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1. INTRODUCTION TO THE SCIENTIFIC RESULTS OF LEG 125[1]

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INTRODUCTION

The present-day tectonic configuration of the Izu-Bonin and Mariana regions (Fig. 1) comprises, from east to west: the trench; the forearc region (between the trench axis and the active volcanic arcs of the two systems), made up of an inner trench wall that in the Bonin system has a 40-km-wide along-strike terrace or ridge, an outer-arc high, a forearc basin, and a frontal-arc high; the active Izu-Bonin and Mariana volcanic arcs; the actively spreading Mariana Trough, a backarc basin; the actively rifting Izu-Bonin backarc rift basins; the West Mariana Ridge, a remnant arc; the Parece Vela and Shikoku marginal basins; and the Palau-Kyushu Ridge, the westernmost remnant arc. Subduction of Pacific oceanic lithosphere is currently taking place at absolute velocities between 8 and 10 cm per year to the northwest; the subduction angle is about 12° at shallow depths, steepening in some places to nearly vertical below about 80 km.

The evolution of these arc and basin systems is thought to have begun in the early-middle Eocene when westward subduction of Pacific lithosphere began beneath the West Philippine plate (Karig, 1975). Development of the system continued through the early Oligocene, forming an intraoceanic volcanic arc on top of a 200-km-wide forearc region composed of volcanic rocks primarily of tholeiitic to boninitic affinities (Natland and Tarney, 1981). In the Mariana area, this arc formed on or near the edge of the West Philippine Basin, whereas in the Bonin area, it formed on the edge of the Amani-Oki Daito province, a series of island arcs and intervening basins of Santonian to Paleocene age (Taylor et al., 1990b). Middle Oligocene rifting split the arc, and late Oligocene to early Miocene backarc spreading in the Parece Vela and Shikoku basins isolated a remnant arc (the Palau-Kyushu Ridge) from an active Bonin-Mariana arc (Kobayashi and Nakada, 1979). The initiation of this backarc spreading event was not synchronous along the length of the Oligocene arc. Spreading began at about 31 Ma in what became the central Parece Vela Basin and propagated both north and south, giving the basin its bowed-out shape. A second spreading episode began by 25 Ma in what became the northernmost Shikoku Basin and propagated south (Kobayashi and Nakada, 1979). By 23 Ma the two systems had joined at what is now approximately 25° N, and both basins shared a common spreading axis until spreading ceased at 17–15 Ma.

A repetition of this cycle of events began in the late Miocene when the southern part of the arc split again. Subsequently, 6–8 m.y. of spreading in the Mariana backarc basin isolated the active Mariana arc from, and increased its curvature with respect to, a remnant arc, the West Mariana Ridge (Karig et al., 1978; Hussong and Uyeda, 1981). Spreading in the Mariana backarc basin may now be propagating to the north, "unzippering" the Mariana arc from the West Mariana Ridge (Stern et al., 1984). The Izu-Bonin arc is still in the early rifting stage of backarc formation, undergoing extension along most of its length (Honza and Tamaki, 1985). The major zone of rifting lies immediately west of the active volcanic chain, but some volcanoes near 29° N are surrounded by grabens (Taylor et al., 1985; 1991). Volcanism is continuing along both the active and remnant arcs, and volcanic centers have also developed in the rift basins. The latter contain lavas with a bimodal basalt-rhyodacite composition (Fryer et al., 1990). The basalts have major and trace element abundances that resemble the backarc basin basalts of the Mariana backarc basin rather than the island arc basalts of the adjacent active Izu-Bonin arc (Fryer et al., 1985a; Hochstaedter et al., 1990).

