the volcanic front.

To understand the evolution of the whole IBM crust, we will drill the Izu rear-arc region west of the modern volcanic front to recover a complete record of rear-arc volcanism from the present back to its likely inception in early Oligocene or Eocene times. The rear arc contains the record of the "other half" of the subduction factory output, and recovering that record is essential to the IBM drilling strategy.

Schedule for Expedition 350

Project IBM: arc evolution and continental crust formation

Key questions for comprehending arc crust formation include

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 the International Ocean Discovery Program (IODP) at the Izu-Bonin-Mariana (IBM) arc system (Fig. **F1**). Four proposals to IODP to drill at the IBM arc system, including three riserless holes (proposed Sites IBM-1, IBM-2, and IBM-3) and one ultradeep riser hole (proposed Site IBM-4), focus on addressing these questions. Drilling at the four sites will result in comprehensive understanding of arc evolution and continental crust formation. Ultradeep drilling (proposed Site IBM-4) will follow riserless drilling with the R/V *JOIDES Resolution* at three sites (proposed Sites IBM-1–IBM-3) scheduled for 2014.

Site IBM-1: nature of the original crust and mantle (IODP Expedition 351)

Preexisting nonarc 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 arc system, preexisting oceanic crust is present west of the arc, under 1–1.5 km of sediment in the Amami Sankaku Basin adjacent to the Kyushu-Palau Ridge (KPR) remnant arc (Fig. **F1**) (Taylor and Goodliffe, 2004).

Site IBM-2: initial arc crust and subduction initiation (IODP Expedition 352)

A section through the volcanic stratigraphy of the outer fore arc 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.

Site IBM-3: the rear arc: the missing half of the subduction factory (IODP Expedition 350)

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 *Initial Science Plan* (ISP) (Bickle et al., 2011). 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 fore arc and thus the magmatic evolution of the volcanic front through 50 Ma. 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 intracrustal differentiation.

Site IBM-4: continental crust formation at intraoceanic arc: ultradeep drilling to the middle crust of the Izu-Bonin-Mariana arc

This proposal is for the ultradeep drilling site of a series of IODP proposals in the 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 intraoceanic arc upper crust and into the in situ middle crust that may be a nucleus of continental crust.

The IODP *Initial Science Plan* states that "The creation and growth of continental crust remains one of the fundamental, unsolved problems in Earth science" (Bickle et al., 2011). The formation and evolution of continental crust is a first-order problem of terrestrial geochemistry because for many trace and minor elements, this reservoir is quantitatively important despite its volumetric insignificance on a planetary scale. In the latter part of the 1960s, Ross Taylor (1967) proposed the "andesite model" for the origins of continental crust on the basis of similarities between "calc-alkaline" or orogenic andesite formed in island arcs and the "intermediate" bulk composition (~60 wt% SiO_2) of this crustal type. For many arc enthusiasts, this observation has been a prime motivation for studies of island and continental arc systems. Subsequent studies have substantiated Taylor's estimate of continental crust bulk composition and have noted that distinctive continental trace element fractionations (e.g., high U/Nb and Pb/Ce) are only found in suprasubduction-zone magma types (Hofmann, 1988).

The andesites of most young oceanic arcs, however, have been found to be more depleted elementally and isotopically than average continental crust, at least at the volcanic front. An old idea, still generally valid, that may explain part of this problem is the Kuno-Dickinson-Hatherton *K*-*h* relationship (Kuno, 1959; Dickinson and Hatherton, 1967): at a given SiO_2 content, the K_2O of related volcanic series is positively correlated with depth (*h*) to the Wadati-Benioff Zone. Thus, geochemical asymmetry in arcs was known prior to the advent of plate tectonics and may be what makes juvenile arc crust "continental" in key elements like Th and light rare-earth elements (LREEs) as well as intermediate in silica content. Potential processes to produce this asymmetry might be that

1. Magma is first extracted from the mantle in the rear arc and is then extracted a second time as the depleted mantle moves toward the volcanic front where it is fluxed by fluid from the slab (Hochstaedter et al., 2000, 2001),
2. The rear-arc magma source contains more slab-derived sediment melt (Ishizuka et al., 2003a, 2006; Tamura et al., 2007),
3. The degree of melting is smaller beneath the rear arc (e.g., Tatsumi et al., 1983; Sakuyama and Nesbitt, 1986; Kushiro, 1994), or
4. There is more recycling of old crust at the magmatic front (Kimura and Yoshida, 2006).

In addition to these petrological considerations, paleo-arcs are an essential part of most mountain belts from the Archean to Tertiary. Their geological architecture represents a fundamental aspect of the formation of continental crust. Most rocks in the upper crust of arcs are volcaniclastic, highly vesicular, and vitric. Models for their facies architecture have relatively good constraints for the subaerial arc front and for some aspects of submerged arc-front volcanoes, but knowledge of the rear-arc facies architecture is limited by the paucity of mapping, drilling, and sampling from modern rear-arc settings. Facies models depend largely on ancient successions now uplifted and dissected (e.g., McPhie and Allen, 1992), but incomplete preservation and exposure limit the value of such models. Nevertheless, facies models underpin a great deal of fold belt research worldwide, particularly tectonic interpretations, structural analyses, paleogeography reconstructions, and resource assessments. For example, in ancient successions, aligned volcanic centers and proximal associations are commonly the basis for reconstructing the arc trend and polarity. The presence of almost orthogonal rear-arc seamount chains in arcs like Izu has serious implications for such reconstructions. If the rear-arc affinities of volcaniclastic sediments can be better defined through this expedition, similar features may be recognized in ancient foldbelt successions. Likewise, knowledge of the eruption and depositional processes at submarine arc volcanoes depends largely on these same ancient successions (Fisher and Schmincke, 1984) and are weighted toward shallow-water volcanic front edifices. The effects of voluminous vesicular glass on water chemistry and microbiology are potentially enormous but largely unknown. Drilling is the only way to obtain information about volcanic eruption, sedimentation, and stratigraphy in oceanic arcs without looking through the effects of collision and accretion (e.g., Haeckel, et al., 2001; Wiesner et al., 2004).

Full crustal velocity profiles for the IBM arc obtained in the last decade show a velocity structure with continuous layers extending ~200 km across the arc (Fig. **F2**). We do not yet know how these layers developed, but testable hypotheses are being developed (Kodaira et al., 2007a, 2007b; Tatsumi et al., 2008). Given the relatively large volume of crust now in a rear-arc position (Fig. **F2**) and its present-day geochemical contrast with the magmas erupted at the volcanic front, it is vital that we understand the structure and compositional variations of the rear arc through time in the same way that we have unraveled the temporal evolution of the fore arc and volcanic front magmas.

A basic premise of this project is that time series of geochemical information about igneous rocks can be obtained from volcaniclastic sediment, mostly turbidites. This potential was realized during earlier Ocean Drilling Program (ODP) drilling in the Izu fore arc (e.g., Gill et al., 1994), and subsequent advances in microanalytical methods (e.g., analysis of clinopyroxene and zircons to obtain igneous geochemical information) make this even more likely now. The fore-arc turbidites preserve a faithful record of arc evolution, which parallels that seen in tephra (e.g., Straub, 2003; Bryant et al., 2003). The mass wasting of submarine edifices guarantees lots of volcaniclastic sediment. Even though mixing makes the signal more of a running average than in tephra, first-order changes (say on a few hundreds of thousands-year scale) are well resolved. Therefore, although many of our ends are igneous in nature, our means are sediments.

Background

The IBM subduction zone began as part of a hemisphere-scale foundering of old, dense lithosphere in the western Pacific at ~50 Ma (Bloomer et al., 1995; Cosca et al., 1998; Stern, 2004), perhaps aided by reorganization of plate boundaries throughout the western Pacific (Okino et al., 2004; Hall et al., 2003; Whittaker et al., 2007). The latter is consistent with the initiation of the Hawaiian-Emperor bend near Kimmei Seamount, suggesting a major change in Pacific plate motion at 50 Ma (Sharp and Clague, 2006). During this stage, the fore arc was the site of prodigious igneous activity (Fig. **F3**). Magmatic products consist of boninite, low-K tholeiite, and subordinate low-K rhyodacite everywhere the fore arc has been sampled, implying a dramatic episode of asthenospheric upwelling and melting associated with seafloor spreading over a zone that was hundreds of kilometers broad and thousands of kilometers long.

After ~5 m.y., the active magmatic front localized ~20 km east of the present front, building the first mature arc from 42 to 25 Ma (Taylor, 1992; Ishizuka et al., 2006). The rear-arc crust of this age is one of our targets (Layer L5, described below). This retreat of magmatism allowed fore-arc lithosphere to cool. Arc volcanism was accompanied until at least 33 Ma by spreading along the west-northwest–east-southeast (present coordinates)-trending Central Basin Fault in the western Philippine Sea (Deschamps et al., 2002; Deschamps and Lallemand, 2002; Taylor and Goodliffe, 2004). Eocene–Oligocene arc rocks have been found both at the frontal arc highs (Taylor, 1992), one of which was drilled at ODP Site 792 and is the target for drilling to the middle crust at proposed Site IBM-4 (Proposal 698 Full2), and at the Kyushu-Palau Ridge (Malyarenko and Lelikov, 1995; Mizuno et al., 1977; Shibata and Okuda, 1975; Ishizuka et al., 2011). In addition, Yamazaki and Yuasa (1998) reported three conspicuous north–south rows of long-wavelength magnetic anomalies in the Izu-Bonin arc that are slightly oblique to the present volcanic front. The eastern row correlates with the frontal-arc highs, the western row coincides with the KPR (the remnant arc), and the middle row lies at 139°E at our proposed site. Yamazaki and Yuasa (1998) attributed all three to loci of Oligocene magmatic centers.

At ~30 Ma, the IBM arc began to form its back-arc basins, the Shikoku Basin and Parece Vela Basin spreading systems, which met at ~20 Ma, stranding the KPR as a remnant arc (Fig. **F3**). This back-arc basin spreading stopped at ~15 Ma, simultaneous with the opening of the Japan Sea. This also caused the northernmost IBM arc to collide with Honshu beginning at ~15 Ma. Izu arc magmatism was minimal or even absent from 25 to 15 Ma during the opening of the Shikoku Basin, and when it resumed, the volcanic front was ~20 km west of its Oligocene position and has remained there ever since (Taylor, 1992). A new episode of rifting of the southern IBM arc began at ~7 Ma, with seafloor spreading to form the Mariana Trough back-arc basin beginning ~3–4 Ma (Yamazaki and Stern, 1997).

Neogene volcanism along the rear-arc seamount chains and at adjacent isolated seamounts began at ~17 Ma, slightly before the Shikoku Basin ceased spreading, and continued until ~3 Ma (Fig. **F4**) (Ishizuka et al., 1998, 2003b). The most obvious features of the Izu rear arc are the several ~50 km long en echelon chains of large seamounts striking N60°E (Figs. **F4, F5**). Basalts to dacites (Fig. **F6**) with ages ranging from 17 to 3 Ma have been dredged from many of the seamounts. Volcanism along these chains occurred sporadically along their total length, but lavas dredged from the top of seamounts in the western part of the chains are generally older than those to the east (Fig. **F5**); rear arc–type volcanism ceased altogether at the initiation of rifting behind the volcanic front at ~2.8 Ma (Ishizuka et al. 2002). The eastern end of the chains lies above the middle row of Yamazaki and Yuasa's magnetic anomalies, and the western end lies on Shikoku Basin crust. In some cases (e.g., Manji and Genroku), the seamount chains seem aligned with large volcanoes on the volcanic front (e.g., Aogashima and Sumisu-jima, respectively) and with areas of thickened middle and total crust, but the association is imperfect.

Several explanations of the seamount chains have been proposed. They may be related to compression caused by collision between the southwest Japan and Izu arcs associated with the Japan Sea opening (Karig and Moore, 1975; Bandy and Hilde, 1983). Alternatively, they may have formed along Shikoku Basin transform faults (Yamazaki and Yuasa, 1998). A third hypothesis, presented in Figure **F7,** is that they overlie diapirs in the mantle wedge, such as the "hot fingers" proposed for northeast Japan (Tamura et al., 2002).

A less obvious aspect of the Izu rear arc is the 100 km wide extensional zone that lies between the Quaternary volcanic front and the eastern end of the seamount chains (Fig. **F4**). This is where all <3 Ma rear-arc rift-type volcanism has occurred, mostly on small cones or volcanic ridges associated with several kilometer–deep rift grabens that lie just behind large volcanoes on the volcanic front. These bimodal volcanic rocks differ in composition from those of the rear-arc seamount chains, which predate them (they are mostly mafic but range to dacite; Fig. **F6**). Post–3 Ma volcanism behind the volcanic front has been "rift type," which is bimodal in silica and distinguishable in trace element and isotope ratios from both the volcanic front and the rear-arc chains. This volcanism is not simply intermediate in composition, as it is in location (Hochstaedter et al., 2001; Ishizuka et al., 2003a). The differences have been attributed to some combination of a transition from flux to decompression mantle melting as arc rifting commences, a change in the character of the slab-derived flux, or a change in the mantle (Hochstaedter et al., 1990a, 1990b, 2001; Ishizuka et al., 2003a, 2006; Tollstrup et al., 2010). Thus, two different magmatic suites occur in the Izu rear arc: "rear-arc type" from 17 to 3 Ma and "rift type" from 3 to 0 Ma. Both lie in the rear arc; neither formed in a back-arc basin.

Large basalt-dominated volcanoes are spaced at ~100 km intervals along the Quaternary volcanic front and correlate with thickened portions of arc middle crust and perhaps total crust (Kodaira et al., 2007a, 2007b). Rhyolite-dominated calderas lie between the large volcanoes of the volcanic front north of 31°N, with gaps of 50–75 km that have no volcanic edifices (Tamura et al., 2009). Similar wavelength along-strike variations in the thickness of middle and total crust also have been imaged in the rear arc from 28° to 32°N (Kodaira et al., 2008). Crustal development in the rear arc appears similar to the volcanic front, although no Quaternary volcanoes exist in the rear arc and Neogene chemical compositions show clear across-arc variations. Thus, the magmatic evolution of the rear arc is vital to understanding the history and composition of Izu arc crust.

The proposed sites for Expedition 350 lie directly above the middle row of north–south magnetic anomalies and near two large seamounts of the Manji seamount chain. Therefore, this row of anomalies may coincide with an area of thickened crust behind Aogashima. It is also within 10–15 km of several <3 Ma cones east of the Enpo chain and therefore should have received volcaniclastic sediment both from the small rift-type cones that were active in the Pliocene–Pleistocene and the rear-arc seamounts that were active in the Miocene. Finally, the proposed sites should overlie Oligocene arc rocks.

Primary proposed Site IBM-3C is at 31°47.38′N, 139°01.58′E and 2114 meters below sea level (mbsl) in the eastern half of the Izu-Bonin rear-arc seamount chain, ~90 km west of the arc volcano Myojin-sho (Fig. F5). The site is located between the Manji and Enpo rear-arc seamount chains where Neogene rear-arc sediments lap onto a Paleogene basement (Fig. F5). Based on site survey multichannel seismic (MCS) reflection data, the site location has been adjusted to be largely isolated from the volcanic front topographically by having a large edifice or trough or both between them. Because complete isolation from the volcanic front is not possible, we will use a combination of rock and mineral chemistry, clast morphology, and general sediment characteristics to identify and exclude volcanic front–sourced material (Fig. **F6**). There may be an inherent problem if volcanic front–type magmas were erupted in the rear arc between the cross-chains (i.e., if the hypothesis of inherent chemical asymmetry is not completely correct) or if in the past the volcanic front was located in the present rear arc. However, there is no evidence that the volcanic front was ever that far west, and Bednarz and Schmincke (1994) successfully used volcaniclast morphology to distinguish proximal from distal sources. We have chosen the best site based on

1. Existing information from dredges and bathymetry (Fig. **F5**),
2. Maximum protection from volcanic front mass wasting,
3. Likelihood of receiving sediment from as much rear-arc diversity as possible (rear-arc seamount chains and rift-type magmas),
4. Location east of the eastern extent of the Shikoku Basin as defined by magnetic lineations (K. Okino, pers. comm., 2013), and
5. Overlying seismically "typical" middle crust with a low velocity gradient (Fig. **F2**).

The tectonic setting of different magmas: arc front (enriched and depleted), rear arc, and rift type

Basalts and andesites of the rear-arc seamount chains are enriched in alkalis, high–field strength elements (HFSE; e.g., Nb and Zr), and other incompatible elements but have less enriched Sr, Nd, Hf, and Pb isotopes compared to the volcanic front (Hochstaedter et al., 2000; Ishizuka et al., 2003a) (Fig. **F6**). Thus, we can clearly identify different magmatic sources (front arc versus rear arc versus rift type) using geochemical criteria such as these.

Figure **F6A** shows K_2O and rare-earth element (REE) differences between the arc-front and rear-arc areas. A striking characteristic of orogenic andesites and associated rocks within many volcanic arcs of modest width is the consistent increase of their incompatible element concentrations, notably K_2O, away from the arc front (Gill, 1981). Basalts and andesites along the Izu-Bonin volcanic front have significantly less K, U, and Th and lower Th/U than those from the rear of the arc (Fig. **F6**), which can be monitored using the gamma radiation logging tool. Rocks from the frontal volcanoes are low-K as defined by Gill (1981), but the rear arc–type lavas are medium- and high-K. Basalt and andesite magmas at the front of the Izu-Bonin arc are so depleted in K_2O

and other incompatible elements that they are dissimilar to the "average continental crust" of Rudnick and Gao (2004).

Figure **F6B** shows a chondrite-normalized REE plot for the Izu-Bonin basalt and andesites. All basalts from arc-front volcanoes are strongly depleted in the more incompatible LREEs compared with the middle and heavy REE (MREE and HREE). In contrast, basalts and andesites from rear-arc sites are enriched in LREE and MREE compared with HREE (Fig. **F6B**). Thus, rear-arc compositions are closer approximations to the average continental crust of Rudnick and Gao (2004).

Detailed descriptions of seismic stratigraphy

Six low-fold MCS profiles intersecting in the area of the possible drilling target (proposed Site IBM-3C) were obtained during Japan Agency for Marine-Earth Science and Technology (JAMSTEC) Cruise KY06-14 in December 2006 and JAMSTEC Cruise KR07-09 in June and July 2007 (Figs. **F8, F9, F10, F11, F12, F13, F14**). Our proposed Site IBM-3C is at the intersection of Lines IBM3d (Fig. **F10**), IBr5 (Fig. **F11**), and IBM3e (Fig. **F12**) (see composite in Fig. **F14**). These profiles between the Manji and Enpo seamount chains enabled us to determine 3-D structural images of sedimentary deposits in the targeted area. This seismic information, along with ages of the rear-arc seamounts, allowed us to determine the age and thickness of each layer and the best drilling site. Many sediment layers are laterally discontinuous. This lateral heterogeneity suggests a proximal nature of these deposits, which are similar to those of the uplifted Izu rear arc (i.e., in the Miocene–Pliocene Shirahama Group of the Izu Peninsula) (Tamura et al., 1991; Cashman and Fiske, 1990).

The reflector sequence can be divided into five layers (L1– L5; Table **T1**). We can estimate the age of the units by combining onlapping relationships and Ar-Ar ages reported by Ishizuka et al. (2003) from dredge samples of nearby seamounts (Fig. **F9**). We describe these characteristics from top to bottom as follows.

Uppermost seismic Layer L1 parallels the seafloor and may represent silicic channel deposits derived from Myojin Knoll. It is 32 m thick and onlaps seismic Layer L2. Layer L1 corresponds to the sediment layer most likely to be derived from the volcanic front.

