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1. Leg 195 Synthesis: Site 1200—Serpentinite Seamounts of the Izu-Bonin/Mariana Convergent Plate Margin (ODP Leg 125 and 195 Drilling Results)[1]

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ABSTRACT

The Izu-Bonin/Mariana convergent plate margin is characterized by a nonaccretionary forearc with numerous serpentinite seamounts that occur along a 50-km-wide ridge in the Izu-Bonin system and are distributed over a zone as wide as 90 km in the Mariana system. The seamounts are formed primarily by mud volcanism; however, seamounts in the two systems differ in tectonic setting and the materials that form them differ in compositional characteristics. These compositional characteristics suggest that there may be regional differences in the suprasubduction-zone mantle within the Izu-Bonin/Mariana system. In the Izu-Bonin forearc, the seamounts and the ridge on which they formed lie at the top of a wedge of low-velocity material that underlies the outer half of the forearc toe. This wedge is interpreted to be serpentinized forearc peridotite remobilized in response to subduction processes. In the Mariana forearc, seamounts form adjacent to major fault traces scattered over a broad zone in the outer half of the forearc. Studies of pore fluids from serpentinite seamounts show systematic variation in composition related to depth to the slab and to various devolatilization reactions that are controlled by pressure and temperature conditions at the décollement. The serpentinized peridotite materials erupted in mud volcanism indicate that the forearc mantle of the Izu-Bonin system has experienced a different history of both magmatic and

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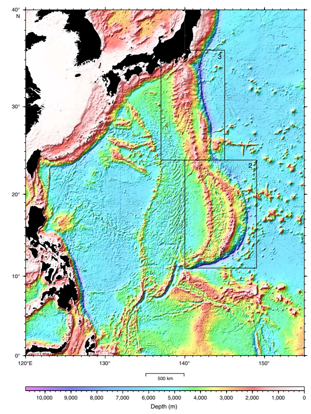
melt-fluid interaction than those of the Mariana system. The mud flows at some of these seamounts bring up altered mafic rocks with compositional characteristics of both oceanic plate and island arc origin and fragments of metabasites that reflect the high-pressure and low-temperature conditions of the subduction zone. Some of these rock fragments are likely derived from the subducted slab. The three seamounts drilled during Ocean Drilling Program Legs 125 and 195 thus provide a window into suprasubduction-zone mantle processes, as well as those at work within the décollement itself.

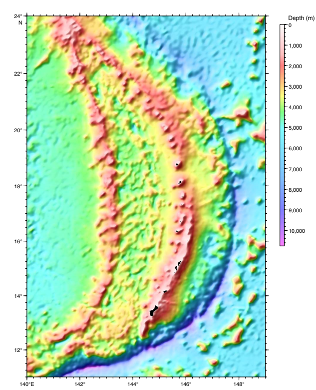
INTRODUCTION

Peridotites of the upper mantle provide us with evidence of magmatic processes that affect the evolution of both oceanic and suprasubduction-zone lithosphere and are the primary material from which we can determine the processes that are involved in evolution of the crust. Exposures of upper mantle in oceanic settings are primarily associated with major fault structures formed in response to several different types of regional processes, such as transition from continental to oceanic crust, off-ridge extensional faults in the deep ocean basins, development of transform faults on mid-ocean ridges, and extension at amagmatic mid-ocean-ridge segments or in forearc areas of convergent plate margins. In these localities the mantle peridotites generally form extensive bodies of serpentinite as a consequence of interaction with seawater making its way through fault zones into the upper mantle or interaction with fluids derived from an underlying subducting plate. Exposures of such bodies occur world-wide in subaerial settings where the relationships of these rocks to the regional structural setting have been determined.

F1. Bathymetric map of the Izu-Bonin-Mariana region, p. 26.

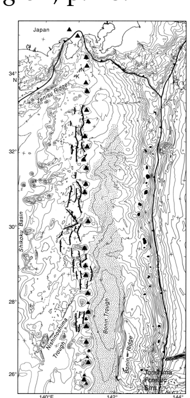


F2. Bathymetric map of the Mariana region, p. 27.



Serpentinite bodies have been targeted at numerous Ocean Drilling Program (ODP) sites over the last two decades. A summary of the results of these drilling efforts and a comparison of the nature of upper mantle peridotites from these settings was given in Fryer (2002). In this paper we focus on a synthesis of studies of the Izu-Bonin/Mariana (IBM) forearc (Fig. F1), highlighting work done during Leg 195 at Site 1200 on the southern Mariana forearc (Fig F2) at the summit of South Chamorro Seamount, a serpentinite mud volcano. We present a summary of the results from drilling Site 1200 and sites drilled during ODP Leg 125, during which the summits and flanks of two serpentinite seamounts farther north on the forearc of this convergent margin system were drilled (Conical Seamount Sites 778–780; Fig. F2) and Torishima Forearc Seamount Sites 783 and 784; Fig. F3). In our discussion section we suggest how these may fit in a broader context of terrestrial exposures. Research on these drill sites shows us that fundamental processes associated with subduction produce mantle effects that differ significantly from most abyssal peridotites and that the suprasubduction-zone mantle varies in composition regionally and probably also in time. It is a far more complex environment than most previous work has suggested.

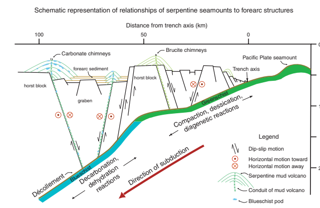
F3. Bathymetric map of the Izu-Bonin region, p. 28.



TECTONIC SETTING

Forearc regions of nonaccretionary convergent plate margins may expose the mantle of the overriding plate deep on the inner slope of the trench because in such forearcs there is no or very little sediment added to the outer edge of the overriding plate during subduction (Fig. F4). Although the concept of tectonic erosion is still controversial, it is clear from the morphology of the southern part of the IBM forearc that some degree of tectonic erosion is taking place along the inner slope of the trench (Fryer et al., 1999, 2000). Recent multichannel seismic (MCS) data suggest that subduction of the Ogasawara Plateau may have scraped off a portion of the underlying forearc mantle in the southern Bonin forearc region (Miura et al., 2004).

F4. Relationship of serpentinite mud volcanoes to faulting, p. 29.



The structures of the Izu-Bonin and Mariana forearcs differ from one another in several fundamental characteristics:

1. The Izu-Bonin system is essentially straight (Fig. F3), whereas the Mariana forearc has a broad curvature (Fig. F2).
2. The Izu Bonin system has a 50-km-wide ridge that runs along the entire length of the system at the base of the inner trench slope, whereas the inner slope of the Mariana forearc varies in morphology along strike (e.g., Stern and Smoot, 1998; Stern et al., 2004).
3. Distribution of serpentinite seamounts on the Izu-Bonin forearc is confined to the 50-km-wide ridge at the base of the inner trench slope. They lie along the top of this ridge and occur as discrete shoals spaced at irregular intervals along the ridge (see Taylor, 1992). By contrast, the serpentinite seamounts of the Mariana forearc are distributed across a broader zone from ~15 to 90 km arcward of the trench axis and lie almost exclusively along fault traces on the outer half of the forearc (Fig. F2).
4. The Izu-Bonin forearc has undergone a history of extension that resulted in the formation of an along-strike graben structure that is progressively more pronounced toward the south (Taylor, 1992). By comparison, the outer half of the Mariana forearc displays mainly along-strike fault lineaments north of ~21°N and a complex of extensional faults south of 20°N with a predominantly northeast trend and a subordinate northwest trend (Stern and Smoot, 1998). This conjugate faulting is most likely caused by extension resulting from the increase in curvature with time of the Mariana forearc (Fryer et al., 1985; Wessel et al., 1994; Stern et al., 2004). The change in structure has been suggested to reflect the change in direction of convergence from nearly orthogonal in the southeastern corner of the system to nearly parallel between 21° and 25°N. Extensional faulting in the Mariana forearc and the resultant structures are the most likely causes of the wider distribution of serpentinite seamounts on the Mariana forearc than on the Izu-Bonin lower trench slope ridge.

Swath bathymetry mapping of the Mariana forearc has revealed large fault-controlled graben structures related to the conjugate extensional faulting mentioned above. Some have throws on fault scarps of up to 4 km. Such deformation can provide access for seawater into lower crust and upper mantle rocks and can facilitate serpentinization of peridotites in proximity to the faults. Exposures of serpentinite have also been recorded from the deep inner slope of several other nonaccretionary forearcs, for instance, the inner slopes of the Tonga and Scotia Trenches. Wherever the upper mantle is exposed in these forearcs, serpentinites can form simply by seawater interaction with peridoties. We would expect little compositional difference between serpentinite formed by this process in either the abyssal or suprasubduction-zone environment (e.g., Fryer, 2002).