The differences in arc and backarc basin evolution between the Mariana and Izu-Bonin systems have produced corresponding differences in their forearc regions. These differences are further accentuated by the fact that seamount chains and aseismic ridges on the subducting Pacific Plate have collided only with the Mariana system and southernmost Izu-Bonin arc. The Izu-Bonin forearc region has experienced little deformation since subduction began (Honza and Tamaki, 1985); thus, it has a broad forearc basin filled with volcaniclastic and hemipelagic sediments that developed behind an outer-arc high (Fig. 2). Biostratigraphic dating of the strata that lap onto this high, both at sea and on its subaerial expression on the Bonin islands (Hanzawa, 1947), suggests that this high has been a positive topographic feature since its uplift in the early Eocene. Several mature, dendritic submarine canyon systems have developed across the Izu-Bonin forearc basin and the outer-arc high by mass wasting and headward erosion. These canyons have incised as much as 1 km into the 1.5–4 km thick sedimentary section (Taylor and Smoot, 1984). A terrace or ridge with its apex located approximately 25 km west of the trench axis parallels the strike of the Izu-Bonin Trench. Chloritized basic and serpentinized ultramafic rocks have been dredged from a chain of local highs located along this terrace. (Fryer and Fryer, 1987; Horine et al., 1990).

The Mariana forearc region (Fig. 3) has a broadly similar structure to that of the Izu-Bonin forearc region, but has undergone extensive vertical uplift and subsidence resulting from seamount collision, and tensional and rotational fracturing associated with adjustments to plate subduction, and to changes in configuration of the arc. Fractures in the forearc region may have provided egress for rising serpentine from the underlying mantle wedge. A broad zone of serpentine seamounts (up to 2500 m high and 30 km in diameter), 50–120 km from the trench axis, occurs along the trench-slope break (outer-arc high) of the Mariana system (Fig. 4). These seamounts are formed by the rise and protrusion of serpentine bodies (Fryer et al., 1985b; Fryer and Fryer, 1987). These serpentine seamounts may represent the nonaccretionary intraoceanic forearc analogue of dewatering zones in accretionary sedimentary wedges. Only very minor, and probably ephemeral, accretionary complexes occur at the bases of the inner walls of the Izu-Bonin and Mariana trenches. There have been localized episodes of accretion of fragments of oceanic plate both in the southern portion of the Mariana forearc, at about 12° to 14° N (Karig and Ranken, 1983), and in the vicinity of the Leg 125 drilling (Johnson and Fryer, 1990; Johnson et al., 1991).

ODP Leg 125 was designed to study two important and poorly understood aspects of these systems. First, the origin and evolution of the forearc terranes was to be investigated by drilling a series of holes through the sediments into the basement of the Izu-Bonin forearc basin and into two serpentine seamounts on the Mariana forearc region and on the Izu-Bonin lower slope terrace. Second,