The top of seismic Layer L2 has strong amplitude and is subparallel to Layer L1. Layer L2 dips southwestward and crops out in Line IBM3a. The lower part of this layer is commonly interrupted and deformed by faulting. The layer is well bedded with high-amplitude reflectors and a transparent portion, and its thickness is almost constant (>0.5 s) along each MCS line. The layer onlaps Manji Seamount (6.5–6.9 Ma) to the north, but sediment from a 1.96 Ma seamount overlies the top of Layer L2 in Line IBM3b to the south. In Line IBM3d (Fig. **F10**), the boundary between Layers L1 and L2 lies on the basement of a 2.77 Ma seamount. Consequently, seismic Layer L2 accumulated after ~3 Ma and coincides with back-arc extension and eruption of rift-type magmas to the east and south of proposed Site IBM-3C.

Like Layer L2, L3 is well bedded and laps onto seamounts of the Manji chain (Fig. **F10**). The interface between seismic Layers L2 and L3 crops out on Lines IBM3a and IBr5 (Fig. **F11**). Thus, Layer L3 seems to be 3–6.5 Ma and coincides with the development of the Manji and Enpo chain seamounts in the vicinity of the proposed site.

Seismic Layer L4 also is well bedded and subparallel to Layer L3, and its upper part laps onto nearby Manji chain seamounts in Lines IBM3d, IBM3e, and IBr5 (Figs. **F9, F10, F11, F12, F13**). The layer's lower part is less clear and may onlap or be intruded by the seamounts. Overall, Layer L4 is more strongly faulted than the overlying units and is characterized by inhomogeneous, discontinuous reflectors of low frequency. From the seismic profile of Line IBr5 (Fig. **F11**), the boundary between Layers L4 and L5 could be as young as 9 Ma.

The age of seismic Layer L5 is important but uncertain. The boundary between Layers L4 and L5 has a high relief that may be erosional. Layer L5 uniformly lacks the well-bedded character of the overlying units, and its chaotic, discontinuous reflectors have low to medium amplitude. We attribute these features to greater lithification or the presence of lava. The simplest interpretation of all these features is that Layer L5 is Oligocene arc volcaniclastic rocks (with lavas?), and the boundary above it represents the unconformity developed during the Shikoku back-arc basin formation. The relationships of Layer L5 with younger units are uncertain; it appears intruded by seamounts of both chains on Lines IBM3d and IBM3e. Because western seamount volcanism becomes younger toward the east, we hypothesize that the unconformity does also (Fig. **F5**). This suggests that Oligocene basement may be uplifted beneath the Miocene rear-arc volcanoes. These hypotheses will be tested by drilling.

In Line IBr5, layers below Layer L1 are deformed by contraction east of proposed Site IBM-3C, closer to the Enpo chain. These structures are imaged as simple folds in other profiles. They may indicate the presence of a transcurrent fault at a high angle to Line

IBr5, with some faults propagated beneath Layer L2. An eastward-dipping reflector (X) is recognized beneath Layer L5 in Line IBr5. This boundary coincides with a velocity gradient in the rear-arc crustal structure (T. Kodaira, unpubl. data) and may be the Eocene basement, but this is too deep to reach by drilling.

New, higher resolution MCS profiles for proposed Site IBM-3C (not shown) confirm the previous seismic interpretation, which is that the Neogene to Oligocene–Eocene transition occurs within volcaniclastic sediment at ~1200 meters below seafloor (mbsf) (Table **T1**). The boundary between Oligocene–Eocene sediment and igneous basement (crystalline rock), which we hope to reach by drilling, is deeper (~2100 mbsf; Table **T1**). Figure **F14** shows seismic images and the velocity structure of the upper 10 km in this rear-arc region along Line IBr5. Generally, the velocity transition to >5 km/s is thought to represent the transition to igneous crystalline rocks. As shown in Figure **F14,** the 5 km/s iso-velocity contour lies at 2080 mbsf at proposed Site IBM-3C.

Supporting site survey data for Expedition 350 are archived at the IODP **Site Survey Data Bank.**

Scientific objectives

The primary objective of proposed Site IBM-3C is to test three pairs of alternative hypotheses about crustal genesis and mantle evolution:

1. Geochemically asymmetric crust, which is most like "average continent" in the rear arc, is either (a) a fundamental trait of crust in oceanic arcs that is produced in a steady state throughout arc history from Paleogene inception or (b) a secondary trait that develops only after back-arc spreading (Fig. **F15**);
2. Intracrustal differentiation amplifies this asymmetry (a) continuously as a steady-state process or (b) mostly during nonsteady-state events such as arc rifting; and
3. After or near the cessation of the Shikoku back-arc basin opening, rear-arc magmatism either (a) started from the western end of the rear-arc seamount chains and migrated eastward (Fig. **F7**) or (b) started at the same time along the length of the rear-arc seamount chains but ended from west to east (Fig. **F5**).

Figure **F15** illustrates the alternatives for Hypothesis 1 that can be tested by drilling. We call them the "from the beginning" and "from the middle" alternatives. Colors in

Figure **F15** simplify chemical differences between the volcanic front and rear arc that are predicted by these two hypotheses. During steady-state arc growth, crust develops that is "continental" in velocity structure and seismically similar beneath both the volcanic front and rear arc but is heterogeneous in chemical composition. Magmas at the volcanic front are rich in fluid-mobile recycled slab components (e.g., Sr, Pb, and U) that swamp the mantle, yet these magmas are so depleted in mantle-derived fluid-immobile elements (e.g., Nd, Hf, and Nb) that they are dissimilar to "average continental crust" in detail. This is less true in the rear arc where the less-depleted mantle, diminished slab fluid signature, possible addition of melt from subducted sediment, and lower degrees of mantle melting create crust that is more typical of the continents and allow the temporal history of the mantle source to be tracked more easily. Although the asymmetry is known in general in Izu from Neogene volcanic rocks obtained by dredging, the best way to assess its variability during the Neogene, and to learn how far back in arc history it extends, is to obtain a temporal record by drilling the volcaniclastic sediment in the rear arc. The alternative hypothesis is that the asymmetry is only true in the Neogene Izu arc and that magmatism was uniformly less depleted and/or uniformly rich in fluid-mobile recycled slab components (e.g., Sr, Pb, and U) during the Oligocene and Eocene. The latter would indicate that the subduction parameters that cause geochemical asymmetry differed in early arc history. These two hypotheses, from the beginning and from the middle (Fig. **F15**), and others can be tested only by recovery of the Eocene–Oligocene tephra and turbidites in the rear arc.

The second hypothesis is that nonsteady-state events play a major role in the evolution of arc crust. One alternative is that intracrustal recycling, which creates felsic magmas and possibly is forming the distinctive 6.0 km/s "tonalitic" middle crust, is heightened during periods of rifting preceding back-arc spreading (e.g., since 3 Ma) and that this recycling amplifies the across-arc chemical asymmetry. We know from ODP Legs 125 and 126 that the current phase of arc rifting produced a marked increase in felsic magmatism at the arc front, and we know from dredging that there are along-arc and across-arc differences in the chemical composition of tonalites and rhyolites, but only drilling can test this hypothesis by providing a stratigraphic record of felsic magmas across the arc, especially in the rear arc. The 7 Ma tonalites from Manji Seamount provide a comparison between extrusive and intrusive rear-arc felsic rocks.

The third hypothesis is that the origin of the Izu rear-arc seamount chains can be related to mantle convection patterns (hot fingers in Fig. **F7**) (e.g., Tamura et al., 2002; Honda et al., 2007). Numerical simulations of small-scale convection under island arcs (Honda and Yoshida, 2005) suggest that a roll (finger)-like pattern of hot and cold anomalies emerges in the mantle wedge starting from the back-arc side of the rolls. Thus the small-scale convection hypothesis predicts that rear-arc magmatism migrated from west to east.

Road map for testing hypotheses

Testing these hypotheses requires obtaining a temporal record of across-arc variation in magma composition from the Eocene to Neogene. This should enable (1) identification of temporal changes of basaltic magma chemistry and interpretation of the source processes and (2) identification of temporal variation of intermediate and felsic magmas and interpretation of crust-level differentiation processes. This information is in hand for the volcanic front but missing for the rear arc, which overlies the majority of crust that is "continent type" in composition. This rear-arc information is also needed in order to compare these characteristics to what is already known about these parameters for the volcanic front. Specifically, our objectives are to establish the temporal history of across-arc variations during five time periods that stand out in the rear-arc evolution:

1. 3 Ma to the present: we will determine whether rear-arc and rift-type magmatism have overlapped since the onset of rifting at 3 Ma, and whether rift-type mafic and felsic magmatism changed during that time.
2. 9–3 Ma: we will also establish whether rear-arc magmatism changed with time, how it compares with arc-front magmatism, and the role of felsic magmatism in producing middle crust in both settings.
3. 17–9 Ma: if rear-arc magmatism migrated from west to east during this time frame, strata of this age should be missing in the proposed drilling site (Fig. **F5**).
4. 25–17 Ma: we will determine whether volcanism stopped in the rear arc during opening of nearby Shikoku Basin, as it did at the volcanic front.
5. >25 Ma: we will determine whether rear-arc magmatism changed with time; that is, whether Oligocene rear-arc and frontal-arc magmas differed in the Oligocene (during the initial stages of arc development), and especially whether felsic materials differed in their abundance, character, and mode of origin during arc evolution.

These determinations will be made using standard igneous geochemical tools applied to volcaniclastic materials (and any lavas encountered). These tools include bulk rock major, trace element, and Sr-Nd-Hf-Pb isotope chemistry and the same applied to glass shards, minerals, and their melt inclusions. Some of these tools (e.g., REE + HFSE trace elements and Nd-Hf isotopes, especially in minerals like pyroxenes) are not much affected by the level of alteration expected. Geochronology is essential and will be established using paleontology, paleomagnetism, and Ar-Ar and U/Pb dating of zircon in felsic materials. The provenance and mode of deposition of volcaniclastic sediment is also essential and will be established by examining the morphology of grains and the overall character of sedimentary units (e.g., Bednarz and Schmincke, 1994; McPhie and Allen, 2003).

These five objectives will establish the effects of a fundamental characteristic of island-arc magmatism (across-arc geochemical variations) on crustal production in that environment and will constrain the fundamental reasons for the variations themselves. This temporal record is also necessary to assess the evolution of the mantle wedge and slab, to evaluate processes of intracrustal differentiation, and to calculate mass balance and flux models of crustal growth.

Additional drilling discovery opportunities

Physical volcanology

As noted in the Introduction, most rocks in the upper crust of arcs are submarine volcaniclastics. Previous studies of the IBM arc system have revealed the importance of thick, pumice-rich pyroclastic units as a component of rift basins and arc-front volcano aprons (e.g., Nishimura et al., 1992; Tani et al., 2008). Pumice-rich pyroclastic units are also common in marine arc-related basin fills exposed on land (e.g., Busby, 2004; Busby et al., 2006), and their ultimate origin as the products of explosive eruptions is widely accepted. However, it is less clear how to distinguish eruption-fed products (e.g., Busby-Spera, 1984, 1986, 1988; Busby et al., 2003), strictly contemporaneous with an eruption, from those generated by resedimentation of temporarily stored pumiceous facies (e.g., Critelli et al., 2002). A further source is the collapse of volcaniclastic aprons, recently recognized as a major sediment source in the Miocene arcs of the North Island of New Zealand (Allen, 2004). Also unclear is how to distinguish the products of totally submerged explosive eruption plumes (Kokelaar and Busby, 1992; Busby, 2005) versus plumes that break the water/air interface or are totally subaerial (e.g., McPhie and Allen, 2003). Data from well-preserved examples where the context is well constrained, such as Izu, have the potential to greatly refine our currently primitive criteria and test some inferences based on outcrop examples. We will attempt to distinguish not simply the compositions of source volcanoes for rear-arc pyroclastic components but also their proximity, vent setting, and whether they were eruption fed or resedimented. We note that these methods led to the serendipitous discovery of a new type of deep seafloor pyroclastic eruption during ODP Leg 126 (Gill et al., 1990), and we believe that more rear-arc drilling will lead to more such discovery.

Drilling at proposed Site IBM-3C will test whether or not there is asymmetry in the physical volcanology of arcs as well as in magma compositions, how the differences evolve temporally, and how the differences can be applied to studies of paleo-arcs worldwide. Plausible cross-arc influences on the physical volcanology of arc volcanoes include

- Magma composition: spatial and temporal gradients in magma compositions, especially SiO_2 and volatiles, should be accompanied by variations in eruption styles and volcano types. Higher SiO_2 and volatile magmas favor powerful explosive eruptions and the production of diverse, widely dispersed pyroclastic facies, as well as lavas and domes. On the other hand, lower SiO_2 and volatile-poor magmas favor lavas or domes and subordinate, weakly explosive eruptions.
- Vent environment: vents for rear-arc volcanoes are likely to be submerged; in contrast, vents for arc-front volcanoes can be either submerged (particularly in the early stages of arc evolution) or subaerial. The presence of water greatly alters the dynamics of eruptions and, hence, also the products. Deep water may suppress explosive activity, whereas shallow water may introduce the possibility of magma-water interaction; any water promotes quench fragmentation. Additionally, water depths can control styles of mineralization at vents (e.g., volcanic-hosted massive sulfides do not form in shallow water).
- Presence or absence of wet sediment: ancient successions show that magmas intrude, rather than erupt, in submerged settings where wet sediment has accumulated, forming peperites (e.g., Busby-Spera and White, 1987; Skilling et al., 2002). The products are sill-sediment complexes and/or cryptodome complexes showing complex contact relations with the host sediment. Sill-sediment and/or cryptodome complexes are predicted to be a common feature of the rear arc in contrast to the arc front, where they may be present but largely limited to the earliest stages of arc evolution.

Microbiology

Proposed Site IBM-3C represents a potentially exciting opportunity to study the microbiology of the deep subseafloor, in the opinion of microbiologists including K. Edwards (University of Southern California, USA) and M. Schrenk (Department of Biology at East Carolina University, USA) with whom we have consulted. Of all IODP sites on the horizon, this one should have the most abundant vesicular basaltic glass. Such glass has extremely large amounts of reactive surface area and, based on what is known from dredged lavas, should have high levels of the oxidant Fe^{3+} and the nutrient P (certainly relative to mid-ocean-ridge basalt [MORB] lava). The site would also provide new pressure, temperature, and pore water conditions in which to explore for subseafloor microbial ecology and biogeochemistry (20–50 MPa, ≤100°C, and high $Ca\text{-}Cl_2$ pore water). We predict relatively unaltered glass in at least the uppermost 600 m and quite altered glass below 1500 mbsf, with increasing alteration in between, based on what was found at ODP Sites 792 and 793 in the Izu fore arc. There, the lower depth corresponded to a marked change in pore water chemistry (increased Ca and inorganic C and decreased Si, SO_4, and Mg) and decrease in porosity (Egeberg, 1992). It is uncertain whether the level of microbiological activity would be abnormally high (because of bioavailability of oxidants and nutrients) at proposed Site IBM-3C or low (because of decreased permeability and increased rock/water equilibration). However, we feel that this scientific objective should continue to be explored at this site.

Tonalite emplacement, mineralization, and exhumation

The proposed site lies downslope from the only known submarine example of porphyry copper mineralization in a rear arc, at Manji Seamount (Ishizuka et al., 2003c). Rounded cobbles of chalcopyrite-bearing quartz-magnetite stockwork and 7 Ma gabbroic to tonalitic plutonic rocks have been dredged from its flat-topped, subaerially eroded summit, which currently lies at 700 mbsl). The *Shinkai* 2000 diving survey discovered exposures of classic potassic and propylitic alteration, indicative of activity of hypersaline fluids, and closely associated plutonic rocks. Because rounded cobbles occur on the seamount's flanks, clasts and heavy minerals (sulfides) also may be found at proposed Site IBM-3C. If so, we might discover a history of rear-arc tonalite intrusion, mineralization, exhumation, and submergence.

Drilling and coring strategy

Expedition 350 will begin with a 2 day effort at proposed Site IBM-4GT, coring a 150 m deep geotechnical test hole for potential future deep drilling (5500 mbsf) at proposed Site IBM-4 (Izu fore arc) using the riser D/V *Chikyu*. The Center for Deep Earth Exploration (CDEX) requires sediment property information at a site considered for a potential future deep drilling program. In particular, shear strength data are needed to design the top hole for riser installation. Preliminary data from ODP Site 792 (0–64 mbsf) indicate a formation strength that is weaker than those for other *Chikyu* riser expeditions (Nankai and Shimokita). Based on IBM proposal proponent and Expedition 350 co-chief support, IODP-Texas A&M University (TAMU) agreed to honor a request by CDEX to provide the geotechnical test cores at proposed Site IBM-4GT.

Following initiation of operations at proposed Site IBM-4GT, the operations strategy for Expedition 350 is to core and log through the Neogene to Oligocene–Eocene volcaniclastic sediment and rock sequences and, if possible, into the crystalline basement at one site in the IBM-3 rear arc area in the eastern half of the Izu-Bonin rear-arc seamount chains, ~90 km west of the Myojin-sho arc volcano (Figs. **F4, F5, F8, F9**). The IBM-3 sites are based on six intersecting low-fold MCS profiles obtained during JAMSTEC Cruises KY06-14 (December 2006) and KR07-09 (June and July 2007) (Figs. **F9, F10, F11, F12**). Proposed Site IBM-3C is the primary site and is located at 31°47.38′N, 139°01.58′E in 2114 m water depth. Three alternate proposed Sites IBM-3D, IBM-3E, and IBM-3F are specified a few kilometers northwest and west of primary proposed Site IBM-3C in case the latter proves unsuitable (mainly because of the proximity of a submarine cable). Objectives for the alternate proposed sites would be the same as those for the primary proposed site, and the stratigraphy is essentially the same.

Although many of the scientific objectives can be met by penetrating the Neogene seismic Layers L1–L4 (1200 mbsf; Table **T1**), we hope to reach the igneous basement. The transition of seismic velocity to >5 km/s is generally thought to represent the transition to igneous crystalline rocks. As shown in Table **T1** and Figure **F14,** the 5 km/s iso-velocity contour is estimated at 2080 mbsf at proposed Site IBM-3C based on the analysis of ocean bottom seismic (OBS) refraction data.

Expedition 350 will begin on 30 April 2014 with a 5 day port call in Keelung, Taiwan. The transit to the IBM-4 area will take 4.2 days. After completion of the geotechnical test hole at proposed Site IBM-4GT (1.4 days), the transit to the IBM-3 area will take 0.3 days. At the end of operations, the *JOIDES Resolution* will sail to Yokohama, Japan, which will take 0.9 days. This leaves ~50 days for onsite operations at Site IBM-3 (Table **T2**).

Our drilling and coring plan at proposed Site IBM-3C includes two scenarios: one without casing and one with casing. Both scenarios may reach a total depth of ~2100 mbsf if good to excellent hole conditions prevail; however, hole problems may limit the actual total depth reached. In both scenarios, we begin with a jet-in test to determine the length of 20 inch casing that can be deployed as a stinger to the reentry cone, taking <1 day (Hole A). Next, we use the advanced piston corer (APC) and extended core barrel (XCB) systems to core the soft to firm sediment at the top of the sequence. Based on ODP Leg 126 results, the expected APC/XCB penetration is ~200 m and will take ~1 day (Hole B). At this point, the drill pipe is recovered and the rotary core barrel (RCB) assembly is made up and deployed (Hole C).