The fundamental difference between the serpentinites of the IBM forearc region recovered during Legs 125 and 195 and those recovered from other oceanic sites is that in the peridotites from suprasubduction-zone serpentinite seamounts, the IBM forearc peridotites have reacted with slab-derived fluids (and/or melts) resulting in compositions that reflect subduction zone processes. The muds from the serpentinite seamounts drilled during these legs indicate a suprasubduction-zone provenance for the peridotitic protolith and a slab source for the fluids (Saboda et al., 1992; Mottl et al., 2003; **Savov et al.,** this volume).

GEOPHYSICAL STUDIES

The structural differences between the Izu-Bonin and Mariana forearcs have led to interesting hypotheses regarding the formation of the serpentinite seamounts in these regions. In seismic refraction profiles using ocean bottom seismometers across each system, investigators have identified bands of low-velocity material overlying the subducted slab and have interpreted them as zones of serpentinized mantle (Fryer et al., 1985; Taira et al., 1998; Takahashi et al., 1998; Kamimura et al., 2002). Detection of a potential serpentinized region overlying the subducting slab led Fryer et al. (1985) to suggest that fluids from the slab may have interacted with the overlying mantle. *Alvin* dives conducted in 1987 showed that active serpentinite mud volcanism was occurring at Conical Seamount (Fryer et al., 1990); Conical Seamount was subsequently drilled during Leg 125. As a result of drilling during Leg 125, Fryer (1992) suggested that the seamounts formed as a consequence of the mobilization of fault gouge on deep forearc faults during seismic events that were associated with the release of fluids.

Recent MCS surveys of the IBM system in the Izu arc region at ~31°N reveal the décollement interface and the Mohorovicic discontinuity (Moho) of the subducting oceanic plate. According to Kamimura et al. (2002), the mantle wedge above the slab has a velocity lower than that of average oceanic mantle, suggesting that it has been subject to interaction with slab-derived fluids. These authors describe a layer between the two plates, which they term the “plate boundary layer” (PBL), that has lower velocity than the forearc just beneath the serpentine seamounts and that thins and increases in velocity westward of the seamount, where it connects to the mantle wedge. The distribution of the low-velocity (serpentinite) zone suggests to these investigators that the seamounts are diapiric with a root that follows the low-velocity zone to depth beneath the forearc. A seismic line run along strike of the system showed a homogeneous velocity character (Kamimura et al., 2002). An interesting additional suggestion by Kamimura et al., looking at the MCS data, and Sato et al. (2004), looking at ocean bottom seismometer data, is that the PBL may contain significant amounts of chrysotile, the fibrous phase of serpentine, which may act as a lubricant and facilitate subduction of the plate, resulting in low seismic activity at the décollement.

Velocity and density of serpentinized peridotite clasts from Site 1200 were determined postcruise by **Courtier et al.** (this volume) and agree with values measured aboard ship (Shipboard Scientific Party, 2002). As noted by **Courtier et al.** (this volume), however, the 14 samples measured show a narrow range of velocity and density in comparison with the velocity and density range for the forearc mantle wedge and indicate that the degree of serpentinization of the clasts is greater than that of the mantle wedge. Specifically, in comparing the velocity of clasts from Torishima Forearc Seamount (Sites 783 and 784) measured by Ballotti et al. (1992) with velocities suggested by Kamimura et al. (2002) for a line run across Torishima Forearc Seamount, the percent serpentinization estimated from MCS data is 54%, which is lower than the value calculated by **Courtier et al.** (this volume) (66%) from laboratory measurements on serpentinized clasts. They conclude that the degree of serpentinization beneath the seamounts (Conical, Torishima Forearc, and South Chamorro) is greater than that of the surrounding mantle wedge, a conclusion consistent with the idea that the mud volcanoes tap a more highly serpentinized local source beneath the seamounts.

PORE FLUID STUDIES

Ever since the unusual composition of the pore fluids from these seamounts was first noted (Fryer et al., 1990) and attributed to a slab origin, the fluids have been a major focus for study. The muds recovered in drilling operations during Legs 125 and 195 from two active serpentinite seamounts (Conical and South Chamorro) contain pore fluids with compositions that indicate a slab derivation (Fryer et al., 1990, 1999; Sakai et al., 1990; Mottl, 1992; Mottl and Alt, 1992; Ryan et al., 1996; Benton, 1997; Benton et al., 2001). One of the objectives of drilling during both Legs 125 and 195 was to characterize the nature of fluid flux through the forearc region of the IBM convergent margin.

For decades it has been recognized that the output from subduction zone arc volcanoes is not in balance with the input flux of volatiles at subduction zones and that this imbalance can be significant (Peacock, 1990; Kerrick and Connolly, 2001; Sadofsky and Bebout, 2003). Estimates regarding the flux of volatiles vary regionally, but only ~16% of the H_2O and <20% of the CO_2 delivered to the IBM trench system can be accounted for in the arc magmatic output (smaller than the global average of 50% CO_2 flux through arcs [e.g., Marty and Tolstikhin, 1998; Shaw et al., 2003]). The rest of the H_2O and CO_2 must be released either through the forearc, incorporated into the mantle of the overriding plate, lost as exsolved magmatic gases, stored in subcrustal intrusions, or returned to the deep mantle. With respect to large-ion lithophile (LIL) elements, only 20%–30% of the to-the-trench inventory of these elements can be accounted for by the magmatic outputs of volcanic arcs (Morris and Ryan, 2003). It is important that the subduction-related processes by which slab constituents are recycled be adequately quantified because of their obvious importance for the geochemical cycles of volatile species.

Nonaccretionary convergent margins (Uyeda, 1982), where faulting of the forearc is prevalent and where the possibility of interaction with large sediment wedges is minimal, have been suggested as ideal localities in which to study the composition of slab-derived fluids (Fryer, 1996b). Upwelling water and seafloor seeps in a nonaccretionary forearc provide a unique window into processes of devolatilization of the subducting slab (Fryer et al., 1990, 1999). Fluids migrating upward through such a forearc mantle wedge pass through a matrix of already serpentinized depleted-mantle peridotite that is chemically simpler than typical crustal rocks and sediments. Therefore, a deep slab-derived component in the upwelling water is easier to recognize than it is in accretionary convergent margins where fluids must migrate through, and react with, a large sediment wedge.

Some of the processes that release water from the subducting plate include:

a. Diagenetic transformation of opal-A, including the expulsion of interlayer water at ~30°-80°C (e.g., Kastner et al., 1977; Moore and Gieskes, 1980; Kastner, 1981);
b. Expulsion of interlayer water from smectite and its transformation to illite at ~50°–150°C (Koster van Gross and Guggenheim, 1984, 1986, 1989; Vrolijk, 1990; Ransom and Helgeson, 1995); and
c. Metamorphic dehydration of chlorite, amphibole, and other hydrous phases in the basaltic ocean crust, beginning at ~450°–500°C (Peacock, 1990).

We can also anticipate that certain elements, such as K, Rb, and B, are removed from seawater and sequestered in secondary minerals during alteration at low temperature but are leached from rock into solution at high temperature (e.g., Seyfried and Bischoff, 1979; Seyfried and Mottl, 1982). These predictions are consistent with observations of unusual fluid composition (high pH, B, Rb, and alkalinity and low Cl, and Li) in active chimneys on Conical Seamount (Fryer et al., 1990) and in pore waters recovered during Leg 125 from Conical and Torishima Forearc Seamounts (Mottl, 1992).

Conical Seamount, located 90 km west of the trench near 19.5°N, was the first serpentinite mud volcano drilled in the Mariana forearc. In 1987 submersible dives with *Alvin* revealed chimneys at the summit composed of aragonite, calcite, and amorphous Mg silicate; when one chimney was disturbed it began to emit a weak flow of cold (1.5°C) water with a pH of 9.3 and elevated dissolved carbonate, methane, sulfate, and reduced sulfur relative to the surrounding seawater (Fryer et al., 1990). Drilling at the summit recovered unusual pore fluids that had less than half the chloride and bromide of seawater, a pH of 12.6, and were highly enriched in dissolved carbonate, light hydrocarbons, sulfate, bisulfide, Na/Cl, K, Rb, and B (Mottl, 1992). Near-surface gradients in chloride indicate that this water was upwelling at 1–10 cm/yr (Mottl, 1992). Pore water recovered from Torishima Forearc Seamount, an inactive serpentinite mud volcano in the Izu-Bonin forearc near 31°N, reflects reaction of cool (4°–11°C) seawater with harzburgite and contrasts greatly with that from Conical Seamount (Mottl, 1992). The distinctive composition of water upwelling at Conical Seamount implies that it originates by dehydration of the subducting Pacific plate. Based on earthquake depths, this occurs ~29 km below the seafloor (Hussong and Fryer, 1982; Seno and Maruyama, 1984) and the compositions of the ascending fluids probably originate at temperatures of 150°–250°C (Mottl et al., 2003, 2004). The unusual oxygen, carbon, and strontium isotopic signatures (Haggerty, 1991; Haggerty and Chadhuri, 1992) and the presence of organic acids (Haggerty and Fisher, 1992) in Conical Seamount pore fluids also suggest derivation of the fluids from the subducting slab and require that they have interacted with the ultramafics through which they migrated. The upwelling H_2O is in excess of that which serpentinizes the overlying mantle wedge during its ascent and represents one of the first returns of slab-derived volatiles to the oceans during the subduction process (Mottl et al., 2003, 2004).