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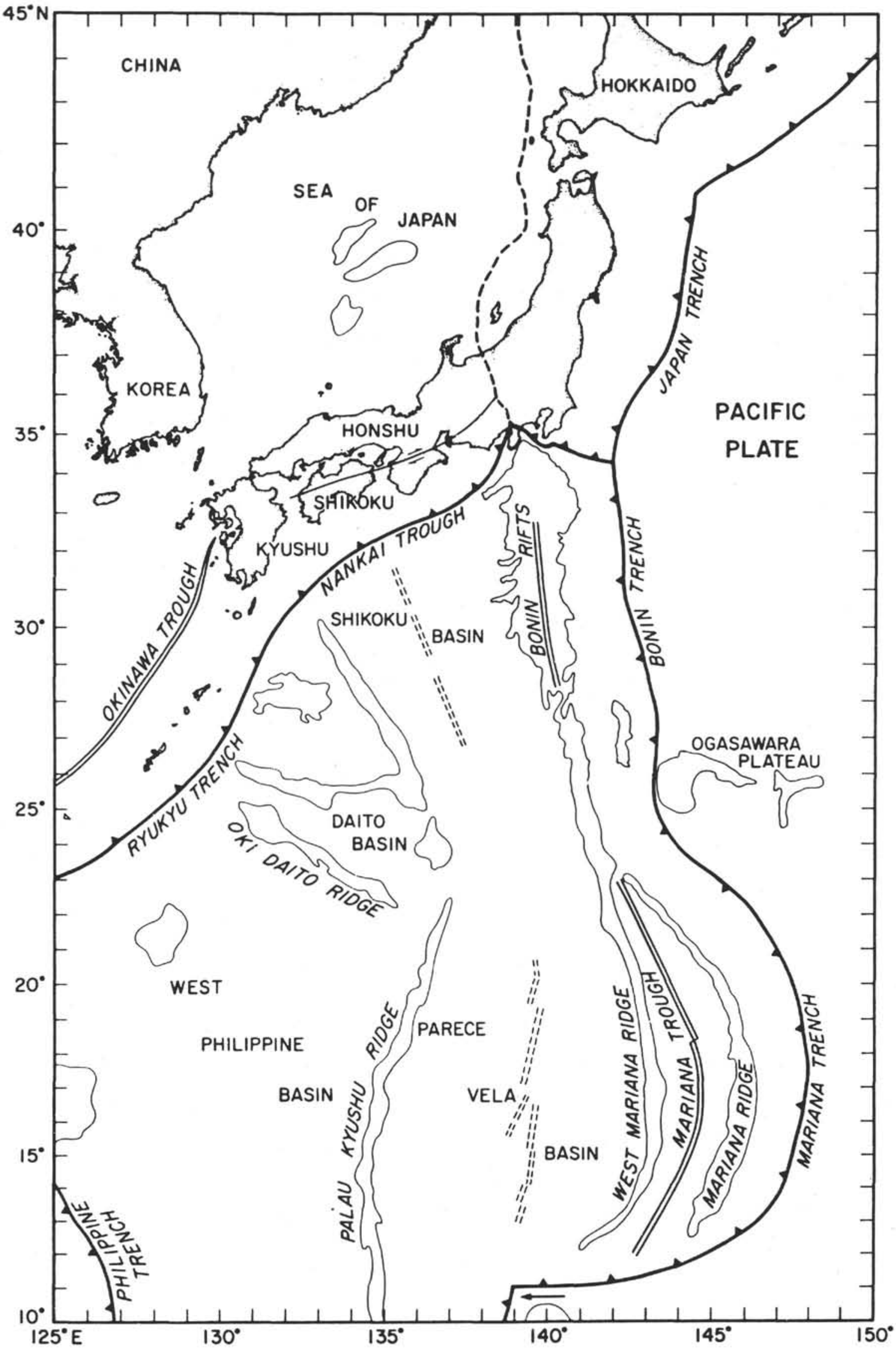

Figure 1. Bathymetry and geologic features in the Philippine Sea region. Basins and ridges are outlined by the 4-km bathymetric contour, except for the Izu-Bonin arc, West Mariana Ridge, and Mariana arc, which are outlined by the 3-km contour. Barbed lines locate axes of trenches; medium double lines locate active spreading centers; dashed double lines locate relict spreading centers.