In Scenario 1, RCB coring in Hole C is assumed to proceed without hole problems and reach total depth of 2300 mbsf in ~41 days. Coring will be followed by ~4 days of wireline logging.

In Scenario 2, coring in Hole C is terminated at 600–1200 mbsf after ~7 days because of hole conditions that warrant casing of the upper section. Wireline logging is conducted for ~2 days. Next, a reentry cone with a 20 inch casing stinger is deployed and jetted-in to begin Hole D. Hole D is then drilled (without coring) to somewhat less than the total depth of Hole C. Casing strings, 16 and 10¾ inch, are made up and deployed to depths determined by the logs of Hole C. RCB coring is then resumed to a total depth of 2100 mbsf, followed by ~3 days of wireline logging, for a total operational time in Hole D of ~34 days.

Downhole measurements strategy

Logging will play an important role in achieving the scientific objectives of Expedition 350. Previous drilling in similar environments, in particular during ODP Legs 125 and 126, has achieved only partial core recovery in some intervals, and logs will allow us to fill gaps in recovery. The gamma ray tool should clearly distinguish sediments derived from the proximal volcanic front (low K, U, Th, and Th/U) from the rear arc (opposite). The magnetic susceptibility sonde (MSS) will help identify and delineate volcaniclastic units. The Formation MicroScanner (FMS) electrical images will help characterize any structural deformation as well as the deposition sequences, in particular to delineate turbidites and their thickness and direction. A vertical seismic profile (VSP) will be acquired. Combined with synthetic seismograms generated from the density and velocity logs, the VSP will tie our results to the site survey data and calibrate the existing seismic stratigraphy models.

Three logging strings will be deployed. First, the traditional triple combination (triple combo) tool string (gamma ray, porosity, density, and resistivity) will be run with the MSS to provide full characterization of the formation and hole conditions. The FMS-sonic tool string will record compressional and shear velocity and capture high-resolution electrical images of the borehole. Finally, the Versatile Seismic Imager (VSI) will used to acquire the VSP. The VSI will be anchored to the side of the borehole at fixed intervals (20–50 m) to record the waveforms generated by a seismic source (a Sercel G-gun 250 in^3 parallel cluster) held ~7–11 m below sea surface. The order of deployment of the last two strings will depend on the requirement to limit the operation of the seismic source to daylight, in order to be able to monitor the presence of protected species and interrupt operations if necessary.

Main logging operations will take place after full completion of coring. Depending on drilling scenario (see **"Drilling and coring strategy"**) and based on the progress of coring and on the drilling conditions, it may be necessary to log the shallower units at an earlier stage of drilling, prior to deploying casing, or using a dedicated logging hole.

Risks and contingencies

Expected major risks

Borehole instability

The drill site is in the rear arc, which seems tectonically inactive as compared to the area from the subduction front to the back-arc rift; therefore, large differential horizontal stresses producing borehole breakouts are unlikely.

The formations to be drilled are mostly well stratified in seismic profiles and expected to consist of volcaniclastic sediment and hemipelagic mud from the Quaternary to the Pliocene downhole to 1196 mbsf. Below that depth, volcaniclastic and volcanic rocks of the Oligocene are expected downhole to total depth (2200–2400 mbsf). Similar formations have already been cored or drilled during previous ODP legs on the fore-arc side without significant borehole problems downhole to 1682 mbsf (ODP Site 793). As long as the hydrostatic pressure is balanced with the formation pore pressure, the borehole is expected to be stable beyond the previous deepest penetration depth.

No hydrocarbon occurrence is expected at the proposed rear-arc sites.

Submarine cables

Submarine cables exist in the vicinity of the proposed IBM-3 sites. Submarine cable companies generally recommend that any seafloor operation be kept clear of the cables by a safety distance three times that of the water depth. Given the water depth of 2114 m at proposed Site IBM-3C, that distance would be ~6.5 km. However, the actual distance of the nearest cable is ~3 km south of proposed Site IBM-3C. To mitigate the risk of damaging the submarine cable, a seafloor camera survey should be conducted prior to spud-in.

Mechanical failures and delay caused by metaocean conditions

Potentially rough sea conditions may cause operational delays not only caused by waiting-on-weather but also caused by mechanical problems in drilling and logging tools. The probability of a typhoon is highest during May and August to October (up to 2 per month), and November to March and June are months of relatively frequent rough sea conditions. If the Kuroshio Current passes the drill site, an event that has occurred five times since 1967, vortex-induced vibration may affect the drill string and cause mechanical failures to drilling equipment and logging tools.

Contingency plan

If the primary proposed Site IBM-3C presents unexpected challenges, operations will be carried out at one of the alternate proposed Sites IBM-3D, IBM-3E, or IBM-3F to the northwest and west of proposed Site IBM-3C.

Sampling and data sharing strategies

Every member of the science party is obligated to carry out scientific research for the expedition and publish that research. Shipboard and shore-based science party members must therefore submit sample requests detailing their science plan (**web.iodp.tamu.edu/sdrm/**). Shipboard and shore-based science party members should refer to the IODP Sample, Data, and Obligations Policy (**www.iodp.org/program-policies/**). This document outlines the policy for distributing IODP samples and data. It also defines the obligations incurred by sample and data recipients. Any policy changes that may occur with the beginning of the International Ocean Discovery Program in October 2013 will be distributed to the Shipboard Scientific Party and interested shore-based scientists as soon as possible.

All requests for core samples and data must be approved by the Sample Allocation Committee (SAC). The SAC is composed of the Co-Chief Scientists, Expedition Project Manager, and IODP Curator on shore and curatorial representative in place of the Curator onboard the ship.

The sample and data request submission deadline for shipboard scientists is 30 November 2013. Shore-based scientists are not necessarily identified or informed at that time and may submit requests any time before or during the expedition. The earlier shore-based requesters submit their proposals, the better their chances to be integrated into the shipboard sampling plan. Shipboard requests have priority over shore-based requests if conflicts cannot be resolved through collaboration.

Based on sample requests submitted by 30 November and additional input from the scientific party as necessary, the SAC will prepare a tentative precruise sampling plan consistent with expedition objectives. The tentative plan will be subject to modification during the expedition depending upon the actual material recovered and collaborations that may evolve between scientists during the expedition. This planning process is necessary to coordinate the research to be conducted and to ensure that the scientific objectives are achieved.

All sample frequencies and sizes must be justified scientifically and address expedition objectives. Approval will depend on the full spectrum of other requests and final sample yield will depend on core recovery. Some redundancy of measurements among participants is unavoidable, but minimizing the duplication of measurements among the shipboard party and identified shore-based collaborators will be a factor in evaluating sample requests. Success will require collaboration, integration of complementary data sets, and consistent methods of analysis. The science party will also identify potential gaps in the overall research plan and seek shore-based collaborators if necessary. All shipboard scientists are expected to collaborate and cooperate within the framework of this plan.

Shipboard subsampling of cores will include samples for shipboard analysis and samples for postcruise studies. Whole-round samples may be taken for shipboard and shore-based pore fluid chemistry, physical property, and possibly microbiological experiments. Our intent is to take all subsamples needed by investigators for their first 2 y of postcruise studies on the ship (as opposed to holding a dedicated postcruise sampling party).

The SAC reserves the right to pause or defer sampling if critical intervals are recovered, or recovery drops to a critical level, so as not to yield sufficient material to meet the demands of the existing sampling plan. Critical intervals or very low recovery may require special handling, a higher sampling density, reduced sample size, or continuous core sampling for the highest priority research objectives. The SAC may require an additional formal sampling plan before such intervals to maximize scientific participation and to preserve some material for future studies.

Following Expedition 350, cores will be delivered to the IODP Kochi Core Center (KCC) in Kochi, Japan. All collected data and samples will be protected by a 1 y moratorium period following the completion of the expedition, during which time data and samples are available only to the Expedition 350 science party and approved shore-based participants. A limited number of samples may be taken on shore by core repository staff during the moratorium, if approved by the SAC.

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Table T1. Seismic layers and iso-velocity depths at Site IBM-3C.

Seismic layer	Age (Ma)	Two-way traveltime (s)	Assumed sonic velocity (km/s)	Depth (mbsf)	Thickness (m)	Description	Iso-velocity pick from OBS (km/s)	Depth (mbsf)
L1	0–1	2.83–2.87	1.59	0–32	32	Silicic volcaniclastic channel deposits from Myojin Knoll		
L2	1–3	2.87–3.17	1.85	32–309	277	Biomodal volcaniclastics from the back-arc extensional zone to the east		
L3	3–6.5	3.17–3.58	2.28	309–777	467	Manji and Enpo rear-arc volcaniclastic record		
							2.0	560
L4	6.5–9	3.58–3.90	2.62	777–1196	419	Same as Layer L3, but more faulted?		
L5	25–35	3.90–5.41	4.26	1196–4412	3216	Oligocene to Eocene arc volcaniclastics (and lavas?)	3.0	1400
							4.0	1700
							5.0	2100
						Crystalline basement?		
							6.0	4900

Table T2. Operations plan for proposed sites, Expedition 350.

Site	Location	Seafloor depth (mbrf)	Operations description	Port and transit (days)	Drilling and coring (days)	Logging (days)	Subtotal (days)
			Keelung, Taiwan, port call	5.0			5.0
			Transit ~1000 nmi to IBM-4 @ 10.5 kt	4.2			4.2
IBM4-GT	32°23.89′N	1799	Hole A - APC core to 150 mbsf		1.4	0	
	140°21.93′E						1.4
			Transit ~77 nmi to IBM-3C @ 10.5 kt	0.3			0.3
IBM-3 Scenario 1: no casing (other than reentry cone stinger)							
IBM-3C	31°47.39′N	2125	Hole A - Trip in, SLM and rabbit tubulars, perform jet-in test		0.7		
	139°1.58′E		Hole B - APC/XCB core to 200 mbsf		1.2		
			Hole C - RCB core to 2250 mbsf; one logging run at end of expedition		41.1	3.6	
			Scenario 1 subtotal:				46.6
IBM-3 Scenario 2: casing from top of hole to 900 mbsf (600–1200 mbsf casing depths vary little in time)							
IBM-3C	31°47.39′N	2125	Hole A - Trip in, SLM and rabbit tubulars, perform jet-in test		0.7		
	139°1.58′E		Hole B - APC/XCB core to 200 mbsf		1.2		
			Hole C - RCB to ~1200 mbsf; establish casing set points; log		7.9	1.9	
			Hole D - reentry hole with triple string of casing;		12.9		
			RCB core 900–2100 mbsf		20.8	2.7	
			Scenario 2 subtotal:				48.1
			Transit ~222 nmi to Yokohama, Japan, at 10.5 kt	0.9			0.9
			Expedition total for Scenario 1 (days):				58.4
			Expedition total for Scenario 2 (days):				59.9

APC = advanced piston corer, SLM = steel-line measurement, XCB = extended core barrel, RCB = rotary core barrel

Figure F1. 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 are active in the Mariana Trough (7–0 Ma) and relict in the Shikoku and Parece Vela Basins (30–15 Ma) and West Philippine Basin (50–35 Ma). The Ogasawara and Amami Plateaus and 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. Black dashed lines = locations of wide-angle seismic profiles (1) along the present-day volcanic front (Kodaira et al., 2007b), (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 = proposed drill sites. Basalt-dominant Quaternary volcanoes on the volcanic front: Mi = Miyakejima, Ha = Hachijojima, Ao = Aogashima, Su = Sumisu, To = Torishima; andesite Oligocene volcano east of the front: Om = Omachi Seamount. Numbered circles = sites drilled during Ocean Drilling Program Legs 125 and 126. The 6.0–6.3, 7.1–7.3, and 7.8 km/s layers correspond to parts of middle crust, lower crust, and upper mantle, respectively.

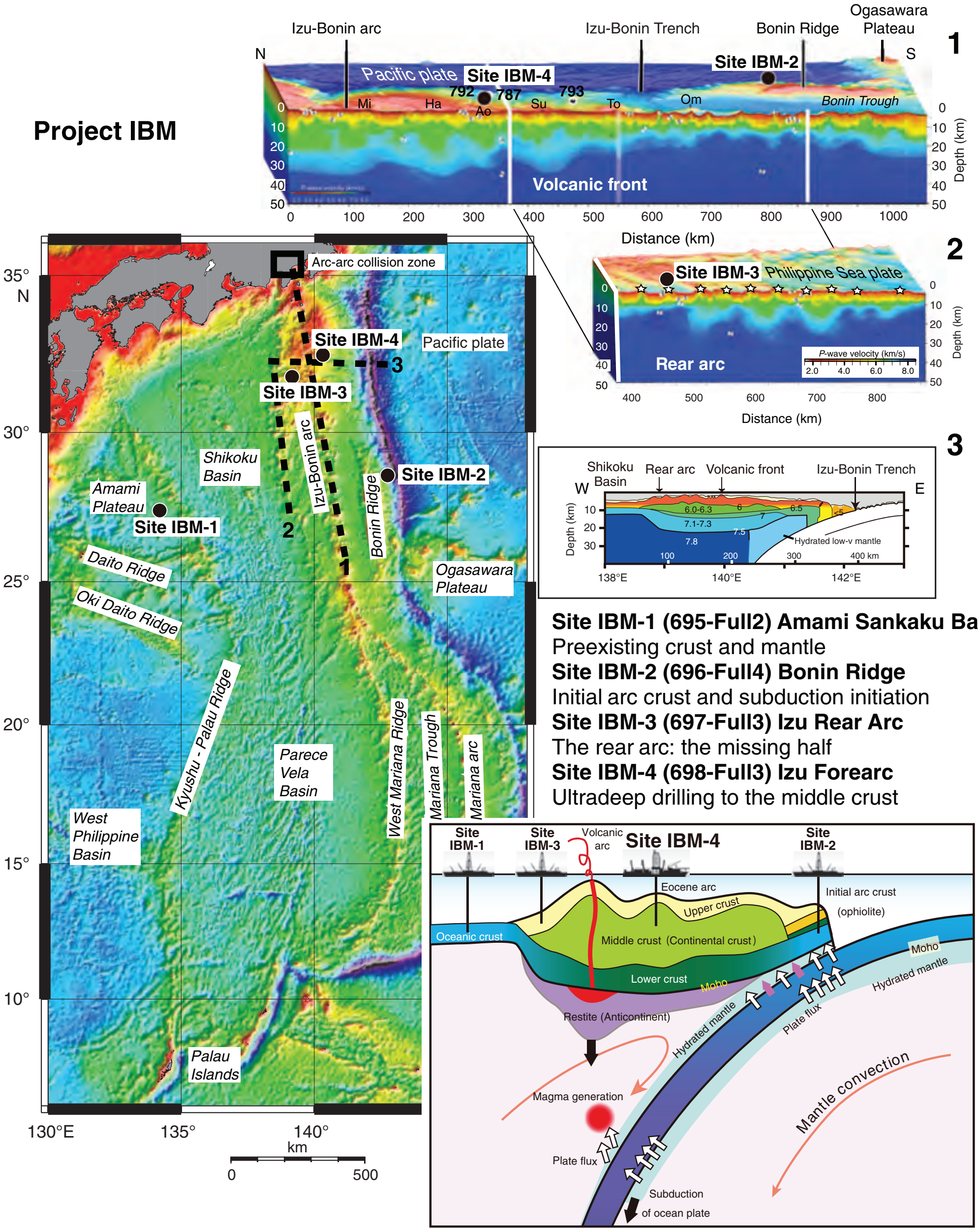


Figure F2. Izu-Bonin arc seismic stratigraphy (*P*-wave velocity; km/s) after Suyehiro et al. (1996). Red bar = proposed Site IBM-3C. Black bars = previous sites (Ocean Drilling Program Sites 786, 791, 792, and 793).

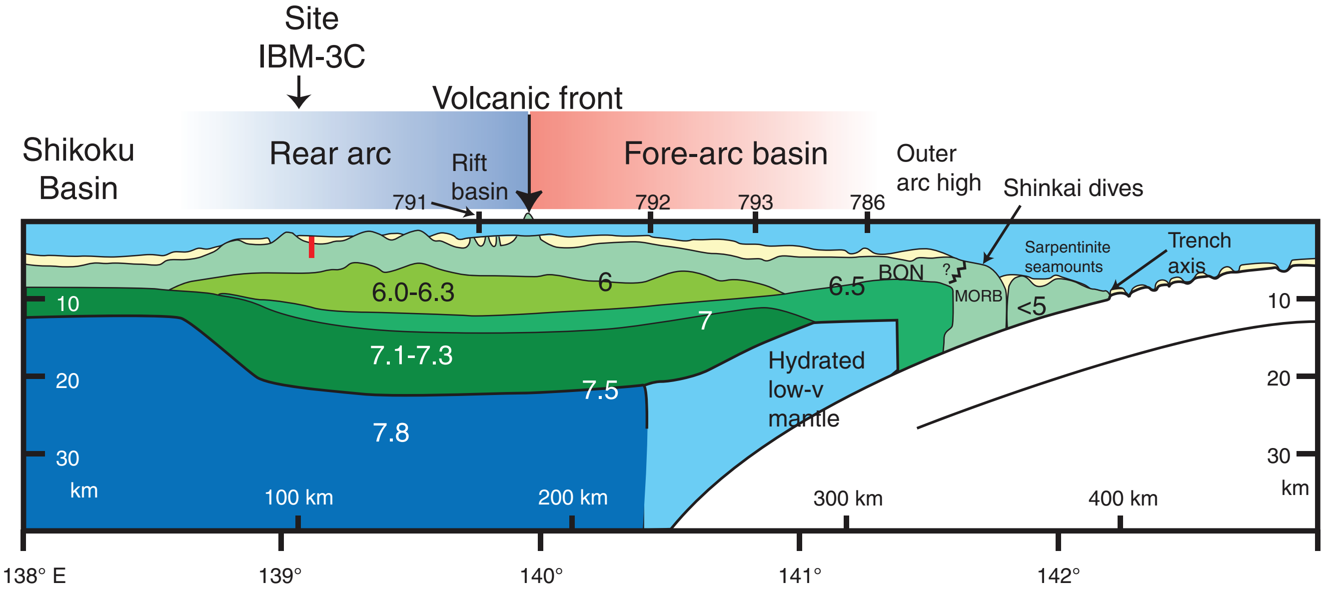


Figure F3. Model for the tectonic evolution of the Philippine Sea region, after Hall (2002). NNP = North New Guinea plate, PHS = Philippine Sea plate, PAC = Pacific plate, IBM = Izu-Bonin-Mariana arc, KPR = Kyushu-Palau Ridge. Yellow stars = paleo- and present positions of proposed Site IBM-3C. Red and yellow stars = Eocene–Oligocene crust, which formed an across-arc section until 25 Ma.