Pore fluids recovered from the summit of South Chamorro Seamount at Site 1200 have a composition that is similar to that of pore fluids from Site 780 on the summit of Conical Seamount (Table T1) (Mottl et al., 2003). The two seamounts are 630 km apart but are about the same distance from the trench axis (85 km for South Chamorro Seamount and 90 km for Conical Seamount). Mottl et al. (2003) point out that differences between the seamounts include the fact that the waters upwelling through Conical Seamount have lower chlorinity and higher sulfate than those at South Chamorro. The composition of pore fluids sampled by gravity and piston coring from active seeps on several other serpentinite mud volcanoes varies across the Mariana forearc with distance from the trench, indicating that there is a progressive devolatilization of the subducting slab (Mottl et al., 2004). The nature of chemical cycling can be determined by species that partition strongly into the fluid phase, and this gives us an insight into the nature of fluid-mantle interaction in the suprasubduction zone region. Recent studies of some of these constituents show that the process may be quite complex.

T1. Composition of pore water from serpentinite seamounts vs. seawater, p. 30.

Recent detailed studies of the compositions of drill samples comparing pore fluids, muds, and the included rock clasts indicate aspects of this complexity. Work by Peacock and Hervig (1999) suggests that a decrease in $\delta^{11}B$ in slab sediments enriches ^{11}B in derivative fluids. Boron isotopic systematics in fluid samples from Conical Seamount support the observation that some degree of B isotopic mass fractionation occurs during release of structurally bound B from the slab and enriches the slab-derived fluids in ^{11}B (Benton et al., 2001). The temperature effect in the range predicted for the Mariana forearc beneath both Conical and South Chamorro Seamounts (~100°–250°) and pressures of ~0.8 GPa (Peacock, 1996; Mottl et al., 2003) is to increase $\delta^{11}B$ (Wei et al., this volume). In order to produce the observed $\delta^{11}B$ signatures of the Conical Seamount serpentinites, Benton et al. (2001) suggested that shallow devolatilization removes a slab-derived B component that is isotopically heavier than any specific slab component.

Wei et al. (this volume) focused studies on details of B concentrations and isotopic composition in 28 pore fluid samples from Site 1200 at South Chamorro Seamount. Isotopically, serpentine concentrates ^{10}B because ^{10}B-rich B(OH) is preferentially incorporated into the low-temperature serpentine structure (Benton et al., 2001). B is derived from several sources in the downgoing plate (e.g., compaction of sediment, clays, mineral dehydration, alteration of igneous rocks, and possible release of bound B from carbonates). Wei et al. (this volume) show that for very shallow depths below the seafloor B concentrations are significantly elevated. The samples also have lower than normal Br/Cl and $\delta^{11}B$. Wei et al. (this volume) note that this may be a consequence of pressure control because of the size difference between the halogens and OH^- (Vanko, 1986). Halogens chiefly substitute for OH^-, and Zhu (1993) predicted that they are a sensitive indicator of pH. Wei et al. (this volume) noted very high concentrations of iodine in the pore fluids with even higher concentrations in the muds. The iodine results indicate the potential for significant recycling of this element in the subduction process along the IBM system. Wei et al. (this volume) note that the iodine concentrations they measured were the highest ever measured in nonsedimentary rock types. Effluent from a nonserpentine mud volcano in the Black Sea also shows high I contents and Wei et al. (this volume) suggest the possibility that mud volcanism of all types (serpentinite and sedimentary) may be an important contributor of recycled I into the world's oceans. No difference in I content was noted between the Conical Seamount and South Chamorro Seamount samples. The data from **Wei et al.** (this volume) for $\delta^{11}B$ concentrations compared with data from Site 780 at the summit of Conical Seamount (Benton et al., 2001) show that $\delta^{11}B$ is a little higher, ~16% vs. 13%, at Site 1200 on South Chamorro Seamount. **Wei et al.** (this volume) suggest a mixing with seawater is required at shallow depths in a ratio of 1:2 to produce the observed concentrations and $\delta^{11}B$. The estimated total B recycled at the Mariana subduction zone is likely a significant proportion of the discrepancy between the large estimated output flux (2.5 $\times 10^{10}$ mol/yr) and the estimated input flux (0.6 $\times 10^{10}$ mol/yr). **Wei et al.** suggest an output of 0.03 $\times 10^{10}$ mol/yr for nine known seamounts for a total of 0.3 $\times 10^{10}$ mol/yr.

Benton et al. (2004) examined Li systematics in pore fluid and serpentinite mud samples from South Chamorro Seamount and Conical Seamount sites. They note that Conical Seamount muds have high Li contents compared to mantle values (3–7 ppm) and a mean δ^7Li value of +6%. Their serpentinized ultramafic clasts, however, generally have lower Li content, with a range of δ^7Li (6% to +10%). Higher δ^7Li clasts generally have higher overall Li contents. They conclude that there may be a depth control over Li exchanges between forearc mantle and slab-derived fluids. Furthermore, they point out that the δ^7Li variability does not occur in Mariana arc lavas or, in fact, in any other mature arc. They also note that there is no large difference between Li outputs in the forearc versus those in the volcanic front, despite the fact that other alkaline species (e.g., Ba, Sr, and K) do show changes across the Mariana subduction system. Their interpretation of these systematics is that Li is released in the shallow part of the subduction system and may be transported in down-dragged hydrated mantle to depths where arc magma is generated. A similar conclusion was offered for B isotopic variations in Izu arc volcanics (Straub and Layne, 2002). Savov et al. (2005) suggested the same sort of process might be involved in recycling of LIL elements in the Mariana system.

The work of Savov et al. (2005) on LIL elements concentrated on drill samples from Conical Seamount in which they noted that serpentinized peridotites from the drill sites at the summit and on the flanks of the edifice have U-shaped rare earth element (REE) patterns (as do boninites). They observe a high depletion in U, Th, and the high–field strength elements (HFSE), which vary in concentration by up to 2 orders of magnitude. Their data and subsequent pore fluid analyses (Mottl et al., 2004) show that the fluids from the subducting Pacific slab were reducing. Some fluid-mobile elements are substantially enriched in the serpentinized peridotite clasts that Savov et al. (2005) analyzed. They were able to calculate very large slab inventory depletions in B (79%), Cs (32%), Li (18%), As (17%), and Sb (12%). They conclude that if these highly enriched serpentinized peridotites dragged down to depths of arc magma generation they may represent an unexplored reservoir that could help balance the input-output deficit of these elements as observed by previous workers. Some species, thought to be mobile in fluids, such as U, Ba, Rb, and to a lesser extent, Sr and Pb, are, however, not enriched relative to the depleted mantle peridotites, and they estimate that <2% of these elements leave the subducting slab in the outer forearc (to a depth of 40 km). They suggest that enrichments of the latter elements in the volcanic arc and backarc basin indicate changes in slab fluid composition at greater depths.

BIOLOGICAL COMMUNITIES

Biological communities identified at the summit of Conical Seamount using the *Alvin* submersible include presumed biological coatings on carbonate chimney structures (no microbial studies were performed on the materials), limpets, and small high-spire gastropods (Fryer et al., 1990). Dives at the summit of South Chamorro Seamount with the *Shinkai* 6500 discovered and sampled three cold springs that support the growth of carbonate crusts and chimneys and communities of mussels, small tubeworms, gastropods, and galatheid crabs (Fryer, 1996a; Fryer and Mottl, 1997). Drilling at South Chamorro Seamount also revealed a remarkable extremophile microbial community living in the upper 30 meters below seafloor (mbsf) at a pH of 12.5, while generating carbonate alkalinity by oxidizing methane from the upwelling fluid and reducing sulfate from both the upwelling fluid and seawater (Shipboard Scientific Party, 2002; Mottl et al., 2003). The population is dominated by Archaea (Mottl et al., 2003) but also contains unique bacteria (Takai et al., 2005).

Takai et al. (2005) examined the culturability of bacteria in the serpentine muds at South Chamorro Seamount and identified a new species of *Marinobacter* (*M. alkaliphilus*). This new species predominantly flourishes in the shallow serpentine mud to ~2.95 mbsf, where pH levels in the pore fluids are ~10. Deeper in the serpentine muds, pH levels are too high for optimal growth conditions. The highest bacterial population at Site 1200 is at 0.05 mbsf, based on bacterial biomass estimation by phospholipids fatty acid (PLFA) analysis (Mottl et al., 2003), suggesting to Takai et al. (2005) that seawater infiltrating the serpentine mud is likely the source of inoculation of the mud with *M. alkaliphilus* and may explain why the species appears to be absent from the deeper microbial populations below 2.95 mbsf. The elevated pH of the pore fluids favors the survival of *M. alkaliphilus* over other bacteria derived from seawater, but the low temperatures of the near-surface muds (1.7°–1.9°C, below the limit for growth in the laboratory) suggest that the alkaliphilic species are either dormant or have extremely low growth rates (Takai et al., 2005).