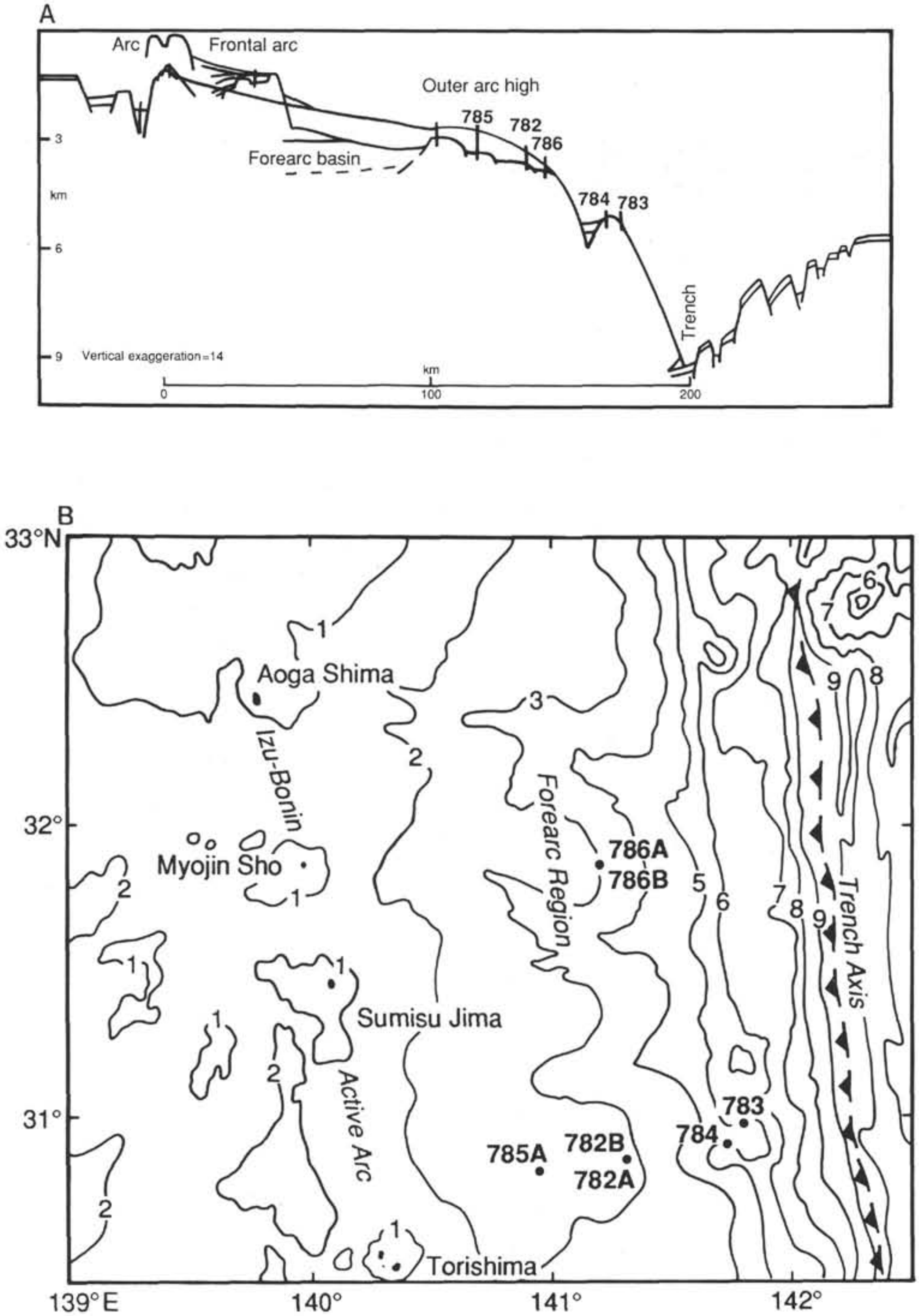

Figure 2. Schematic cross section (**A**) of the Izu-Bonin forearc region showing the morphology of the frontal arc (both adjacent to arc volcanoes, as in the upper trace, and in intervolcanic regions, as in the lower trace), the outer-arc high (locations of Sites 782, 785, and 786), and a sediment-draped ridge along the inner wall of the trench (locations of Sites 783 and 784). Bathymetry (**B**) of the Izu-Bonin forearc showing the location of the Leg 125 drill sites. Contours are in 1000-m intervals.

dewatering of the subducted lithosphere was to be investigated indirectly from the composition of the forearc basin and arc volcanic rocks recovered from sites on the Izu-Bonin forearc region, and directly from the analyses of fluids, chemical precipitates, and metamorphic rocks from the serpentine seamounts on the forearc regions of both systems.