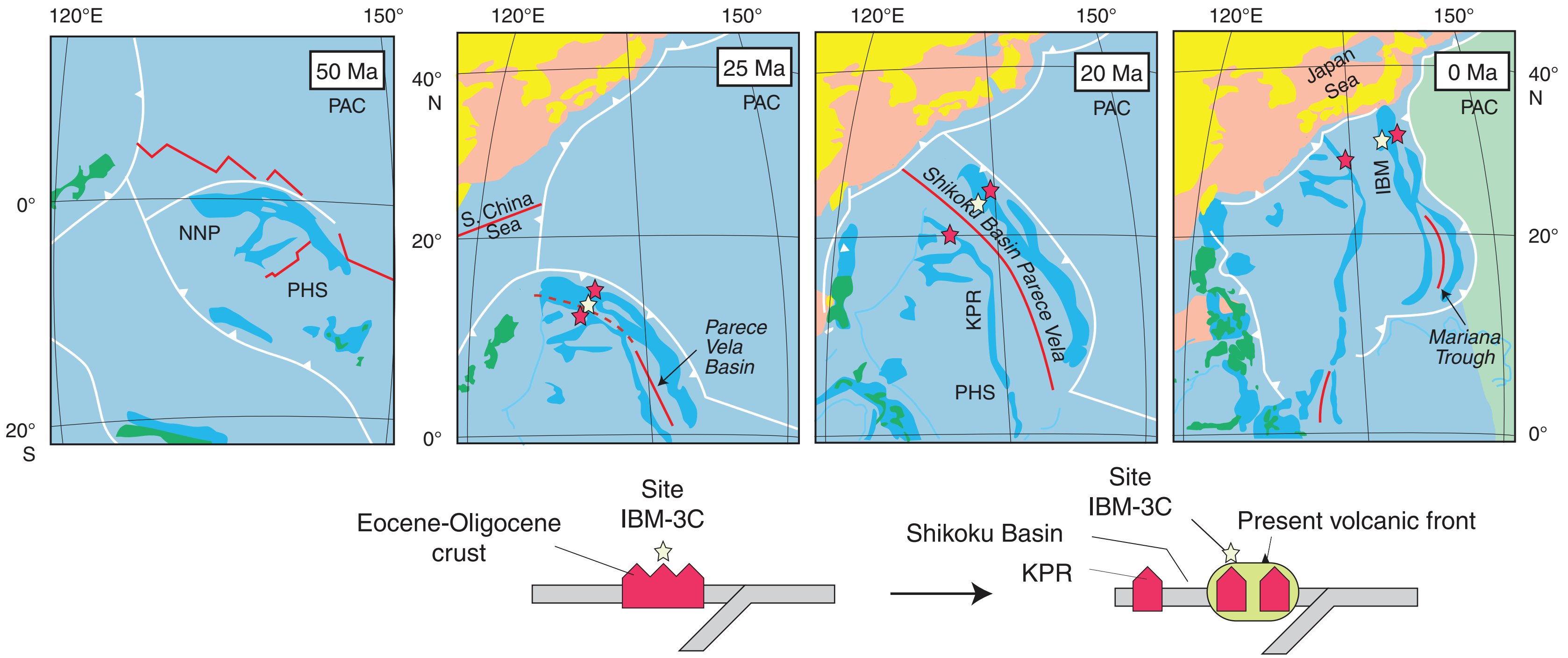


Figure F4. Location map of the northern Izu-Bonin-Mariana (IBM) arc system. White star = primary proposed Site IBM-3C. Four tectonic settings of magmatism are referenced during this project: the volcanic front, which includes the named volcanoes; active rifts, which are located just behind and between the volcanic front volcanoes; a 100 km wide extensional zone that extends westward from the active rifts; and rear-arc seamount chains including Enpo and Manji that start in the Shikoku (back arc) Basin west of the arc and continue into the extensional zone. We refer to magmatism in the active rifts and extensional zone as "rift-type" and magmatism in the rear-arc seamount chains as "rear-arc type."

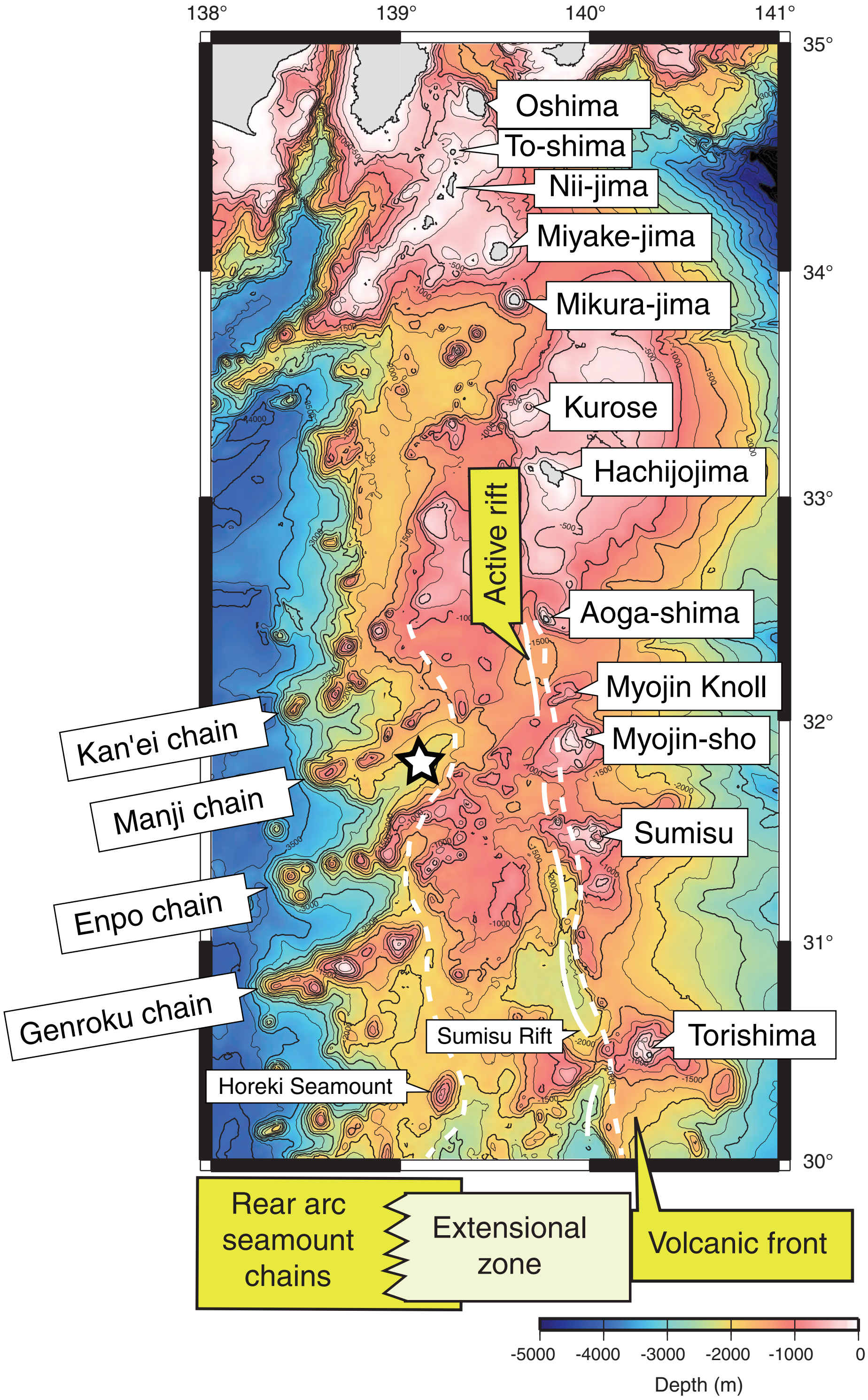


Figure F5. Temporal variation of locations of volcanism in the Izu-Bonin arc (left) and location vs. ^{40}Ar/^{39}Ar age plot for the rear-arc volcanics (upper right) (after Ishizuka et al., 2003b). Ocean Drilling Program Sites 786 and 792 were drilled ~1000 m through volcaniclastic sediment into Eocene basement. Red dots in <1–3 Ma boxes = samples with "rift-type" compositions; red dots in 3–17 Ma boxes = samples with "rear-arc type" compositions (shown in Fig. F6). Dating of dredged lavas provides only a minimum age for the edifice and cannot constrain relative eruption rates, which can be estimated from sedimentation rates. The data from Enpo chain (red outline in right map) just south of the proposed drill site are shown in the geochemical figures with other rear-arc chains to show the essential differences between the volcanic front, rift-type, and rear-arc type magma compositions. Yellow stars = proposed drill sites. L1–L5 = seismic layers summarized in Table T1 and described in detail in text.

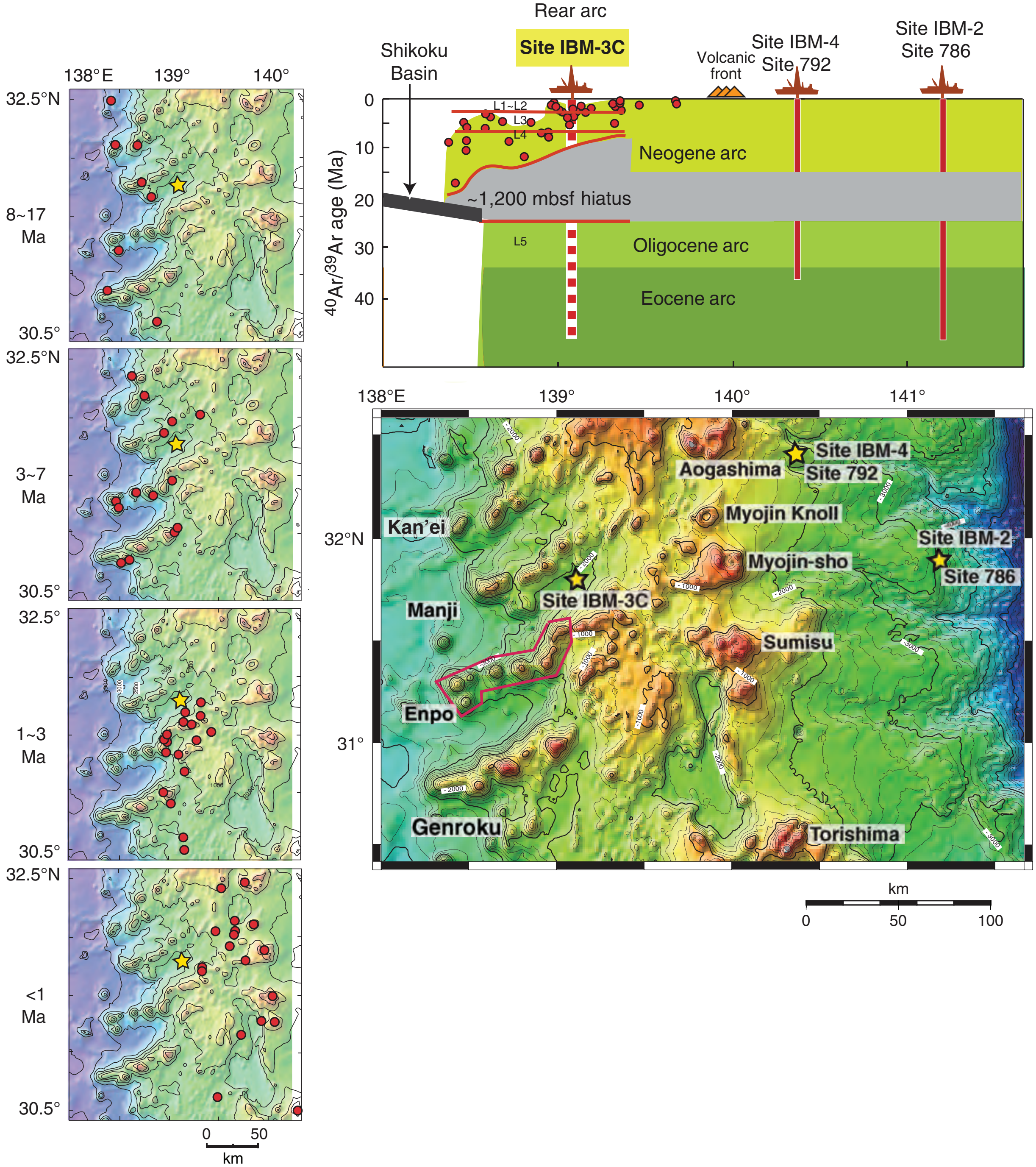


Figure F6. **A.** K_2O vs. SiO_2 of lavas of the volcanic front (Oshima, Miyake-jima, Mikura-jima, Hachijojima, Aoga-shima, Myojin Knoll, Sumisu, and Torishima), the rear arc (Kan'ei, Manji, Enpo, Genroku, and Horeki), and average continental crust (Rudnick and Gao, 2004). Data from Tamura and Tatsumi (2002) and references therein, Machida and Ishii (2003), Tamura et al. (2005, 2007), and Machida (unpubl. data). Data for the Enpo chain are similar to other rear-arc type magmas. No data are shown for rift-type magmas (<3 Ma) for reasons of clarity. **B.** Chondrite-normalized rare earth element (REE) abundances in the volcanic front and the rear-arc basalts and andesites and average continental crust (Rudnick and Gao, 2004). Volcanic front (Oshima, Miyake-jima, Hachijojima, Aoga-shima, Sumisu, and Torishima) data from Taylor and Nesbitt (1998) and Tamura et al. (2005, 2007). Rear-arc (Kan'ei, Manji, Enpo, Genroku, and Horeki) data from Ishizuka et al. (2003b), Hochstaedter et al. (2001), Machida and Ishii (2003), and Ishizuka (unpubl. data). Data for the Enpo chain similar to other rear-arc type magmas. Rear-arc patterns are similar to average continental crust in heavy REE.

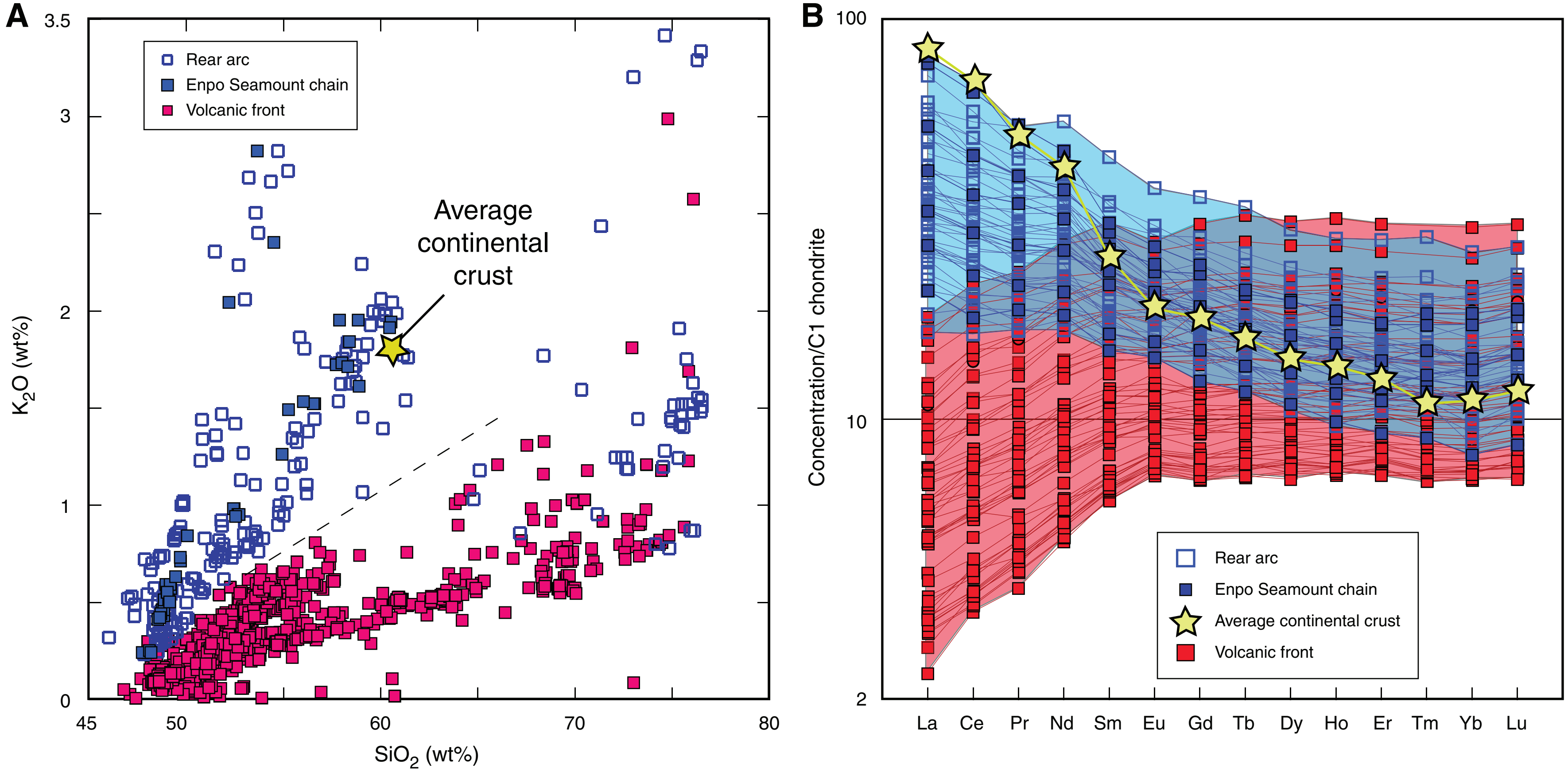


Figure F7. "Hot fingers" hypothesis of Tamura et al. (2002), proposed for northeast Japan, showing diapirs in the mantle wedge above the rear arc, extending toward the arc front with time.

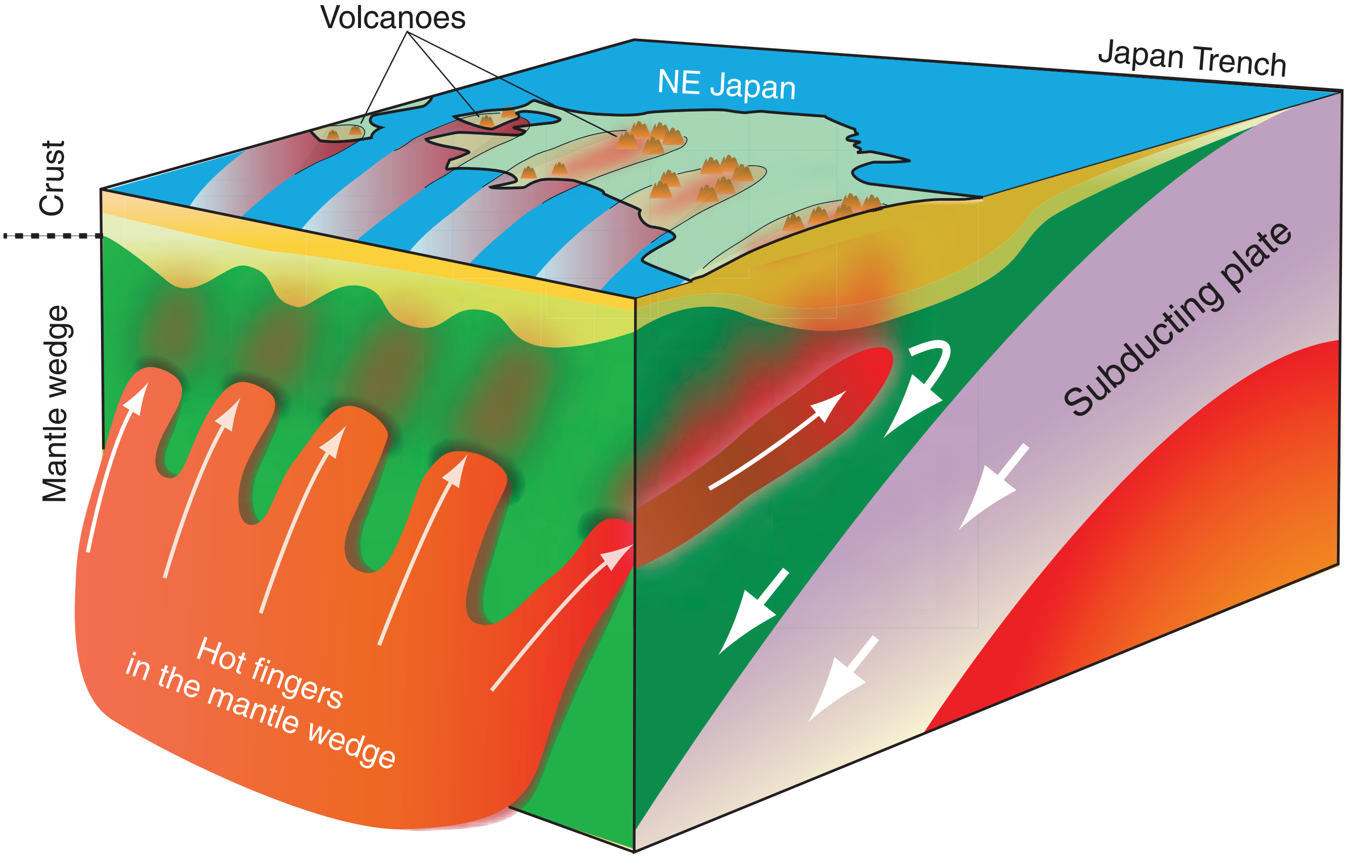


Figure F8. **A.** Multichannel seismic Profile IBr5 (unpubl. dada, JAMSTEC, 2007), uninterpreted time section. Common depth point (CDP) interval = 12.5 m. Vertical exaggeration = ~10. **B.** Locations of multichannel seismic reflection (MCS) data.