PETROLOGIC STUDIES

The serpentinite mud recovered during Legs 125 and 195 consists mainly of clay- and silt-sized particles of lizardite, chrysotile, brucite, metabasic particles, and carbonate crystals (Shipboard Scientific Party, 1990; **Savov et al.,** this volume), but suspended within the serpentinite mud matrix and supported by it are clasts of various rock types, including dominantly serpentinized peridotites with minor altered or metabasic rocks (Fryer et al., 1990, 2000; Fryer, 1992; Parkinson et al., 1992; Johnson, 1992; Saboda et al., 1992; Maekawa, et al., 1993, 1995; Shipboard Scientific Party, 2002). The same diversity of rocks has been recovered by dredging, which has also recovered rare fragments of chert (Hussong and Fryer, 1982; Bloomer and Hawkins, 1983; Bloomer et al., 1995; Fryer et al., 1985; Fryer and Fryer, 1987; Johnson et al., 1991), by submersible dives (Fryer et al., 1990, 1995), and by gravity and piston coring (Fryer et al., 1999). Similar rocks have been recovered on the Izu-Bonin forearc in dredges from several locations (Ishii, 1985).

The harzburgite recovered during Leg 125 from a Mariana serpentinite mud volcano (Conical Seamount) is variably serpentinized with

40%–100% replacement of original minerals (Fryer et al., 1990; Saboda et al., 1992). The clasts consist of ~76% harzburgite, ~16% dunite, and 8% metamorphosed mafic rocks (Ishii et al., 1992; Johnson, 1992). Generally, the peridotites preserve enough of the original textures to permit estimates of original mineralogy. The harzburgite was 70%–90% olivine, 5%–30% orthopyroxene, and <1% clinopyroxene (mostly as exsolution lamellae in orthopyroxene) and trace spinel (Fryer et al., 1990; Saboda et al., 1992). The serpentine forms mesh texture (after olivine) and occurs as bastitic replacement of pyroxene. Microgranulation of olivine, kink banding of pyroxene, elongation of spinel, and deformation of clinopyroxene exsolution lamellae in orthopyroxene indicate deformation of the clasts (Saboda et al., 1992). Girardeau and Lagabrielle (1992) examined petrofabrics of the serpentinized peridotites from Conical Seamount to study the formation and deformation history. After the initial formation of the peridotites under high-temperature asthenospheric conditions, they were remelted and invaded by fluids during a period of high-temperature/low-stress deformation that occurred either before subduction began or during the initial stages of subduction and proto-arc formation (Fryer, 1992; Girardeau and Lagabrielle, 1992). This sequence of preserpentinization events is similar to that observed in serpentinized peridotites exposed at the margins of rifted continents, in exposures along amagmatic slow-spreading mid-ocean ridges and at transform faults or deep abyssal troughs (see summary in Fryer, 2002). A phase of protracted retrograde metamorphism, including serpentinization, accompanied by the formation of ductile shear zones was then followed by a period of brittle deformation that overprints all earlier structures (Girardeau and Lagabrielle, 1992). The significant difference between the serpentinite found in these various locations is that the trace element compositions and isotope signatures of the serpentinites of the Izu-Bonin and Mariana forearcs and the pore fluids from the active Mariana mud volcanoes show a clear signature of the suprasubduction-zone environment.

Hard rock clasts from Hole 1200A consist predominantly of heavily serpentinized and tectonized harzburgite (64%) and dunites (28%), lherzolite (4%), and metabasic schists (4%) (D'Antonio and Kristensen, 2004). The metabasic fragments are generally less than a few millimeters in diameter and include glaucophane schist, chlorite schist, white mica schist, crossite/white mica/chlorite schist, and amphibolite schists (Shipboard Scientific Party, 2002; Gharib et al., 2002). The observed primary mineral phases are olivine: 0%–35%, orthopyroxene: 0%–35%, clinopyroxene: 0%–5%, and Cr spinel: 1%–3% (**Savov et al.,** this volume). **Savov et al.** (this volume) report the bulk chemical analyses of harzburgite clasts and serpentinite mud from Sites 778, 779, and 780 on Conical Seamount and Site 1200 on South Chamorro Seamount summit. On both seamounts the depleted harzburgite protolith comprises ~80% magnesian olivine (Fo_{92}) and 20% orthopyroxene, with very small contents (0%–2% each) of clinopyroxene and chromian spinel (see also Ishii et al., 1992; Parkinson et al., 1992; Shipboard Scientific Party, 2002). No large clasts of metabasic schist were recovered. The percent of the matrix material that was estimated aboard ship to be metabasic was ~10%, which is similar to shipboard estimates of the >1-mm fraction of the sieved muds. Clasts of serpentinized peridotite material are less abundant in Leg 195 Holes 1200D, 1200E, and 1200F, where the dominant lithology is serpentinite mud. The degree of serpentinization of the dunites varies between ~67% and 100%, whereas that of the harzburgites varies between ~40% and 100%.

Detailed descriptions of the serpentinized peridotites are given in D'Antonio and Kristensen (2004). Microtextures of the South Chamorro Seamount peridotites show a similar sequence of deformation and serpentinization events to those described for Conical Seamount samples by Girardeau and Lagabrielle (1992), suggesting that the southern suprasubduction-zone mantle has undergone a similar magmatic/metamorphic/tectonic history as the central part. The less serpentinized peridotites contain relict olivine and enstatite and minor Cr spinel and diopside, similar to the phases identified at Conical Seamount. Serpentine and brucite with minor magnetite are the main secondary minerals. The most abundant serpentine phases are lizardite and chrysotile, and they have large compositional variations depending on the composition of the primary minerals from which the serpentine was derived. D'Antonio and Kristensen (2004) note that both the serpentine minerals and brucite exhibit wide Mg, Fe, and Mn substitutions, which permit them to estimate an upper temperature limit of serpentinization (200°–300°C) that is in accord with thermal models for the region and with geochemical estimates based on fluid-rock interactions (Mottl et al., 2004).

Parkinson et al. (1992) studied the compositions of clinopyroxenes in the Leg 125 peridotites and showed that the serpentinized peridotites are enriched in Sr, Ce, Zr, and Nd and somewhat enriched in Sm and Eu compared with abyssal peridotites, which suggests that the enrichment took place after the initial melting event of the protolith. Based on a forward modeling technique in which Ti and the heavy REEs were treated as incompatible elements not enriched in the peridotites and assuming 25% partial melting, the authors showed large enrichments in Rb, Nb, La, Sr, Ce, and Nd and some enrichment in Zr, Sm, and Eu in comparison with abyssal peridotites after partial melting (their fig. 12). The trace element concentrations suggest to them a multistage melting and enrichment history for the original peridotites. This involved 10%–15% melting of a normal mid-ocean-ridge basalt (N-MORB) source that produces a depleted spinel lherzolite, which is then enriched by an infusion of slab-derived constituents and then further melted by 10%–15%. They make the caveat, however, that in their attempt to compare the Leg 125 serpentinized peridotites with peridotites from ophiolite sequences interpreted to have formed in suprasubduction-zone environments, they see a wide range in patterns of enrichment. This observation led them to conclude, "if suprasubduction-zone ophiolites do represent a forearc setting, it is possible that enrichment and depletion events in this setting are highly variable and may reflect the residence time of the mantle in question in the forearc" (Parkinson et al., 1992).

Savov et al. (2002, this volume) reached a similar conclusion for the Site 1200 peridotites. They note that the presence of high bulk rock Mg numbers, high normative olivine, and low normative clinopyroxene indicate that the ultramafic protolith suffered a high degree of melt extraction, with dunites experiencing >20% extraction and harzburgites between 10% and 25%. These values are consistent with the conclusions of D'Antonio and Kristensen (2004), based on the high clinopyroxene (cpx) Mg numbers (up to 95.6) and laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) REE measurements revealing highly depleted cpx light REE (LREE) patterns, the peridotite clasts suffered 15% to 20% melt extraction before serpentinization. They suggested the melting started beneath the arc and backarc basin under garnet-facies conditions and continued during the upwelling of the asthenosphere to shallow, spinel-facies levels. The elevated Sr isotope values relative to the depleted mantle are consistent with this view and with the depleted mantle- and chondrite-normalized elemental patterns (**Savov et al.,** this volume). Similar degrees of melt extraction were proposed for Conical Seamount by Parkinson et al. (1992) and Parkinson and Pearce (1998), and the South Chamorro seamount samples overlap the range noted by those authors. As noted for the Conical Seamount samples, the peridotites were then fluxed with LREE-enriched fluids or melts (**Savov et al.,** this volume), presumably from a subducting slab.