ARC/FOREARC DEVELOPMENT: BACKGROUND TO SITES 782, 785, AND 786

Prior to Leg 125 drilling our direct knowledge of intraoceanic forearc basement was based primarily on data from three island chains and two Deep Sea Drilling Project (DSDP) sites: the Mariana and

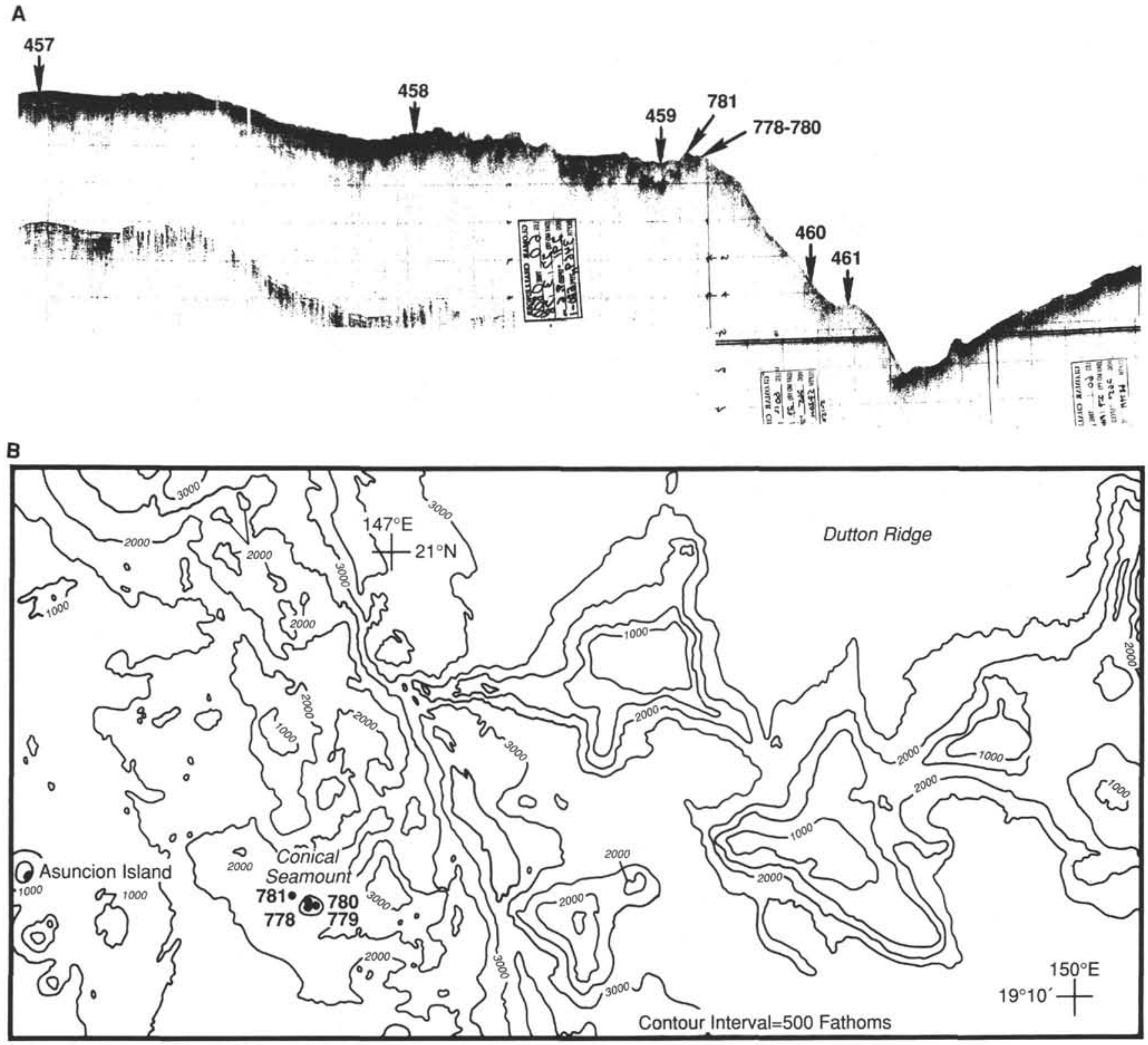

Figure 3. Seismic reflection profile (**A**) of the Mariana forearc region showing the morphology of the region and the relative locations of sites drilled on DSDP Leg 60 (Sites 457–461) and ODP Leg 125 (Sites 778–781). Bathymetry (**B**) of the Izu-Bonin forearc showing the location of the Leg 125 drill sites. Contours are in 500-m intervals.