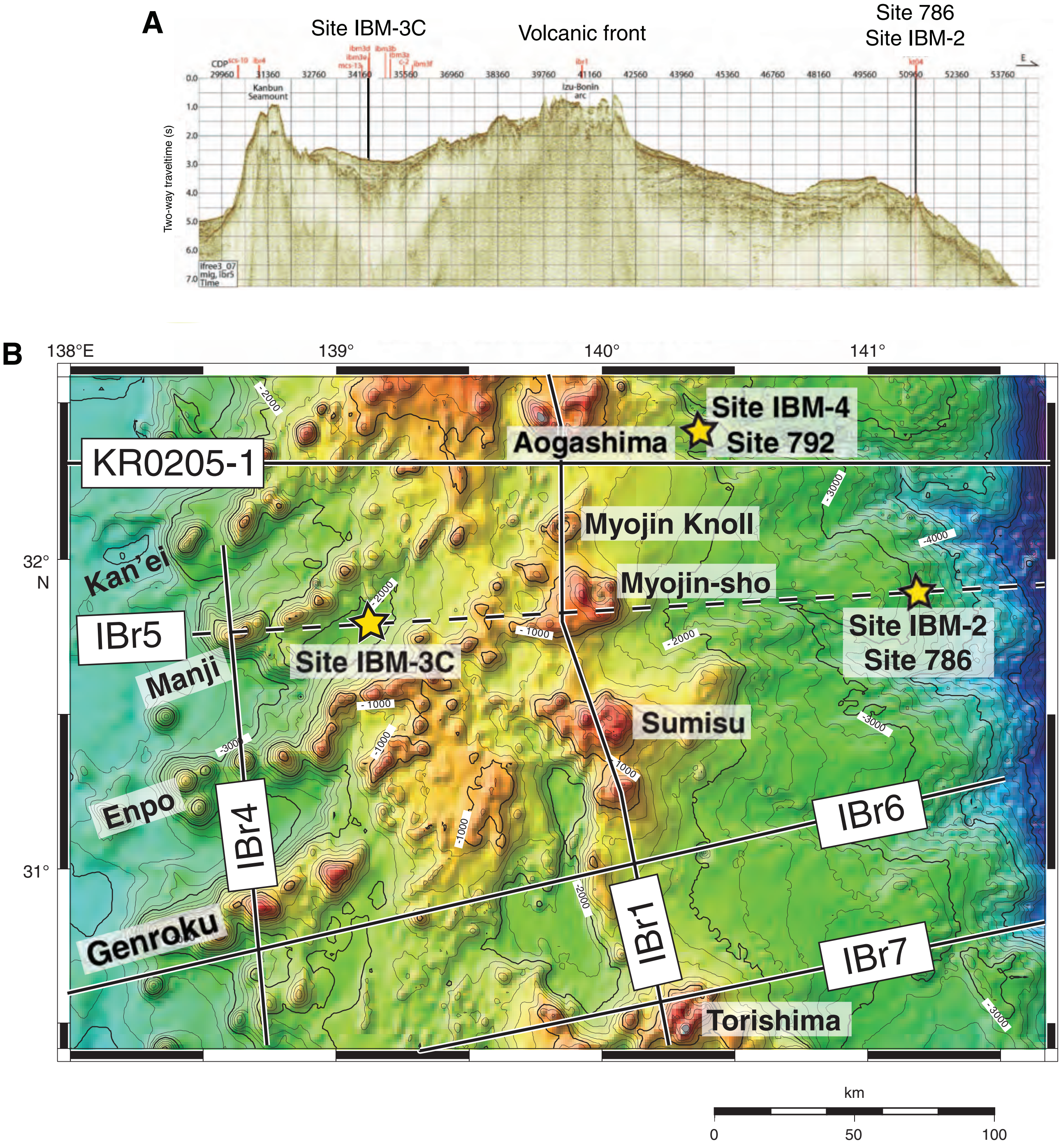


Figure F9. A. Locations of the six multichannel seismic profiles near proposed Site IBM-3C. The intersection of d–d′ with e–e′ is thought to be the best site for drilling. **B.** Ar-Ar and K-Ar ages (Ma) of dredged samples near proposed Site IBM-3C (Ishizuka et al., 2003b). Rear-arc seamounts northeast–west of the drilling area are older than the seamounts on the southwest–east side, and thus the drilling point is chosen as the intersecting point closest to the older volcanoes, having lower heat flow and cooler temperatures.

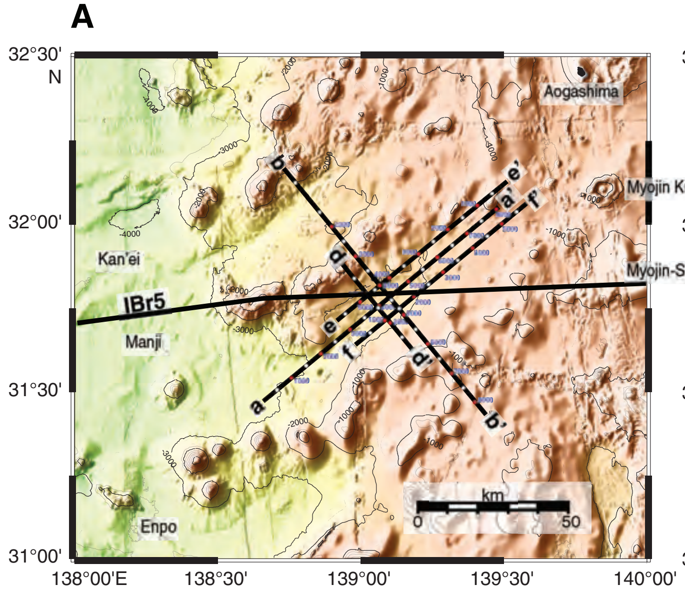


Figure F10. Seismic profile Line IBM3d. CDP = common depth point. **A.** Uninterpreted data. **B.** Interpretation of expanded profile around proposed Site IBM-3C. Pink, red, green, and blue lines = boundaries between seismic Layers L1–L5. Black dotted lines = faults. Black solid lines = the edge of the seamounts around proposed Site IBM-3C.

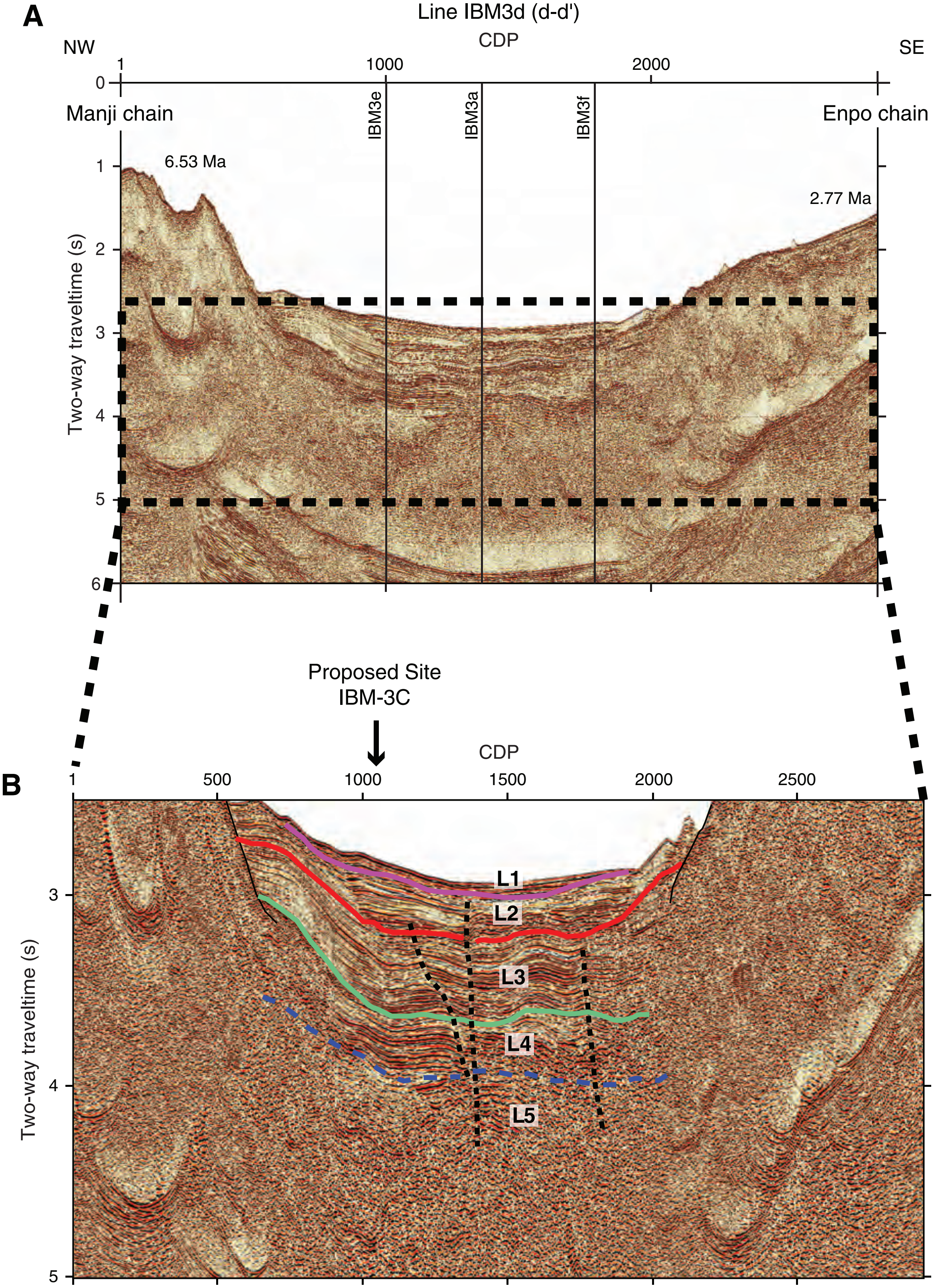


Figure F11. Seismic profile Line IBr5 with interpretation. An eastward-dipping reflector (X) is recognized beneath seismic Layer L5 and is also observed at Line IBr4 (Kodaira, pers. comm., 2013). This might be the contact with Eocene basement lavas. We estimate the depth of the reflector to be 3100 mbsf. CDP = common depth point. Pink, red, green, and blue lines = boundaries between seismic Layers L1–L5. Black dotted lines = faults.

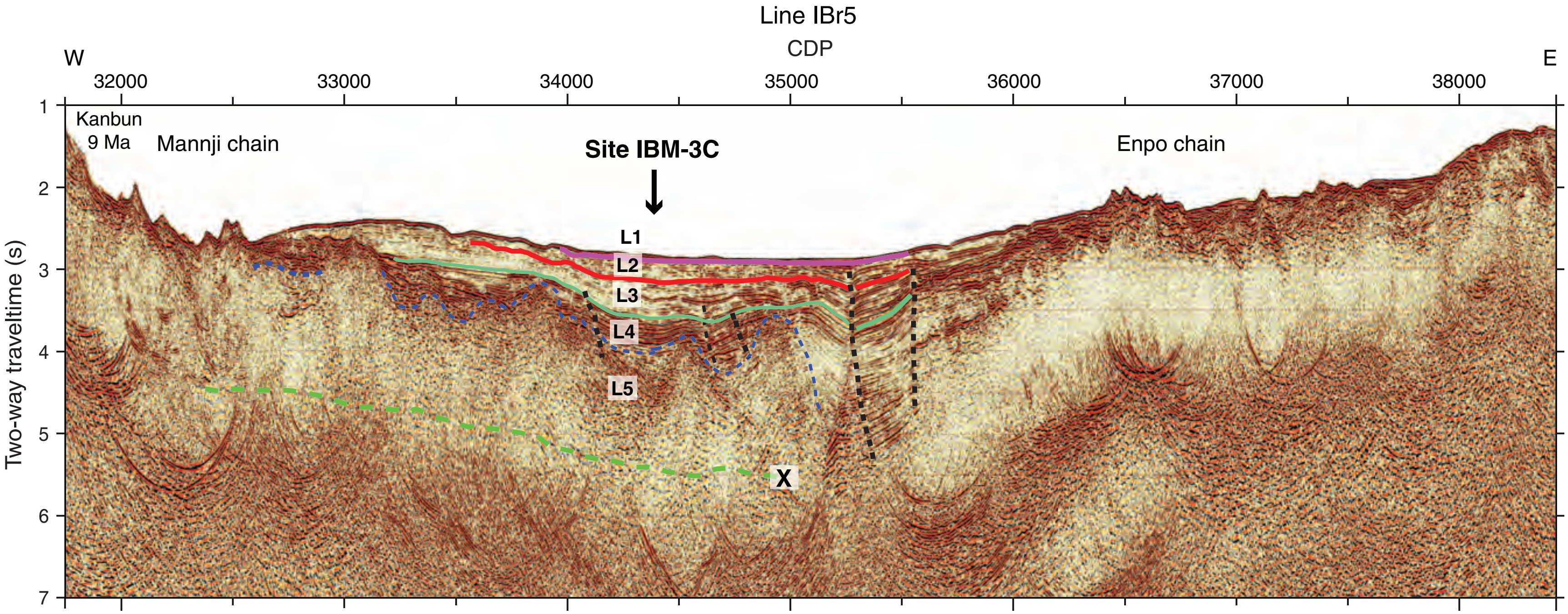


Figure F12. Seismic profile Inline IBM3e. CDP = common depth point. **A.** Uninterpreted data. **B.** Interpreted profile around Site IBM-3C. Pink, red, green, and blue lines = boundaries between seismic Layers L1–L5.

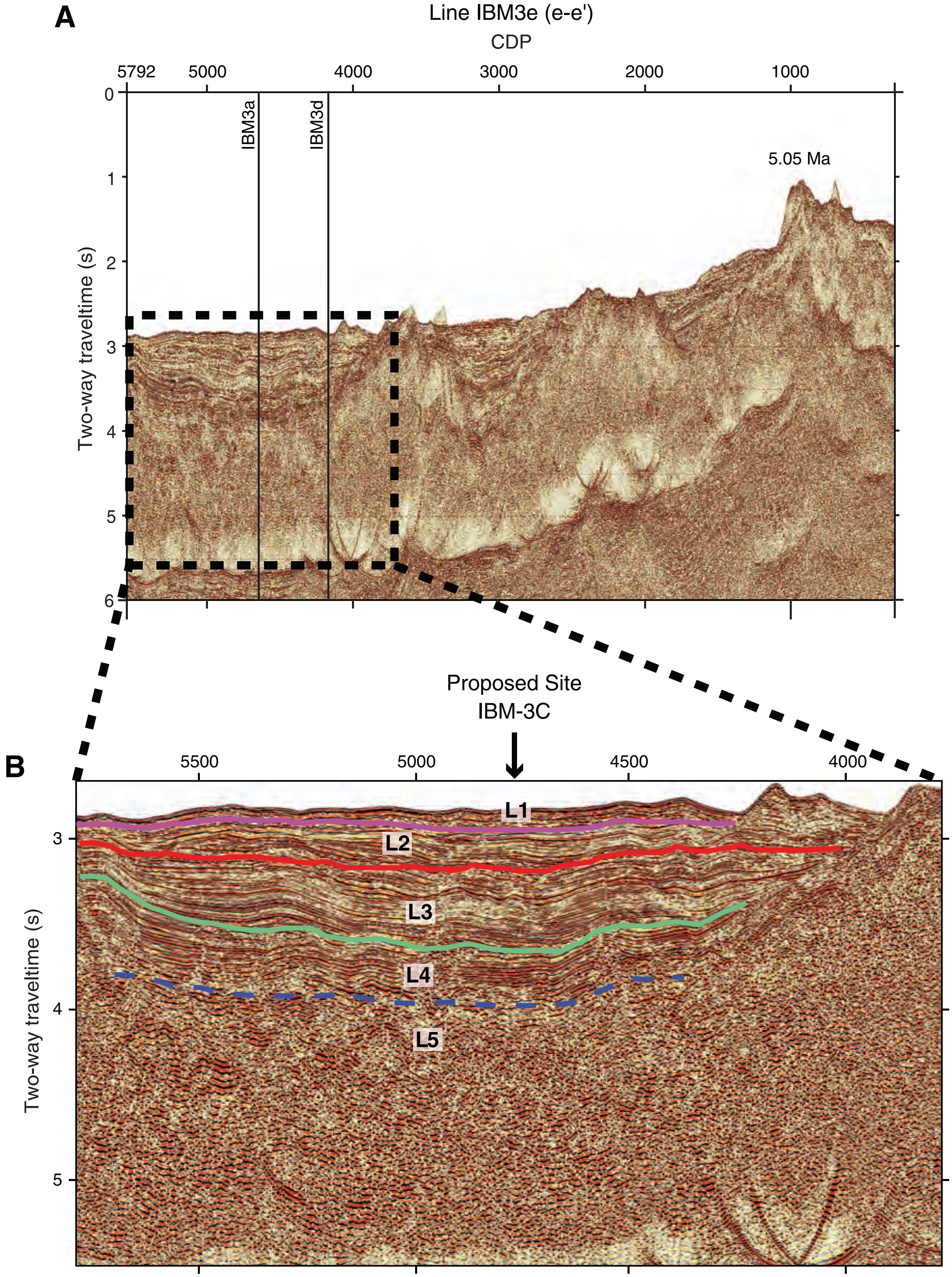


Figure F13. Seismic profile of cross point between Lines IBr5 and IBM-3d around proposed Site IBM-3C, looking toward the volcanic front. The Manji chain is to the left, and the Enpo chain to the right. Pink, red, green, and blue lines = boundaries between seismic Layers L1–L5. Black dotted line = fault.