DISCUSSION

Tectonic Setting

Ultramafic rocks are exposed in many different tectonic settings in the ocean basins, including oceanic core complexes on slow-spreading ridges (e.g., Cannat, Karson, Miller, et al., 1995), the floors and walls of transform faults (e.g., Dick et al., 1991), the tips of propagating rifts such as Hess Deep and other extensional features such as Kings' Trough, the inner slopes of nonaccretionary trenches where mantle is exposed by tectonic erosion, and deep forearc grabens exposed by extensional tectonics. In every case, regardless of tectonic environment, the incursion of seawater leads to serpentinization, and, in some cases, the serpentinization is extensive. At sites of recent exposure, such as some places along the Tonga forearc, serpentinization has not proceeded very far. The form and composition of the serpentinites are quite similar in most of these settings because the fluid involved in serpentinization is seawater and the process of interaction is passive, leaving the outcrops intact for the most part. Some serpentinite in these settings is disaggregated. Although some controversy still exists as to whether this deformation is the result of formation of talus at the base of slopes or is the consequence of extrusive processes, most results of in situ inspection with submersibles and ODP drilling studies suggest the extrusive model for formation of these structures is less likely (Fryer, 2002).

Serpentinites in the IBM forearc setting have distinctive structural and compositional characteristics that reflect the dynamic nature of formation of the edifice and the unusual composition of the fluids that are the source of the serpentinization of the protoliths. As can be seen from geophysical, petrological, biological, and fluid-geochemical studies, the protoliths show evidence of more complicated origin. They may have been formed originally in an oceanic spreading center setting but show overprints of slab-derived constituents and suprasubduction-zone melting and deformation episodes. Trace element ratios of fluids associated with serpentinite muds indicate that these fluids cannot have formed exclusively as a consequence of simple seawater-rock interaction but must have involved a slab-derived component. The muds themselves are similar to some disaggregated deposits associated with exposures in other types of settings described above, but the form and spatial distribution of the mud flows on the serpentinite seamounts is distinctive. The muds most likely consist of highly comminuted fault gouge with angular to subangular fragments of all sizes, dominantly silt- to sand-sized grains, but also include clasts of rock from pebble to boulder size. The muds may derive from anywhere beneath the edifice, from the subducted slab, the region of the décollement, or the suprasubduction-zone mantle and crust. The mud is too weak (relative to surrounding unserpentinized mantle peridotite [see Phipps and Ballotti, 1992]) to displace surrounding mantle peridotite and rise under gravitational instability alone. Thus, we suggest that extensional faulting in the forearc is necessary for rise and emplacement of the muds.

Geophysics

The outer 50 km of the Izu-Bonin forearc is a ridge of variably serpentinized peridotite (Taylor, 1992; Taira et al., 1998; Takahashi et al., 1998; Sato et al., 2004; Kamimura et al., 2002). Torishima Forearc Seamount rests on top of this ridge, as do many others (Taylor, 1992). There is a suggestion that the low-velocity zone beneath the outer forearc, which on MCS profiles extends downdip along the base of the forearc wedge, may represent the source of the serpentinized peridotite that rises to form the Izu-Bonin serpentinite seamounts. This implies that the mechanism for formation of the serpentinite seamounts of the Izu-Bonin forearc may differ somewhat from that of the Mariana forearc. The idea that the Izu-Bonin seamounts are diapiric and represent the head of rising serpentine mush from deep along the décollement seems at odds with the observation of horizontal layering on MCS profiles beneath Torishima Forearc Seamount (see Horine et al., 1990), and this hypothesis will require more detailed study.

The deep low-velocity layer identified by Fryer et al. (1985) in the Mariana forearc also parallels the inferred top of the subducting slab. The interpretation that this low-velocity layer may be serpentinized peridotite of the mantle wedge seems reasonable, but we do not suggest a diapiric origin for the seamounts in the Mariana forearc. The mechanism of emplacement and formation of mud volcanoes on the Mariana forearc may differ from that of the Izu-Bonin system. The forearc of the Mariana system has undergone far more along-strike extension (Fryer et al., 1985; Fryer, 1992; Wessel et al., 1994) than the Izu-Bonin forearc (Taylor, 1992). Faulting in the Mariana forearc takes place on all scales, and conjugate faulting, likely associated with along-strike extension, is dominant in the southern half of the forearc, whereas trench-parallel faulting is dominant in the north (Stern and Smoot, 1998; Stern et al., 2004). Thus, the avenues for egress of serpentinite muds are more widely distributed in the Mariana forearc than in the Izu-Bonin part of the system.

Serpentinization of the mantle overlying the subducting plate may influence the nature of seismicity along the IBM margin because the phase of serpentine present along the décollement may influence its strength. Seismic velocity alone, however, is not sufficient to identify the phase of serpentine that comprises the zones of low velocity in the deep mantle overlying the subducted slab; thus, we must exercise caution in making predictions regarding the potential physical properties of serpentinized mantle near the décollement. O'Hanley (1996) notes that the most common phase of serpentine at the temperatures and pressures most likely along the décollement of the IBM system anywhere along strike is lizardite. Lizardite is also the dominant serpentinite phase present in samples cored from all of the seamounts examined to date. Lizardite has significantly different physical properties from chrysotile and would not be as likely to behave as a lubricant for the subduction zone, as suggested by Sato et al. (2004) and Kamimura et al. (2002). D'Antonio and Kristensen (2004) note that brucite may also be important in determining low-velocity zones in the forearc and in limiting down-slip earthquakes in subduction zones as suggested by

Peacock and Hyndman (1999). Although geophysical data show a low-velocity region under the entire IBM forearc, we cannot yet determine the composition of the phases present nor their proportions from velocity information alone. The idea that serpentine and brucite in some combination provide an explanation for the aseismic character of the shallow mantle in the Izu-Bonin-Mariana subduction zone (e.g., Pacheco et al., 1993) has considerable merit. However, it remains to be determined how metamorphic minerals lubricate the décollement sufficiently to fit the seismological observations.

Fluids

The pore fluids entrained in the mud flows erupting from these seamounts has a composition unique in the world (Mottl, 1992). There is no doubt that fluids rising with the serpentine muds in the IBM mud volcanoes have a slab-derived signature and that the composition of different seamounts varies with distance from the trench in a consistent manner (Mottl et al., 2003, 2004). There is also no doubt that seawater infiltrates the serpentinite muds once they are exposed at the seafloor following eruption (Mottl, 1992; Mottl et al., 2003, 2004; **Wei et al.,** this volume). The extent to which these two fluids interact is still unknown, as is the hydrologic mechanism for seawater incursion into the interior of the edifices. Both drilling data from Conical Seamount (Sites 788–789; see Fryer and Mottl [1992] and Lagabrielle et al. [1992]) and side-scan sonar data from Conical and several other seamounts on the southern half of the forearc (Fryer et al., 1999) show that the seamounts erupt episodically, possibly in association with earthquake activity along the décollement (Fryer, 1990).

As we consider implications for the observed compositional variations in pore fluids, particularly with regard to estimates of fluid flux in the Mariana system, it is important to remember that we have sampled only a small number of the mud volcanoes present on this convergent margin. Further, we must realize that each sampling is merely a snapshot of the process at any given edifice. Stern and Smoot (1998) presented detailed maps of the Mariana forearc that show far more forearc seamounts than the nine already sampled (including the three that have been drilled). Because the seamounts are episodically active (Fryer, 1992; Fryer et al., 1999), the estimated output flux for Conical Seamount and South Chamorro Seamount (Mottl, 1992; Mottl et al., 2003) may be an underestimate. The overall output flux for slab-derived constituents through the Mariana forearc since subduction began in Eocene time may be far greater than the estimates proposed thus far.

Biological Communities

Numerous deposits of serpentinites on land have been termed sedimentary serpentinites in the early literature and sometimes include marine fossils (Lockwood, 1971, 1972). Active sites like Conical and South Chamorro Seamounts support macrobiological communities and include chemosynthetic microbial communities below the seafloor, feeding on nutrients released during serpentinization and products of fluid-rock-microbial interactions (e.g., methane, other hydrocarbons, sulfate, and sulfides).

The nature of the microbiological communities present on the serpentine seamounts is reflected in the pore fluid compositions of the muds. We have yet to examine the rocks included in the matrix to determine whether they contain a similar microbial community. The differences between the Conical and South Chamorro Seamount communities most likely reflect differences in the rates of extrusion and fluid flow: *Alvin* dives on Conical Seamount reveal heavy manganese coatings, and although there are individual flows that lack sediment cover there are also areas that do have a thin veneer of sediment. This suggests the summit of Conical Seamount is not as active as the unsedimented summit knoll of South Chamorro Seamount. No biological communities have been identified at Torishima Forearc Seamount, suggesting that this seamount is extinct or at least dormant.