Tonga frontal arc islands (Guam, Saipan, and 'Eua) and the Bonin islands, which expose Eocene island arc tholeiites and boninites (Reagan and Meijer, 1984; Ewart et al., 1977; Shiraki et al., 1980); DSDP Leg 60 Sites 459 and 458, which sampled Eocene arc tholeiites and lower Oligocene boninites and arc tholeiites, respectively, from the Mariana outer-arc high; and dredges from inner trench walls and large fault scarps (Bloomer and Hawkins, 1983; Bloomer and Fisher, 1987; Johnson and Fryer, 1990; Johnson et al., 1991).

Basement beneath the thickly sedimented upper-slope basin between the frontal arc and outer-arc high had never been sampled. Only in dredge hauls at one site in the Mariana forearc, close to Conical Seamount, had the deep forearc basement beneath the carapace of interbedded arc pillow lavas, flows, and sills been sampled (Johnson and Fryer, 1990). From the available data, it appears that the current 150–220-km-wide Izu-Bonin and Mariana forearc regions formed in large part by volcanism during the initial stages of arc development in the Eocene and early Oligocene. Similar volcanism has not occurred since and cannot to our knowledge be studied as an active phenomenon anywhere on Earth at present.

There are three main alternative hypotheses for the origin and evolution of this forearc terrane: (1) the frontal arc and outer-arc high could have originally been continuous and subsequently separated by forearc spreading; (2) the frontal arc and outer-arc high could have been built separately, but nearly synchronously, on former West Philippine plate crust; or (3) the terrane could form part of a continuous Eocene arc volcanic province, possibly with overprints of later forearc volcanism. Each scenario of forearc basement development implies a different crustal structure for the forearcs. The fundamental question is: how do these different structures relate to ophiolite sheets? Many authors now ascribe a majority of ophiolites to subduction-related settings because of their chemistry and associated sediments. Pearce et al. (1984) proposed that supra-subduc-