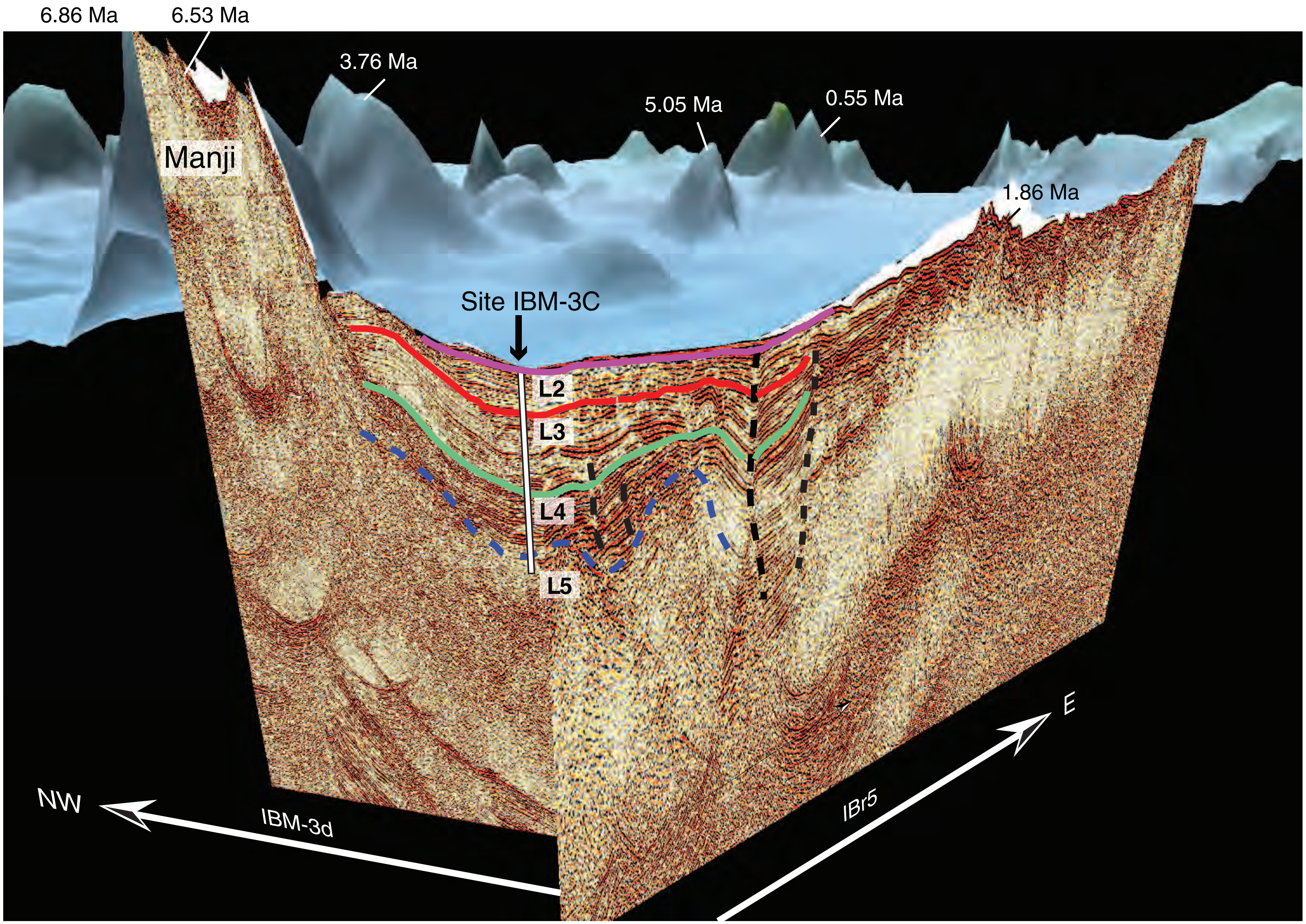


Figure F14. A. Seismic velocity image obtained from wide-angle ocean-bottom seismometer (OBS) data. OBSs are deployed every 5 km along Line IBr5. (Continued on next page.)

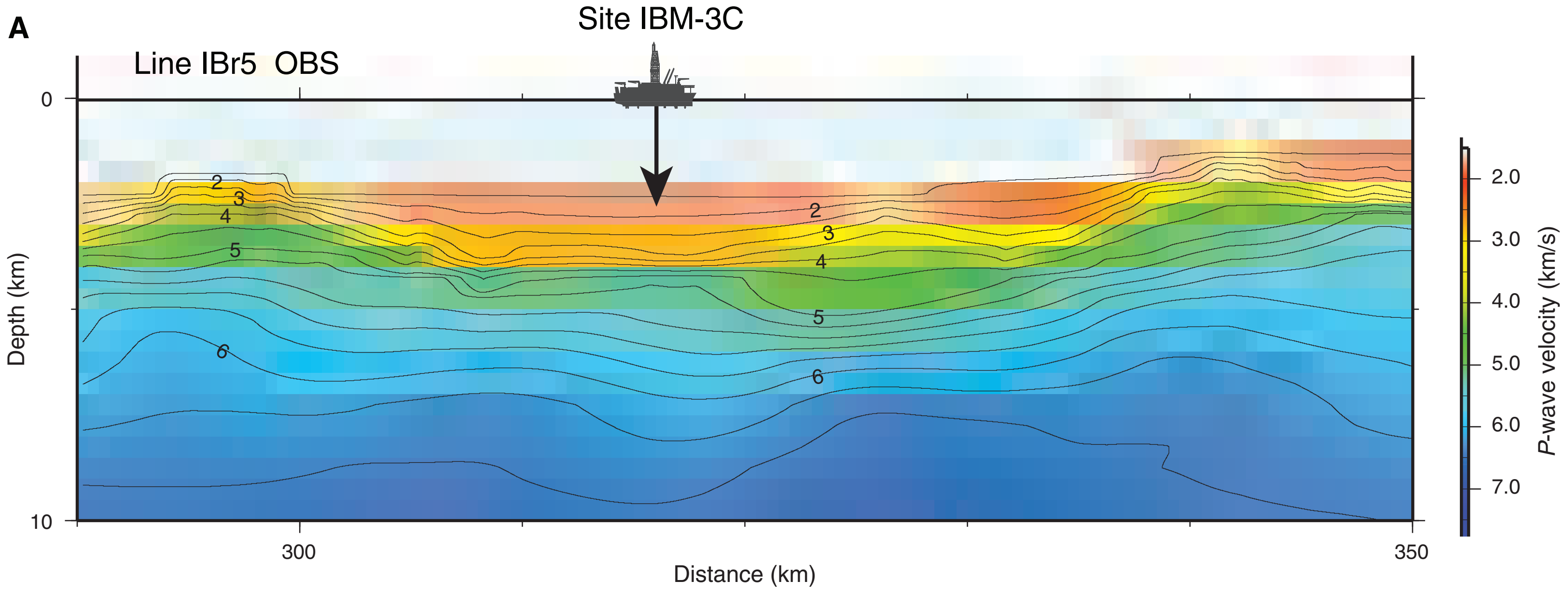


Figure F14 (continued). B. Depth-converted multichannel seismic (MCS) reflection profile along Line IBr5. Yellow lines = iso-velocity contours of 5 and 6 km/s obtained from the seismic velocity image in Figure **F14A,** which are interpreted as the depth to igneous basement (upper crust) and middle crust, respectively. (Continued on next page.)

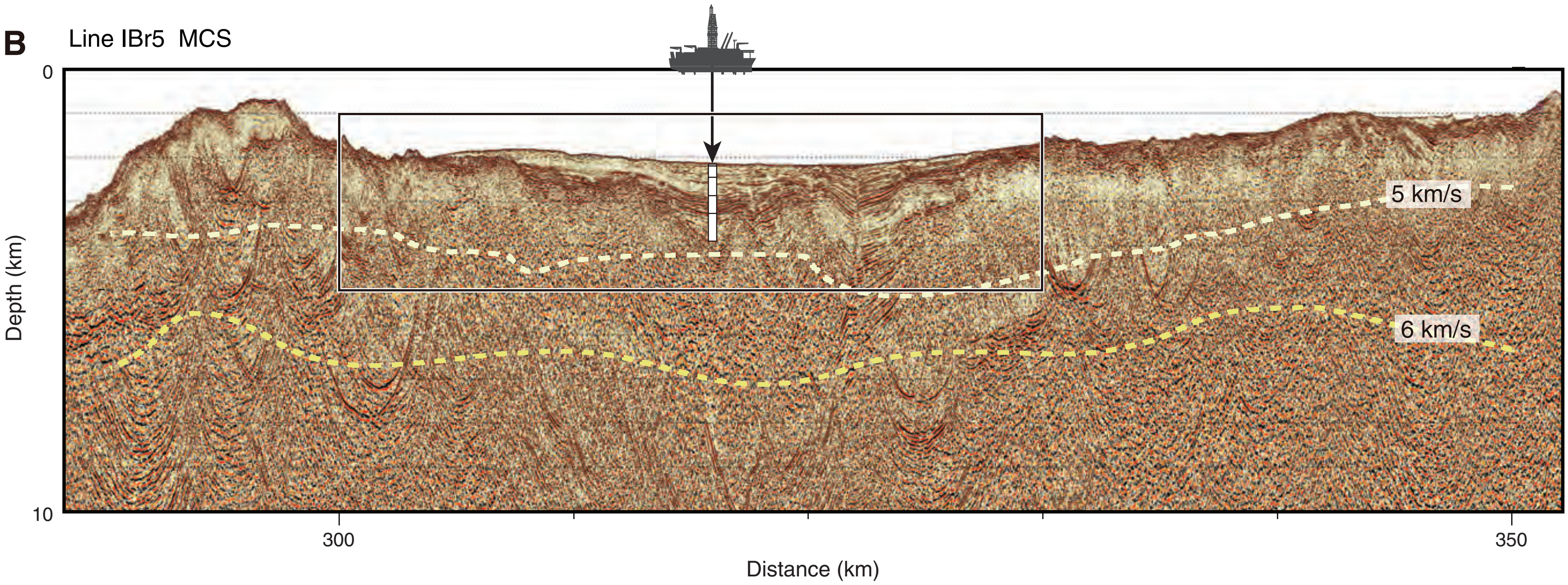


Figure F14 (continued). C. Lithologic interpretation of the seismic image.

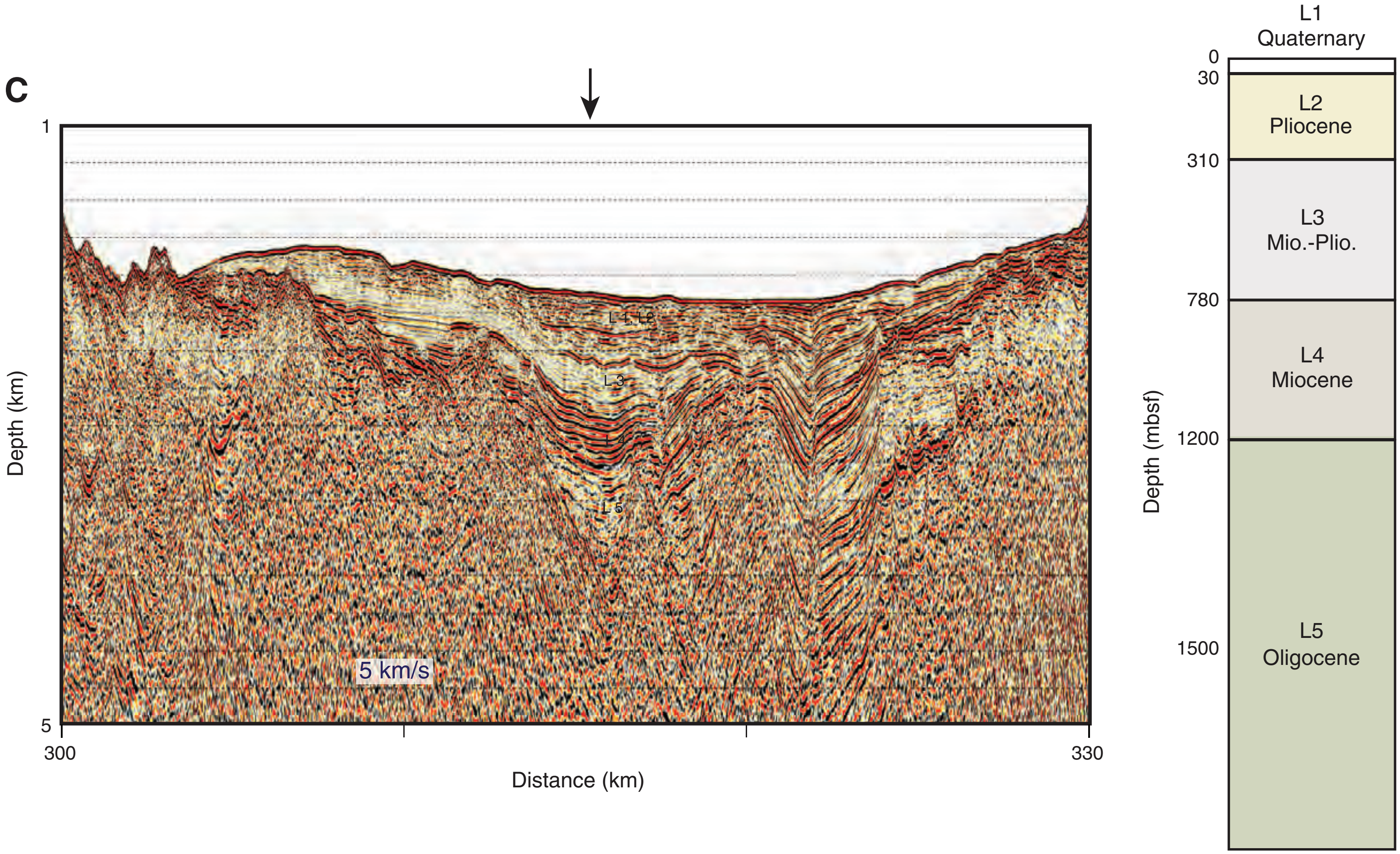
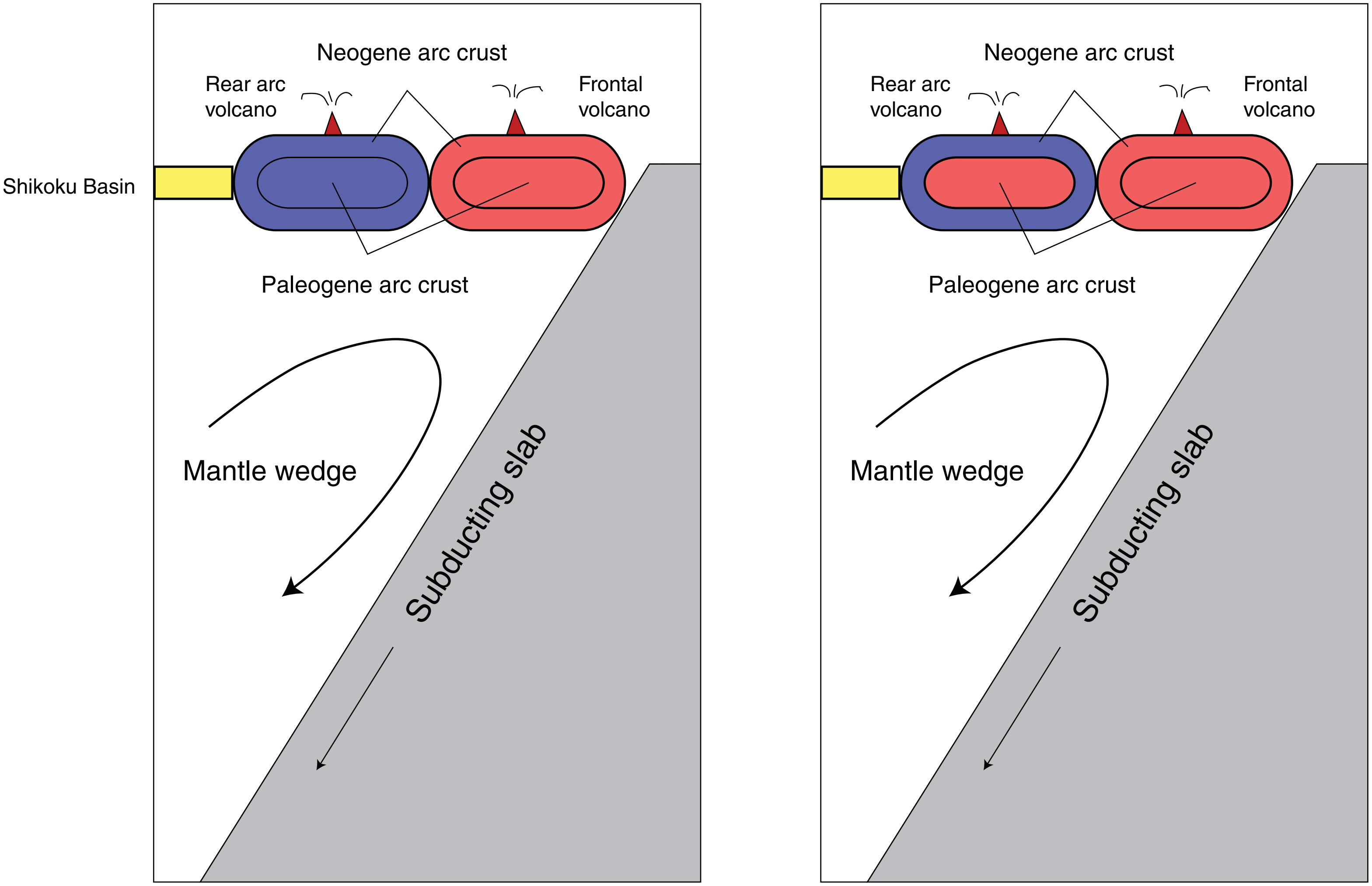


Figure F15. Crust develops that is "continental" in velocity structure and seismically similar beneath both the volcanic front and rear arc but is heterogeneous in chemical composition, schematically shown in blue and red. Red shows crust and mantle that are rich in fluid-mobile, recycled slab components but also strongly depleted in mantle-derived fluid-immobile elements. Blue shows those areas where the diminished slab signature and lower degrees of mantle melting create crust that is more typical of the present-day overall continent composition. The "from the beginning" hypothesis stipulates that this heterogeneity established from the Eocene arc inception through to the Neogene. The "from the middle" hypothesis stipulates that this heterogeneity only developed after the cessation of the Shikoku Basin (i.e., only in the Neogene).