We note microbial communities have only been discovered to date near the surface, Bacteria have been observed to ~3 mbsf (Takai et al., 2005) and Archaea to ~ 30 mbsf (Mottl et al., 2003) at South Chamorro Seamount. Preliminary analyses of recently collected *Jason* 2 remotely operated vehicle (ROV) push cores from several other seamounts show the presence of similar communities on other active seamounts (Curtis and Moyer, 2005). The alkaliphilic bacteria *Marinobacter alkaliphilus*) (Takai et al., 2005) appear to be inoculated into the serpentinite muds from seawater as it infiltrates the newly erupted materials, but both the bacteria (and the more voluminous population of Archaea in the deeper muds [Moyer, pers. comm., 2004]) require the unique geochemical conditions provided by the pore fluids in these muds.

Petrology

The geochemical characteristics of the Izu-Bonin and Mariana forearc serpentinites suggest a close link to subduction processes, both in terms of origin of the fluids responsible for the bulk of the serpentinization and in terms of the mechanism of formation of the mud volcanoes. There is evidence from drilling during Leg 125 that the serpentine seamounts may be long lived (Fryer, 1992). Eocene sediments recovered from Deep Sea Drilling Project (DSDP) Site 459 near one of the serpentine seamounts on the Mariana forearc contain serpentine (Despairies, 1982). Thus, it is possible that the seamount had formed and was shedding serpentinite muds onto the adjacent forearc in the earliest stages of subduction at this convergent margin (Fryer, 1992).

The wide range of rock types in the serpentinite mud flows from the volcanoes of the IBM forearc region indicates that they sample the entire forearc mantle and crust as well as the subducting plate. The clasts include metamorphosed peridotitic and mafic rocks (Maekawa et al., 1992, 1993, 1995; Fryer et al., 1999; Fryer and Todd, 1999; Todd and Fryer, 1999), altered mafic rocks from the subducted plate, including N-MORB, transitional MORB, ocean island basalt (OIB), and even hemipelagic cherts (presumably also derived from the subducted plate), as well as island-arc tholeiite (IAT) and boninite from the suprasubduction-zone igneous basement (Johnson and Fryer, 1990; Johnson, 1992; Johnson et al., 1991). Incipient blueschist metamorphic rocks recovered by drilling during Leg 125 from Conical Seamount provided the first proof that high-pressure/low-temperature metamorphism does indeed occur under active convergent margin systems (Maekawa et al., 1993; Fryer et al., 1999; Fryer and Todd, 1999; Todd and Fryer, 1999). Amphiboles with sodic rims and calcic cores display nearly ubiquitous prograde reactions (Fryer et al., 2000), suggesting a relatively short residence time at high-pressure/low-temperature conditions and a relatively rapid rise to the seafloor from the source region. Although retrograde metamorphic reactions are generally sluggish and high-pressure phases can persist metastably to low pressures, both the décollement source region for the rocks and the conduits of the mud volcanoes are likely to be strongly reactive environments because they are tectonically dynamic and fluid-charged and would thus favor retrograde reactions. If seismic activity along the faults underlying the seamounts triggers episodes of mud protrusion (Fryer, 1992), then the mud flows most likely contain rock clasts derived primarily from the slip surface but could also contain material from anywhere along the route to the seafloor. The subtle variations among flow units from the flank site drilled during Leg 125 show that discrete units, thus discrete source regions, can be distinguished in individual protrusion events. What we do not yet know is the rate of protrusion or the variation in volume of the individual units

There are several models for complexities of mantle flow in suprasubduction-zone regions, but D'Antonio and Kristensen (2004) and Savov et al. (this volume, 2005), based on REE abundances and systematics of cpx grains, propose that deep subarc mantle materials can reach the cold forearc ("corner") region. They suggest that differences in the degree of melting experienced by the subarc mantle could not explain the variations in the degree of depletion recorded in the Izu and Mariana arc lavas alone. They suggest that if this were so, the IBM arc lavas should be similar along strike, but this is not the case. Lavas from the Izu segment are significantly more depleted than Mariana segment lavas (Elliot et al., 1997; Ishikawa and Tera, 1999; Stern et al., 2004). Yamazaki and Yuasa (1998) proposed that there is some evidence from magnetic and gravity anomalies that there was a period of rifting in the middle Miocene that affected the Izu section of the Izu-Bonin arc. This could help to explain some of the along-strike differences in the two arcs. Whether this also explains some of the differences between forearc peridotitic compositions is still unresolved. Macpherson and Hall (2001) noted that the volume estimates for eruptive products in the IBM system given by Bloomer et al. (1995) may be low by a factor of 2 and stress the large extent and volume of boninitic lavas erupted essentially contemporaneously throughout the system. The formation of the ridges west of the Shikoku Basin (Oki-Daito Ridge and Amami Plateau) and the comparatively low volume of boninite in other arc systems may reflect a relatively short period during the early Eocene or earliest middle Eocene in which a hotspot (possibly the Manus plume) influenced volcanism in the nascent IBM system. Macpherson and Hall (2001) also note peculiarities of trace element compositions in the lavas from the early arc and forearc regions of the IBM system that suggest little input from a subducted slab (e.g., Pearce et al., 1999). One interesting corollary of the Macpherson and Hall (2001) hypothesis is that this hotspot model for early influence over the nature of magmagenesis in the IBM system also implies that thermally controlled upwellings (the hotspot plume) and downwellings (associated with the initiation of subduction) in the mantle may occasionally interact (Macpherson and Hall, 2003). If this hypothesis is tenable, how such interaction may have influenced the history of the forearc mantle remains to be determined.

CONCLUSIONS

A process by which serpentinite fault-gouge protruded onto the seafloor in suprasubduction-zone environments was first suggested by

Lockwood (1971, 1972) as mechanism for formation of "sedimentary serpentinite" in a marine setting. The discovery of active serpentinite mud volcanism on the Mariana forearc and recent mud volcanism in the Izu-Bonin forearc during Leg 125 revived the study of this phenomenon. This type of mud volcanism only occurs in nonaccretionary convergent margins, and forearc extensional deformation is key to emplacement of the mud flows at the seafloor. The drilling results from serpentine seamounts drilled during Legs 125 and 195 show us that composition of the serpentinite muds and the metamorphosed peridotite clasts included in them can vary regionally. The slab-derived fluids in these muds are unique among pore fluids from oceanic sediments. The fluids show systematic variation in composition with distance from the trench and are thus related to depth to the slab. The complexity in distribution of various slab-derived volatile-mobile trace elements suggests that the suprasubduction-zone mantle that is altered by them may be being recycled downdip to greater depth beneath the arc. The serpentinite clasts in the muds erupted at sites in the forearc of the Izu-Bonin system shows that the mantle of that forearc has experienced a different history of both magmatic and melt-fluid interaction than that of the Mariana system. Mafic rocks brought up in the Mariana serpentinite mud flows derive from both the subducted slab and the overlying forearc crust (none were recovered from the Izu-Bonin seamount drilled). The slab-derived metabasites have mineralogic and compositional characteristics that have been used to constrain the temperature and depth conditions of their metamorphism and place them in the incipient blueschist facies. The mud flows with their included rock clasts provide a window into suprasubduction-zone mantle processes, as well as those at work within the décollement itself.

Serpentinite mélange deposits occur world-wide, and those that formed by mud volcanism in forearc environments can be recognized by careful analysis of the sheared and unconsolidated matrix serpentines, the variously metamorphosed ultramafic and mafic clasts entrained within the mud flows, and the composition of the of the serpentinites. The chief characteristics that distinguish the serpentinite massifs of convergent margins from those of other tectonic settings in the oceans are the overprint of subduction-derived constituents in the peridotitic protoliths and their derivative melts, the altered and metamorphosed metabasic rocks associated with the serpentinites, and possibly the subtle geochemical and mineralogical consequences of the unique biological activity that characterizes these remarkable sites. Serpentinite mud volcanism may be the origin of some of the world's most complex and voluminous serpentinite terranes on former convergent margins.

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Figure F1. Bathymetric map of the Izu-Bonin-Mariana region color-contoured in shaded bathymetric relief. The two boxes show the locations of Figures F2, p. 27, and F3, p. 28 (map constructed using Generic Mapping Tools [GMT] software [Wessel and Smith, 1995] and the Smith and Sandwell [1977] data set).