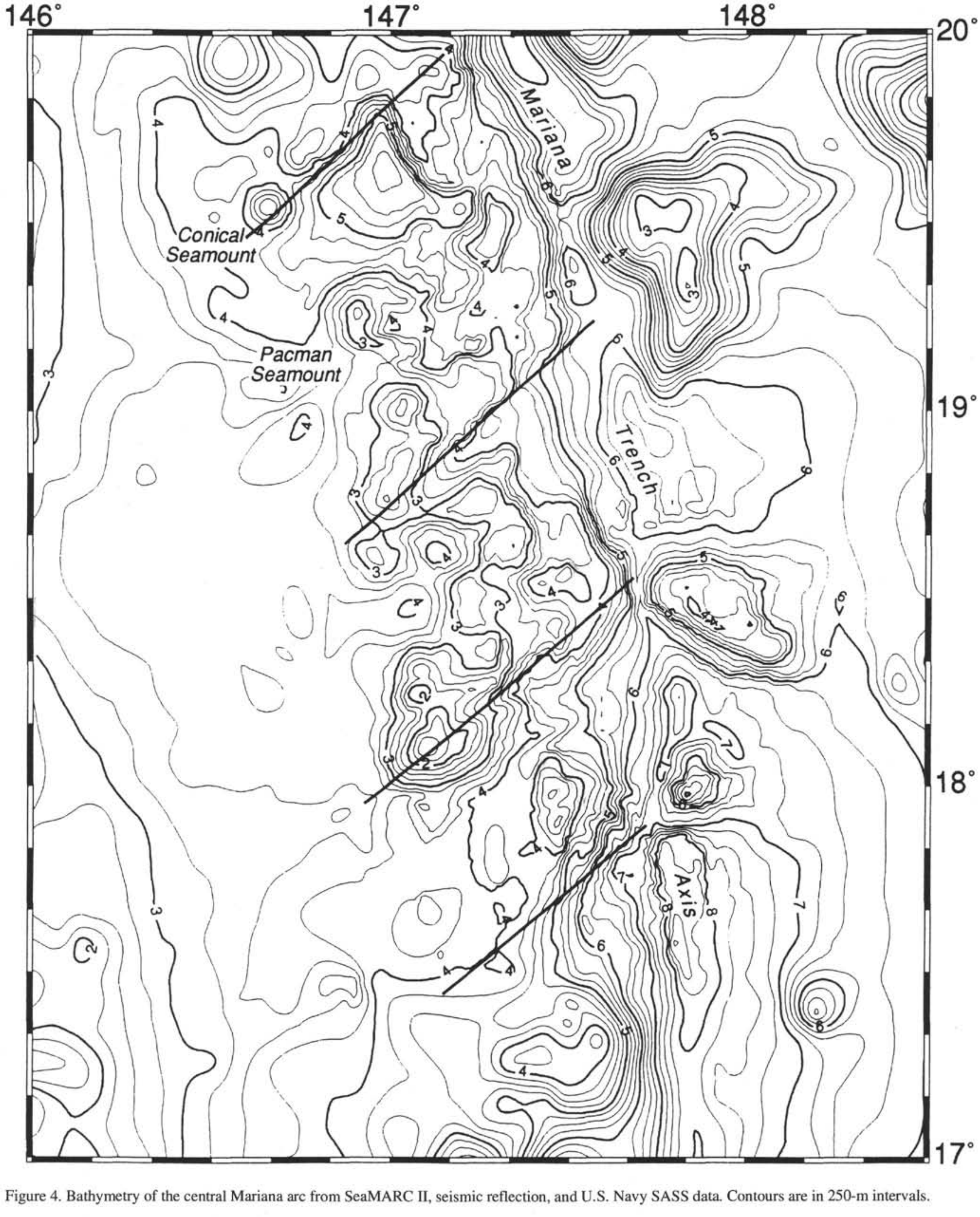

Figure 4. Bathymetry of the central Mariana arc from SeaMARC II, seismic reflection, and U.S. Navy SASS data. Contours are in 250-m intervals.

tion zone (SSZ) ophiolites (having the geochemical characteristics of island arcs, but the structure of oceanic crust) formed by seafloor spreading during the initial stages of subduction prior to the development of any volcanic arc. Boninites, whose type locality is the Bonin Islands, are a common occurrence in SSZ ophiolites. They appear to require variable degrees of hydrous partial melting of a refractory source to produce wet magmas. These magmas then rise to shallow depth while maintaining fairly high temperatures to avoid amphibole crystallization. These unusual conditions may occur only during initial subduction or arc rifting, however, the eruptive style and exact tectonic setting of the Eocene volcanism is unclear. Multichannel seismic (MCS) surveys of the Izu-Bonin forearc region have revealed a complicated basement which is often seismically stratified and cut by dipping reflectors (Taylor et al., 1990a). These reflection characteristics are unlike those of normal oceanic crustal sections and suggest that the Eocene volcanism may have been accompanied by stretching tectonics and/or that it was superimposed on an older arc terrane such as the Amani Plateau (Taylor et al., 1990a). The drill sites in the Izu-Bonin forearc basin sampled the hitherto unstudied forearc basement and the interpretations of data from the holes provide constraints on some of these models for forearc evolution.

The forearc stratigraphy records a history of the variations in intensity and chemistry of arc volcanism and allows the correlation of these variations with such parameters as subduction rate and backarc spreading. Karig (1975) proposed that periods of arc volcanic maxima correlated with periods of marginal basin formation and high subduction rate. Scott and Kroenke (1981) suggested rather that initial periods of backarc spreading are coincident with minimal arc volcanism. Contrary to both, Hussong and Uyeda (1981) inferred that arc volcanism has probably been continuous since the Eocene, but that the initiation of backarc spreading by rifting of the arc produced drastic subsidence of the arc volcanoes, resulting in deep-water eruptions with limited lateral transport of volcanic material. Studies of the tephrochronology, and the frequency and geochemistry of ash and pyroclastic flow deposits in the forearc basin drill cores, enable these various models to be evaluated. Such studies also test whether boninitic (Beccaluva et al., 1980), alkalic (Stern et al., 1984), and/or rhyodacitic (Gill et al., 1984; Fryer et al., 1985a) volcanism characterizes periods of arc rifting.