"From the beginning" hypothesis

"From the middle" hypothesis

Site summaries

Site IBM-4GT

Priority:	Primary
Position:	32.39809°N, 140.36548°E (1.8 km from the nearest submarine cable.)
Water depth (m):	1776.6
Target drilling depth (mbsf):	150
Approved maximum penetration (mbsf):	Not yet approved
Survey coverage:	• Cruise KR08-09, Line IBM-EW5, CDP 8376, and Line IBM-NS5, CDP 8626 (Figs. **AF1, AF2, AF3, AF4**)
Objective(s):	CDEX requires sediment properties information for a potential future deep (5500 mbsf) drilling program at proposed Site IBM-4 with the *Chikyu.* In particular, shear strength data are needed to design the top hole for riser installation. Preliminary data from IODP Site 792 (0–64 mbsf) indicate a formation strength that is weaker than those for other riser expeditions (Nankai and Shimokita).
Coring program:	One hole will be drilled to 150 mbsf using the APC/XCB system. The APC will be used as far as possible, and at APC refusal depth the XCB will be used.
Wireline logging program:	None
Anticipated lithology:	Silty clay

Site summaries (continued)

Site IBM-3C

Priority:	Primary
Position:	31°47.3874′N, 139°01.5786′E
Water depth (m):	2114
Target drilling depth (mbsf):	2350
Approved maximum penetration (mbsf):	2100
Survey coverage:	• Cruise KR07-09, Line IBr5, CDP 34436 (Figs. F8, F9, F11, F13, F14) • Cruise KR08-04, Line IBM3-NE5, CDP 9383 (Figs. F9, F10, F13) • Cruise KR08-04, Line IBM3-NW5, CDP 8409 (Figs. F9, F12, AF5, AF6, AF7)
Objective(s):	The primary objective at proposed Site IBM-3C is to test three pairs of alternative hypotheses about crustal genesis and mantle evolution: 1. Geochemically asymmetric crust, which is most like "average continent" in the rear arc, is either (a) a fundamental trait of crust in oceanic arcs that is produced in the steady state throughout arc history from Paleogene inception or (b) a secondary trait that develops only after backarc spreading. 2. Intracrustal differentiation amplifies this asymmetry (a) continuously as a steady state process or (b) mostly during nonsteady state events such as arc rifting. 3. After or near the cessation of the Shikoku back-arc basin opening, rear-arc magmatism either (a) started from the western end of the rear-arc seamount chains and migrated east or (b) started at the same time along the length of the rear-arc seamount chains but ended from west to east. Testing these hypotheses requires obtaining a temporal record of across-arc variation in magma composition from Eocene to Neogene time. This information is in hand for the volcanic front but missing for the rear arc, which overlies the majority of "continent-type" crust. Specifically, our objectives are to establish the temporal history of across-arc variations during five time periods that stand out in the rear-arc evolution: 3 Ma to present, 9–3 Ma, 17–9 Ma, 25–17 Ma, and >25 Ma. We will determine whether there were across-arc variations even at the initial stage of arc development.
Coring program:	APC/XCB and RCB coring; casing as necessary
Wireline logging program:	Standard downhole logging in one or two phases, depending on hole conditions and need for casing
Anticipated lithology:	Volcaniclastic sediment and rock, perhaps with lava, perhaps crystalline igneous rock near bottom of hole

Site summaries (continued)

Site IBM-3D

Priority:	Alternate
Position:	31°48.12282′N, 139°0.82986′E
Water depth (m):	2080.2
Target drilling depth (mbsf):	2350
Approved maximum penetration (mbsf):	2100
Survey coverage:	• Cruise KR08-04, Line IBM3-NE4, CDP 7567 (Figs. **F9, F10, F13**) • Cruise KR08-04, Line IBM3-NW4, CDP 2526 (Figs. **F9, F12, AF5, AF6, AF7**)
Objective(s):	Same as for proposed Site IBM-3C
Coring program:	APC/XCB and RCB coring; casing as necessary
Wireline logging program:	Standard downhole logging in one or two phases, depending on hole conditions and need for casing
Anticipated lithology:	Volcaniclastic sediment and rock, perhaps with lava, perhaps crystalline igneous rock near bottom of hole

Site summaries (continued)

Site IBM-3E

Priority:	Alternate
Position:	31°47.48946′N, 138°59.89668′E
Water depth (m):	2071.6
Target drilling depth (mbsf):	2350
Approved maximum penetration (mbsf):	2100
Survey coverage:	• Cruise KR08-04, Line IBM3-NE4, CDP 7567 (Figs. **F9, F10, F13**) • Cruise KR08-04, Line IBM3-NW4, CDP 2526 (Figs. **F9, F12, AF5, AF6, AF7**)
Objective(s):	Same as for proposed Site IBM-3C
Coring program:	APC/XCB and RCB coring; casing as necessary
Wireline logging program:	Standard downhole logging in one or two phases, depending on hole conditions and need for casing
Anticipated lithology:	Volcaniclastic sediment and rock, perhaps with lava, perhaps crystalline igneous rock near bottom of hole

Site summaries (continued)

Site IBM-3F

Priority:	Alternate
Position:	31°48.445′N, 138°59.03′E
Water depth (m):	1991.5
Target drilling depth (mbsf):	2100
Approved maximum penetration (mbsf):	2100
Survey coverage:	• Cruise KR08-04, Line IBM3-NW4, CDP 2170 (Figs. **AF8**) • Cruise KR08-04, Line IBM3-NE3, CDP 4000 (Figs. **AF9**)
Objective(s):	Same as for proposed Site IBM-3C
Coring program:	APC/XCB and RCB coring; casing as necessary
Wireline logging program:	Standard downhole logging in one or two phases, depending on hole conditions and need for casing
Anticipated lithology:	Volcaniclastic sediment and rock, perhaps with lava, perhaps crystalline igneous rock near bottom of hole

Figure AF1. Bathymetry with location of proposed Site IBM-4GT (red star). Blue multichannel seismic (MCS) Lines IBM4-NS5 and IBM4-EW5 were obtained during Cruise KR08-09 in 2008. Black MCS lines were also acquired during this cruise.

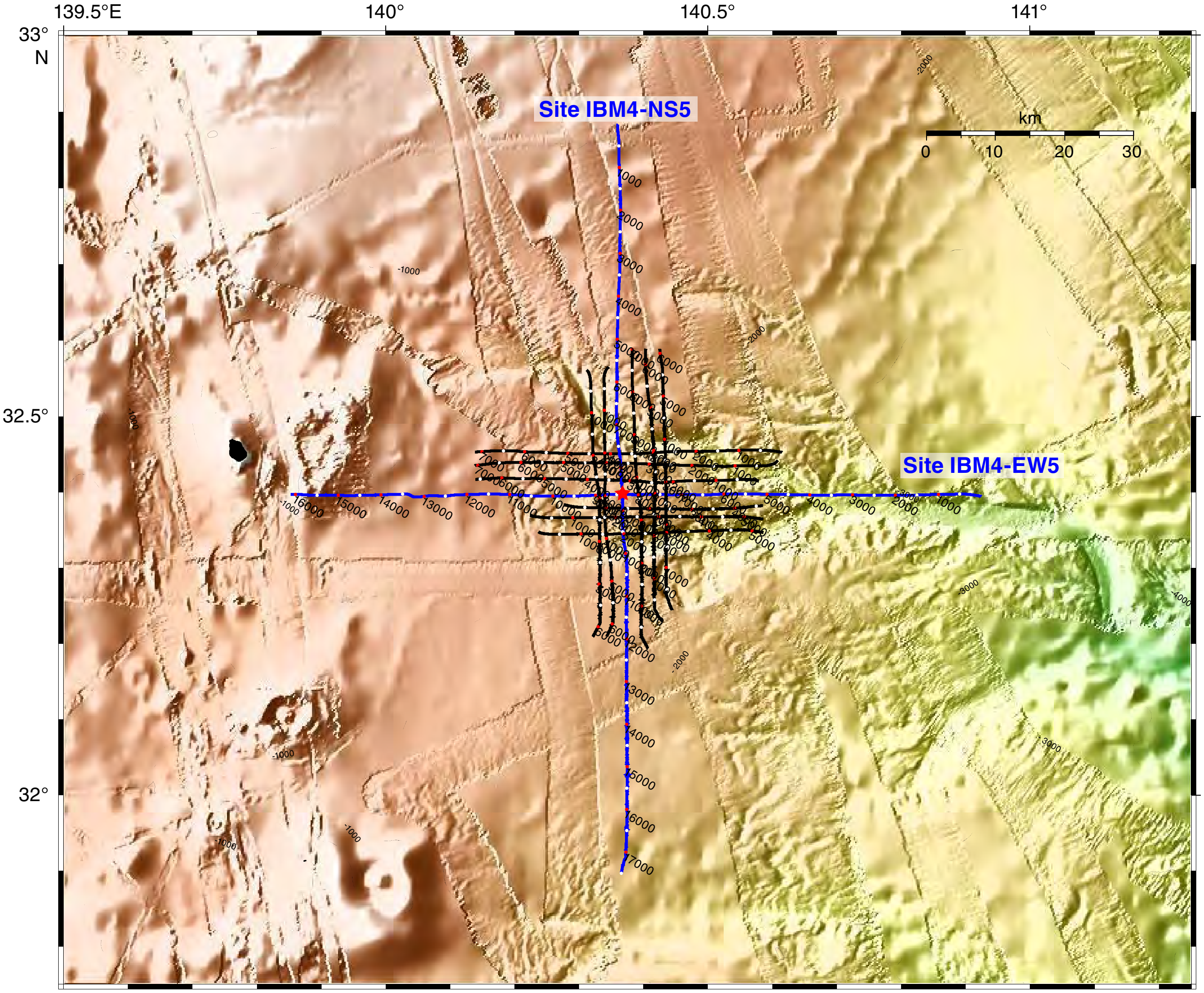


Figure AF2. Location of submarine cables near proposed Sites IBM-4GT and IBM-4.

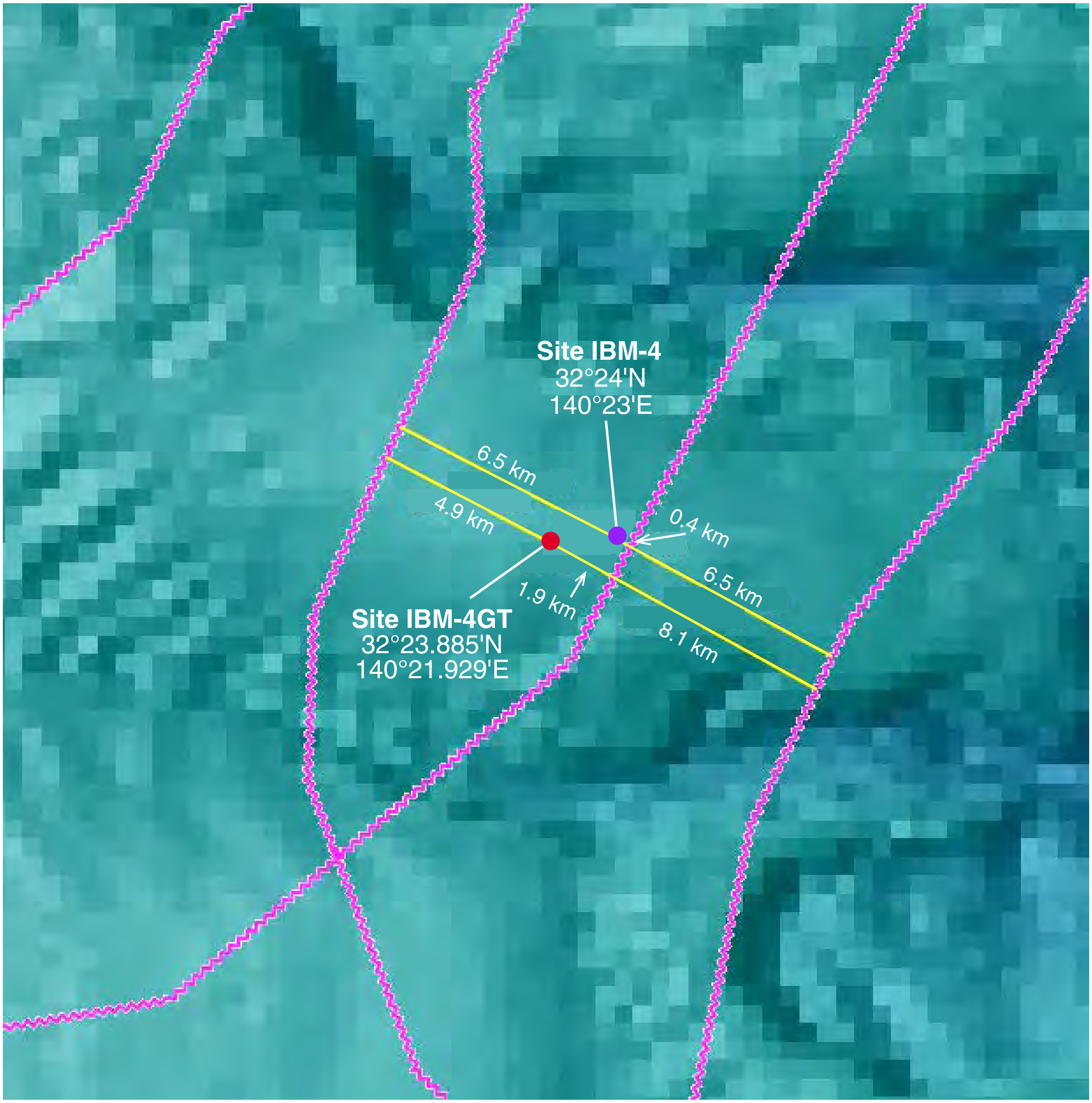


Figure AF3. Seismic reflection profile with location of proposed Site IBM-4GT on Line IBM4-EW5, obtained during Cruise KR08-09. CMP = common midpoint.

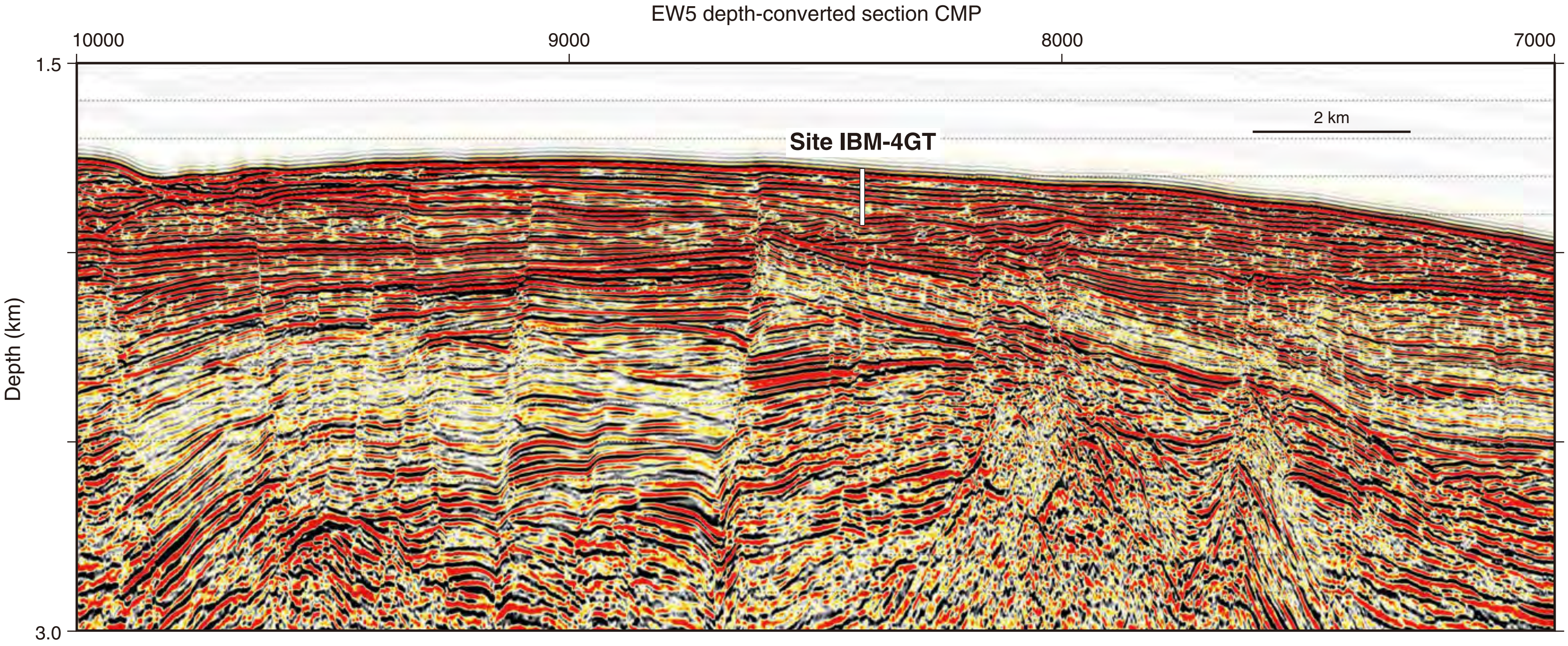


Figure AF4. Seismic reflection profile with location of proposed Site IBM-4GT on Line IBM4-NS5, obtained on Cruise KR08-09. CMP = common midpoint.

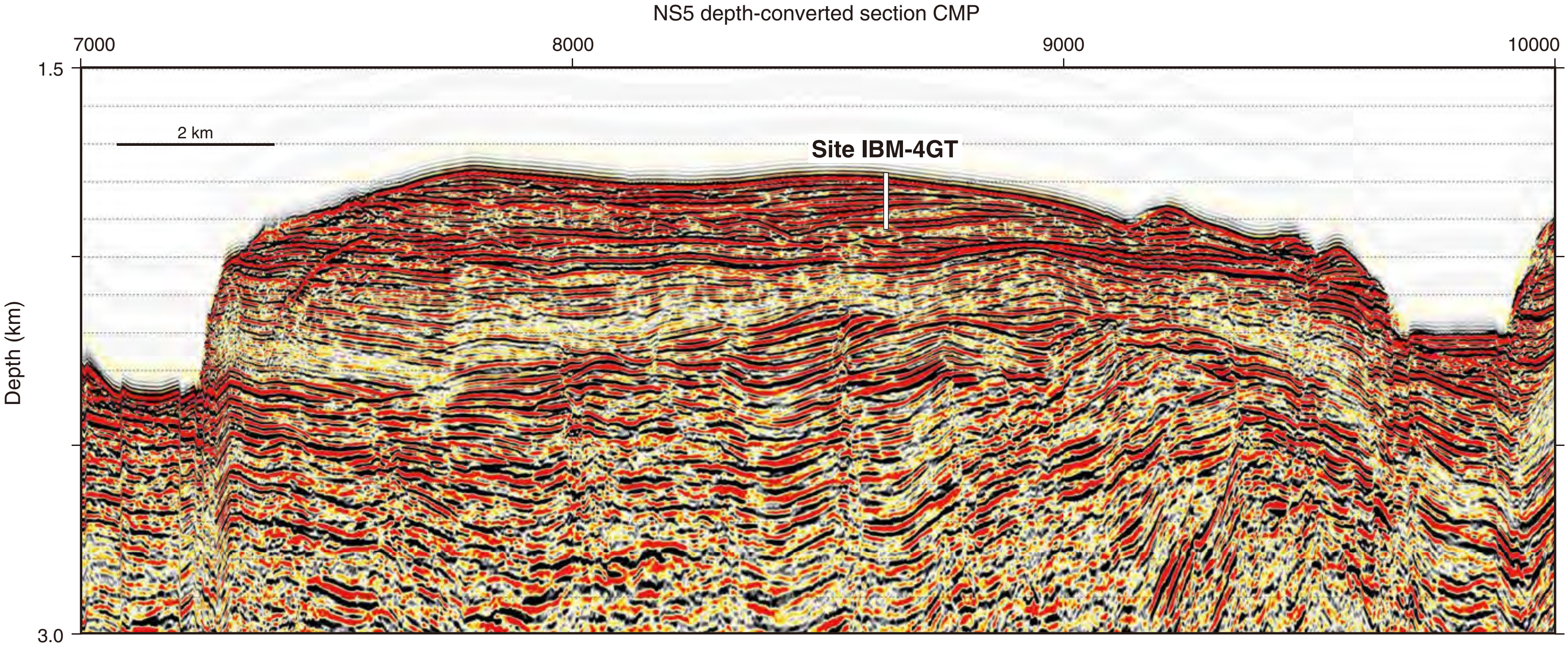


Figure AF5. Bathymetry and seismic tracklines covering the IBM-3 area. Black lines are from the Cruise KY06-14 and KR07-09 preliminary survey (see Fig. F8); blue lines are from the most recently acquired survey obtained during Cruise KY08-04. Proposed Site IBM-3C is the primary site; proposed Sites IBM-3D and IBM-3E are alternate sites.