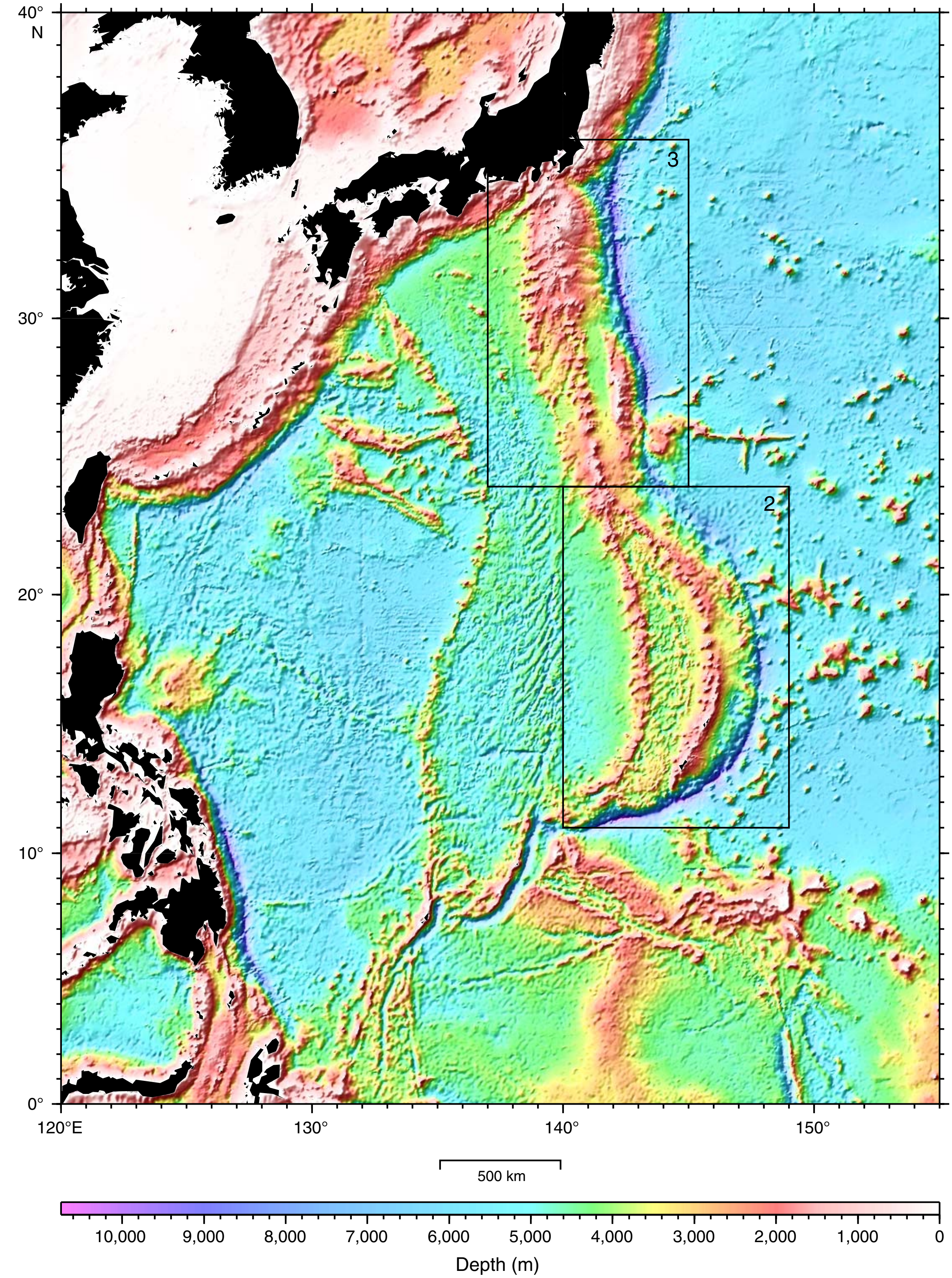

Figure F2. Bathymetric map of the Mariana region color-contoured in shaded bathymetric relief (map constructed using Generic Mapping Tools [GMT] software [Wessel and Smith, 1995] and the Smith and Sandwell [1977] data set).

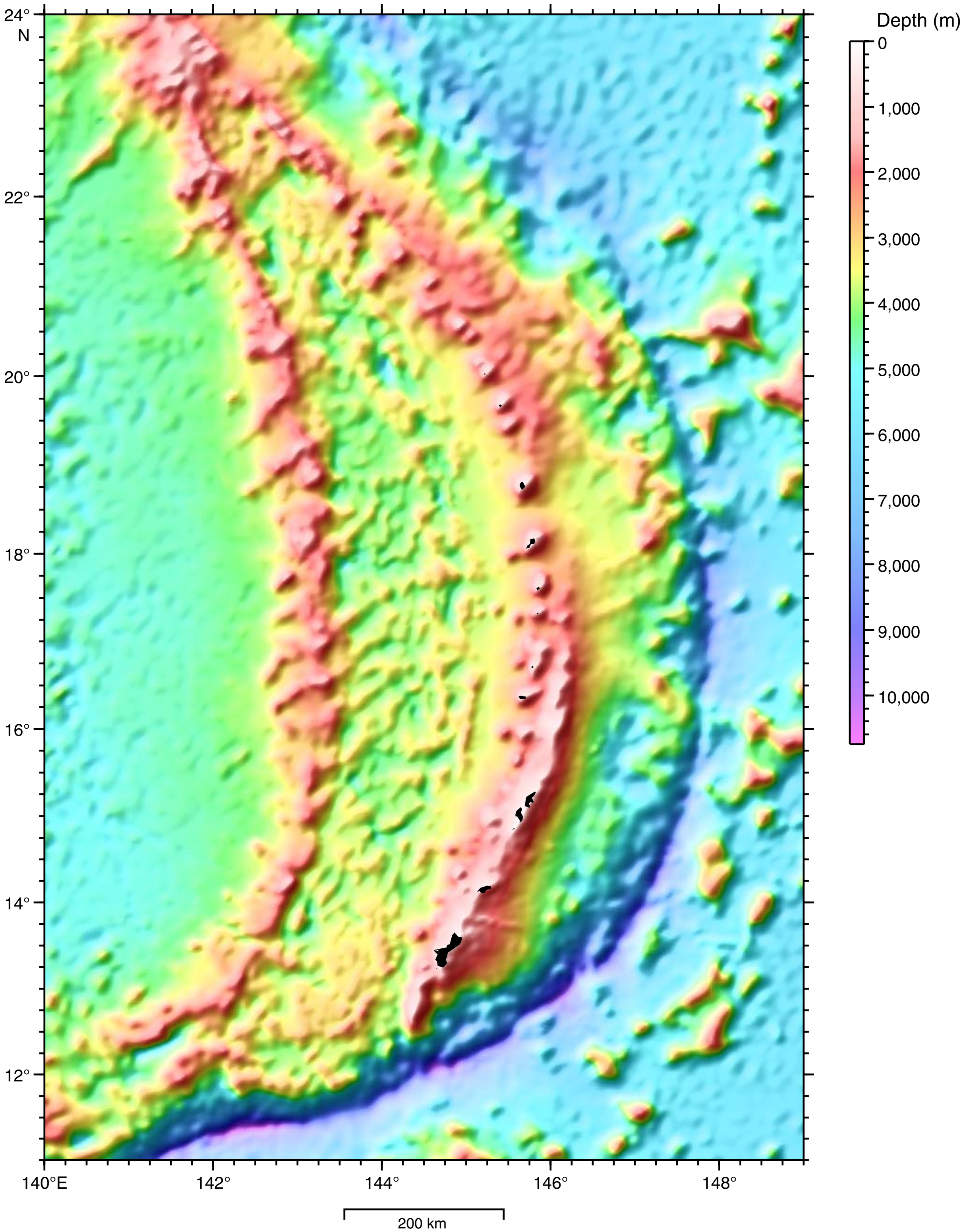

Figure F3. Bathymetric map of the Izu-Bonin region contoured at 500-m intervals (Taylor, 1992).