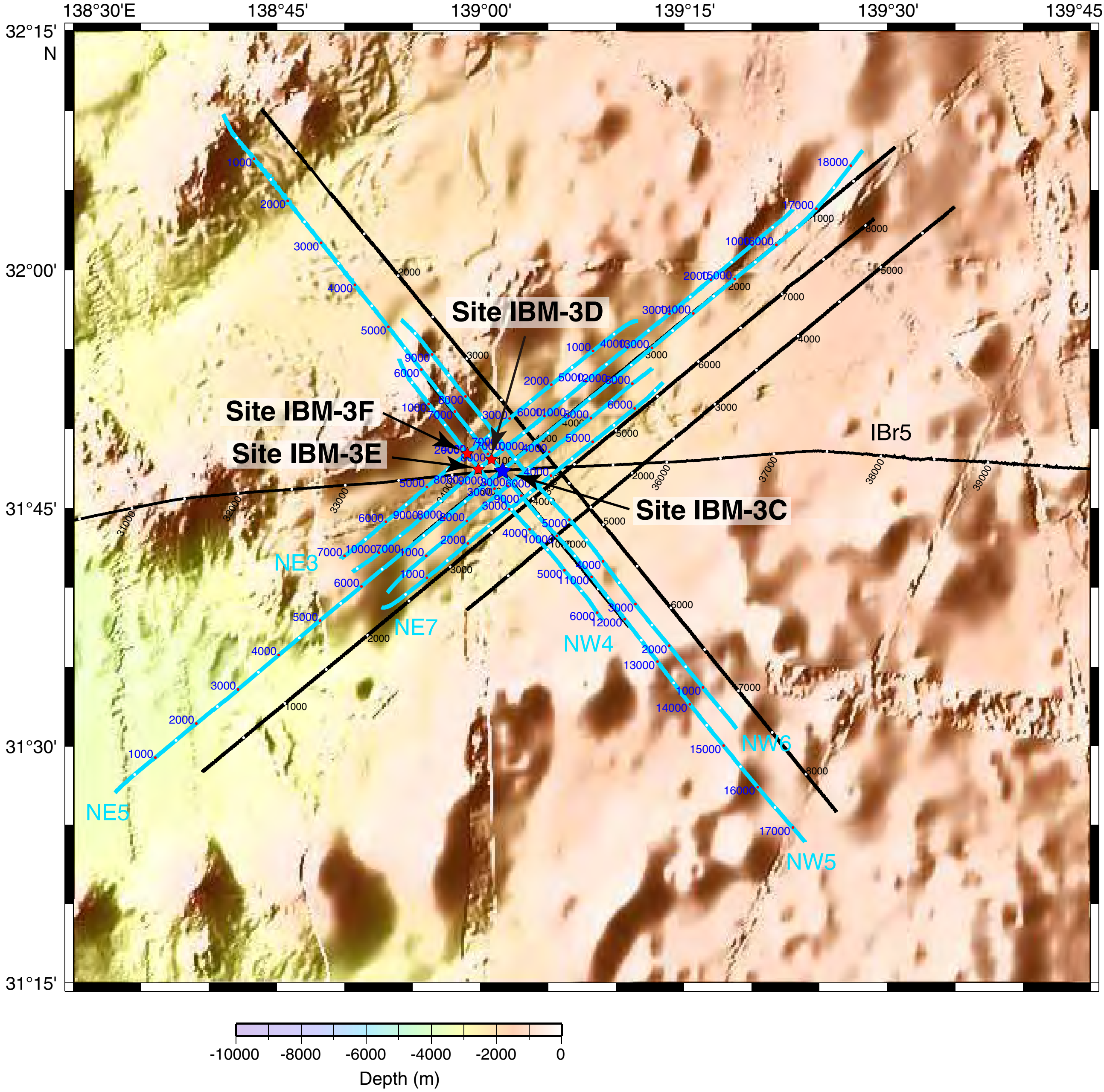


Figure AF6. Primary proposed Site IBM-3C and alternate proposed Site IBM-3D along uninterpreted and interpreted seismic reflection Lines IBM3-NE4 obtained during Cruise KR08-04. CMP = common midpoint.

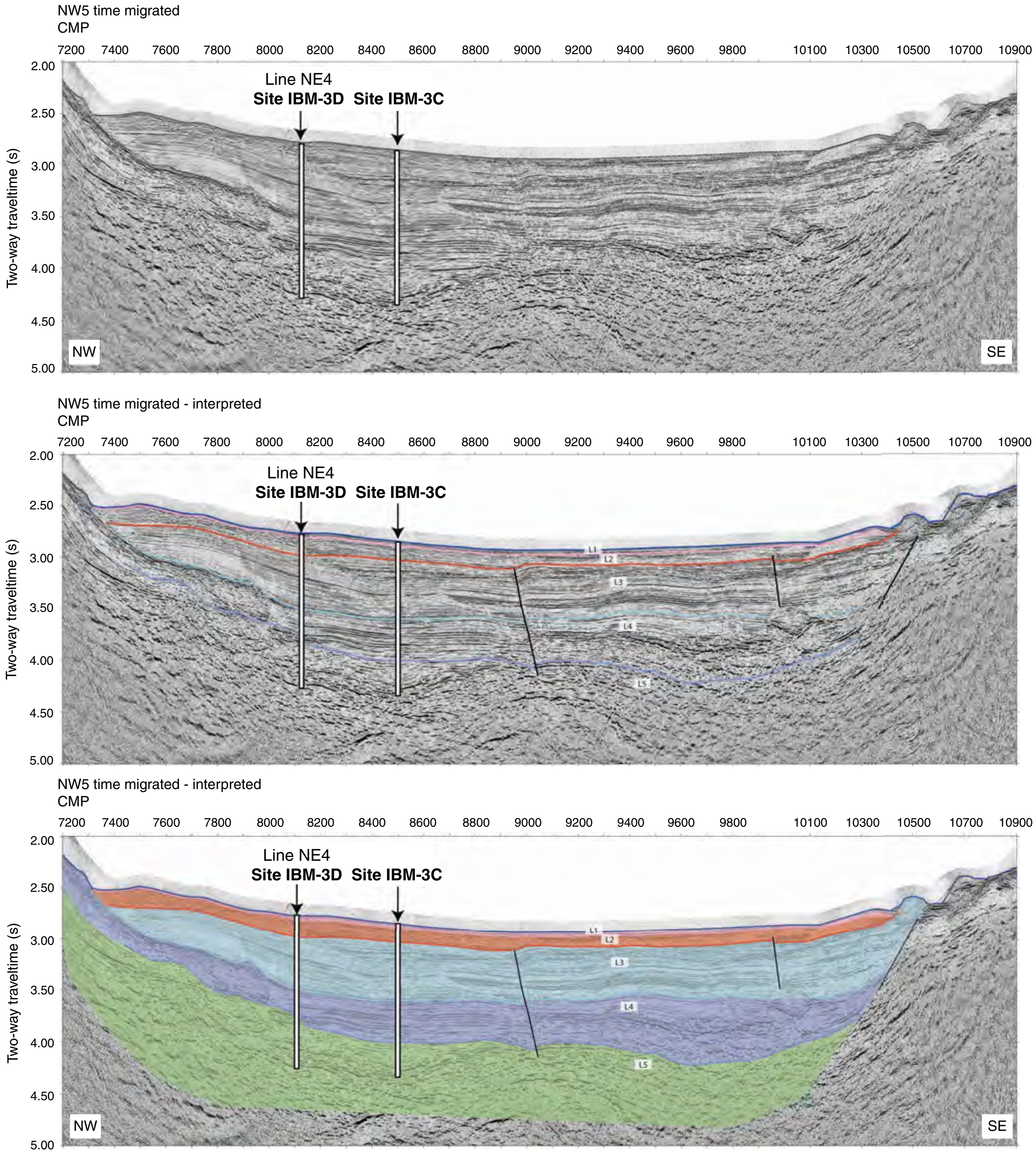


Figure AF7. Alternate proposed Sites IBM-3D and IBM-3E along seismic reflection lines obtained by during Cruise KR08-04. CMP = common midpoint.

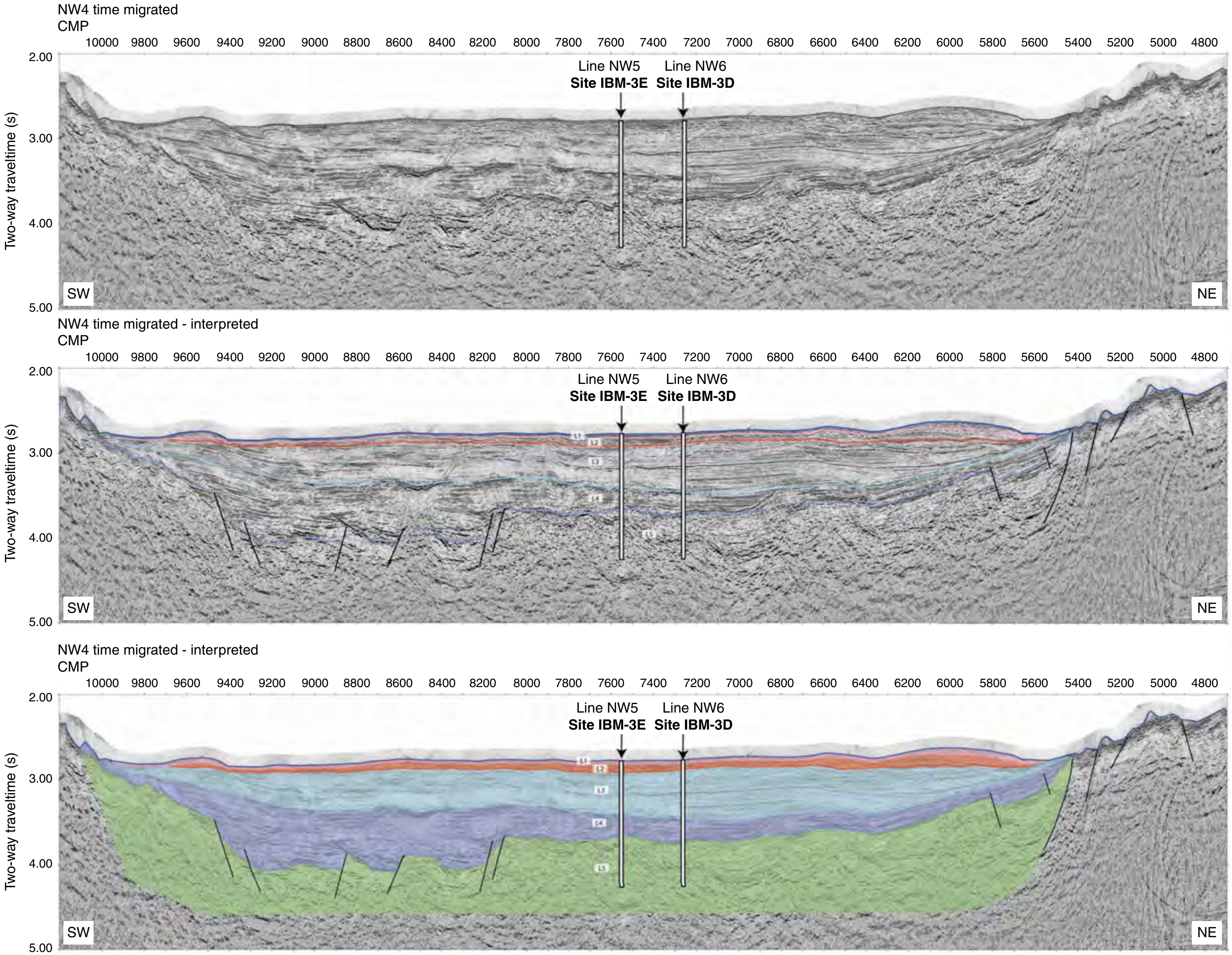


Figure AF8. Alternate proposed Sites IBM-3E and IBM-3F along seismic reflection lines obtained by during Cruise KR08-04. CMP = common midpoint.

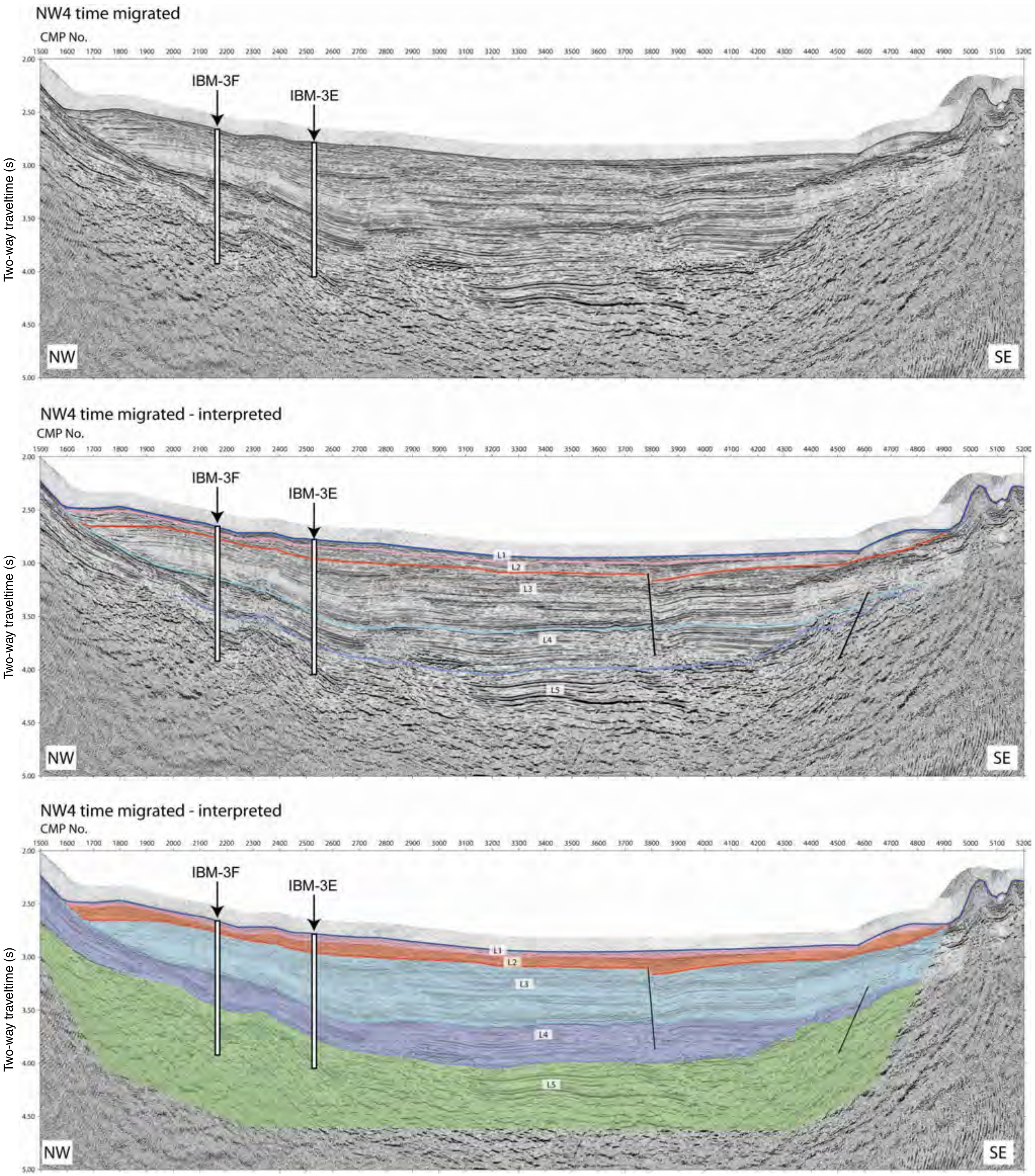
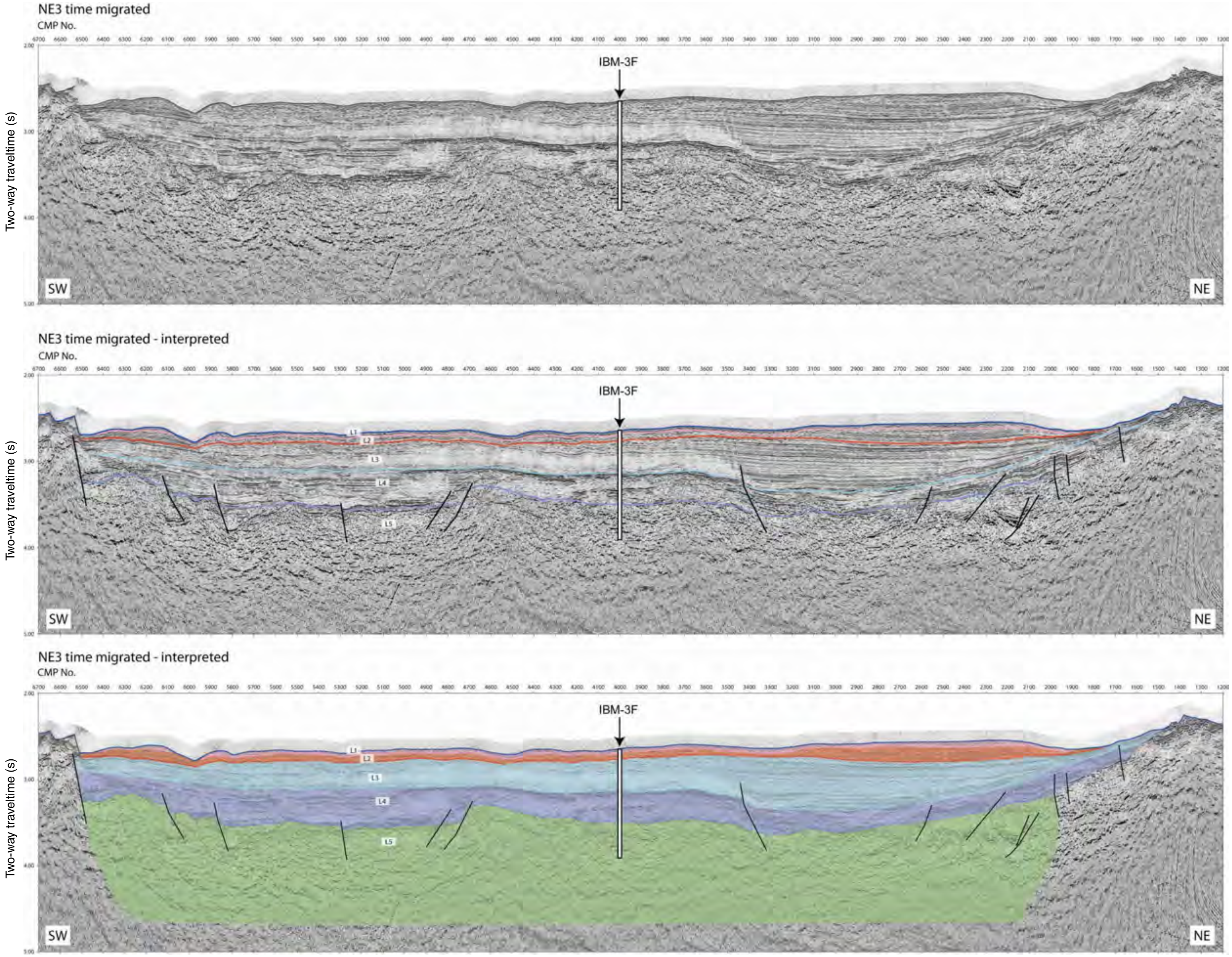


Figure AF9. Alternate proposed Site IBM-3F along seismic reflection lines obtained by during Cruise KR08-04. CMP = common midpoint.



Expedition scientists and scientific participants

The current list of participants for Expedition 350 can be found at **iodp.tamu.edu/scienceops/precruise/izuboninreararc/participants.html.**