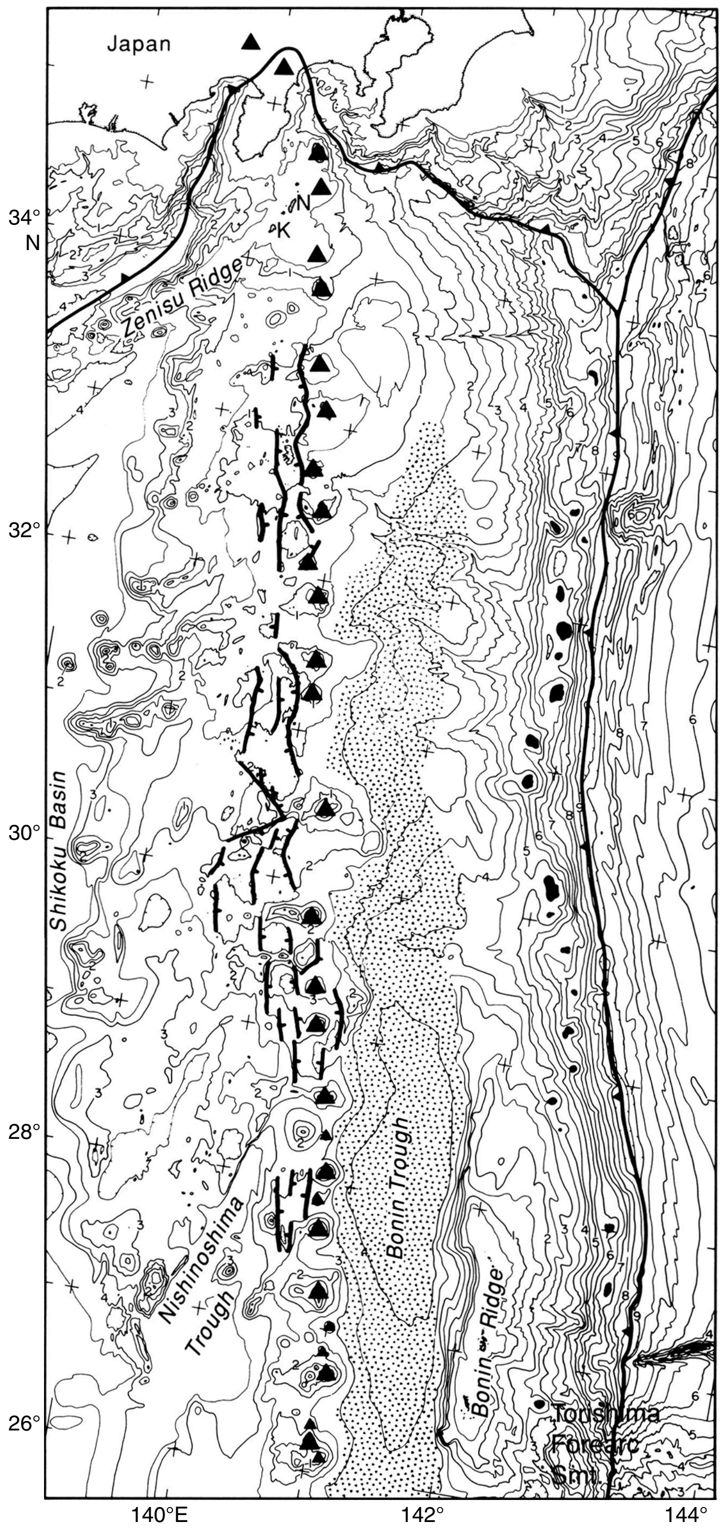

Figure F4. Schematic cross section of the Mariana forearc showing generalized structural relationship of serpentinite mud volcanoes to faulting in the outer half of the forearc (after Fryer et al., 1999).

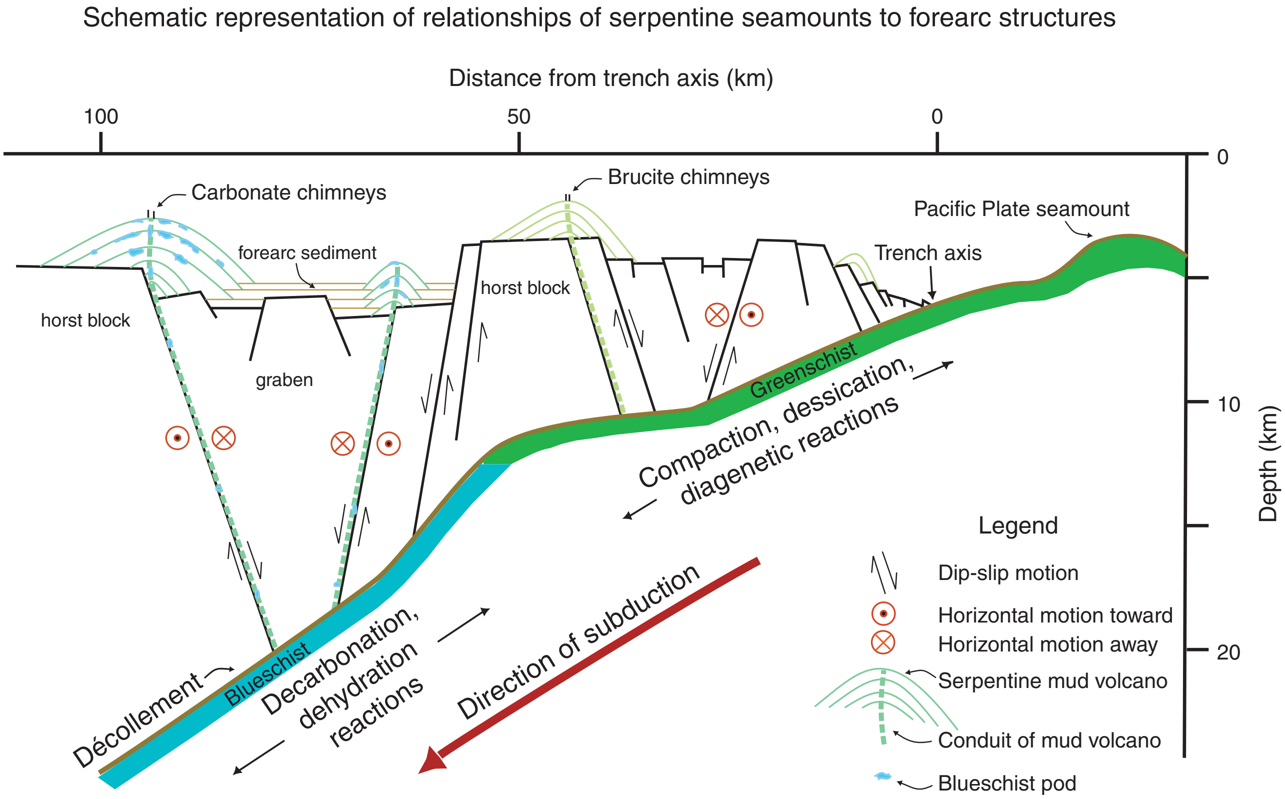

Table T1. Composition of pore water from serpentinite seamounts drilled during ODP Legs 125 and 195 vs. seawater.

Component	Conical	Torishima Forearc		South Chamorro	Seawater
ODP site:	780	783	784	1200	
Location:	19°32.5′N, 146°39.2′E	30°57.86′N, 141°47.27′E	54.49′N, 44.27′E	13°47.0′N, 146°0.2′E	
Deepest sample (mbsf):	130	400		71	
Cations/anions (mmol/kg):					
Chloride	260 ± 25	550 ± 5		510 ± 5	542
Sulfate	46 ± 1	9 ± 3		28 ± 1	28
Alkalinity	52 ± 13	1.3 ± 0.4		62 ± 8	2.3
Carbonate alkalinity (meq/kg)	35 ± 15	1.1 ± 0.4		45 ± 7*	1.9
pH at 25°C	12.5 ± 0.1	9.6 ± 0.4		12.5 ± 0.1	8.1
Na	390 ± 10	460 ± 20		610 ± 10	466
Na/Cl (molar)	1.5 ± 0.1	0.84 ± 0.02		1.2 ± 0.02	0.86
K	15 ± 1	5 ± 1		19 ± 1	10.1
Mg	0.003 ± 0.002	1 ± 1		<0.01	52.4
Ca	1 ± 0.5	55 ± 5		0.3 ± 0.1	10.2
Charge balance (calc.)	3.0 ± 25	7.7 ± 20		1.6 ± 10	0.9
Trace components (µmol/kg):					
CH_4	2000 ± 1000	2 ± 1		2000 ± 1000*	0.0004
Li	1.6 ± 0.5	16 ± 5		0.4 ± 0.1	26
Rb	7.8 ± 0.6	1 ± 0.2		10 ± 2	1.37
Sr	20 ± 10	200 ± 50		10 ± 2	90
Ba	0.1 ± 0.05	1.6 ± 0.7		0.4?	0.14
B	3900 ± 100	180 ± 80		3200 ± 200	410
Si	60 ± 30	10 ± 8		70 ± 20	190
F	NA	NA		47 ± 3	67
Mn	<0.01	0.4 ± 0.2		0.01	0
Fe	2 ± 1	1 ± 0.9		2 ± 0.5	0
Phosphate	0.4 ± 0.3	NA		0.2	2.8
NH_3	265 ± 5	140 ± 20		220 ± 10	0
Reduced sulfur (total)	<250	0		<250	0
C_2H_6	7	0		2	0
C_1/C_2	290 ± 15			780 ± 10	
$^{87}Sr/^{86}Sr$	<0.7062	<0.7070		0.70535 ± 0.0001	0.7091
$\delta^{34}SO_4$ (‰ CDT)	13.7 ± 0.3	31.2 ± 0.4		NA	20.5
$\delta^{18}O$ (‰ SMOW)	4.0 ± 0.6	–0.4 ± 0.2		2.5 ± 0.5	0
δD (‰ SMOW)	3 ± 2	–2 ± 2		12 ± 2	0

Notes: Table after Mottl et al. (2003). Conical and South Chamorro Seamounts represent asymptotic composition of deep upwelling fluid from an active mud volcano. Conical Seamount data are from Mottl (1992), Mottl and Alt (1992), Haggerty and Chaudhuri (1992), and Benton (1997). Torishima Forearc Seamount represents a product of harzburgite-seawater reaction within an inactive mud volcano in the Izu-Bonin forearc (Mottl, 1992). Seawater composition is estimated from local bottom water. Carbonate alkalinity calculated using the PHREEQC program (Parkhurst and Appelo, 1999). CDT = Canyon Diablo troilite, SMOW = Standard Mean Ocean Water. * = $\delta^{13}CH_4$ = –11‰ ± 5‰ Vienna Peedee belemnite (VPDB) and δ^{13}C-DIC = –18‰ ± 3‰ VPDB at 15 mbsf.