Paleomagnetic studies of the subaerial portions of the Izu-Bonin and Mariana forearc regions have shown at least 20° of northward drift and 30° to over 90° of clockwise rotation since the Eocene (see summary in Keating et al., 1983). How and when these motions occur, and the nature of their relationship to the overall structural evolution of the forearc, are enigmatic. One model would suggest that the islands acted as "ball-bearings" between the Pacific and Philippine plates. Karig and Moore (1975) suggested that they might be an exotic terrain introduced from the south by oblique motion. However, marine geophysical data indicate a structural continuity of the Bonin Islands with the outer-arc high (Honza and Tamaki, 1985) and support the model of Keating et al. (1981) that the Bonin Islands (and therefore the Philippine plate) were situated near the Equator in the Eocene, roughly perpendicular to their present trend. If true, this has major implications for reconstructions of the Philippine and surrounding plates, and the related issues of initial subduction and West Philippine Basin evolution.

SERPENTINE SEAMOUNTS: BACKGROUND TO SITES 778–781

Drilling of Mariana and Izu-Bonin forearc sites in serpentinite materials addressed the problems of the nature and origin of serpentine in nonaccretionary, intraoceanic forearcs and provides information on the dewatering of the lithosphere during subduction, the composition of the mantle wedge, and the development of the outer forearc regions of intraoceanic island arcs.

Conical Seamount, Sites 778–781 (Fig. 5), is in the broad zone of forearc seamounts along the Mariana outer-arc high (see Fig. 4). It is a roughly circular seamount, rising 2000 m above the seafloor a distance of 80 km from the trench axis. Recent flows of unconsolidated fine-grained serpentine mantle its surface, and there is evidence within the edifice for recent deformation of the serpentine sequences (Fryer et al., 1990). Fluids are seeping from chimneys and related structures on the summit of the seamount, precipitating carbonate and silicate compounds that are cementing the uppermost portion of the serpentine flows (Fryer et al., 1987; Haggerty, 1987). Prior to Leg 125, studies of the composition of fluids actively seeping from chimney structures on Conical Seamount have revealed high pH, high alkalinity, and enrichment in SiO_2, SO_4, H_2S, methane, and propane (Fryer et al., 1990). The H_2S and hydrocarbons detected in the vent fluids are particularly interesting. The Mariana forearc region has only a small volume of sedimentary substrate (Hussong and Uyeda, 1981) with organic carbon contents typically less than 0.3% (Schorno, 1981), thus the hydrocarbons and sulfide in the Mariana vent fluids are unlikely to have formed by the biogenic processes (Kulm et al., 1986) associated with accretionary complexes. Rather, they may be generated during serpentinization reactions or derive from a source in the underlying mantle or the downgoing oceanic plate. Trace element and stable isotopic compositions of the carbonate chimney materials from Conical Seamount are also consistent with deposition from serpentine-related fluids that contained components either from the forearc mantle, or from the subducted slab, or both (Haggerty, 1987). Overall, the chemical analyses of these fluids imply that deep-seated serpentinization processes, fluids derived from the subducted plate, juvenile mantle fluids, interaction of seawater with crustal rocks, and interactions of seawater with the surficial serpentinite may all contribute to the composition of the fluids. Studies of the pore waters from the sites on Conical Seamount define the constraints on these hypotheses.

The physical properties of the seamount and the mechanism of its emplacement were studied in greatest detail at Site 779. The rising serpentine of Conical Seamount loses entrained fluids during protrusion of the serpentine flows onto the surface. It is likely that settling of the flows occurs soon after they are protruded, perhaps owing to the escape of the entrained fluids (Fryer et al., 1990). Once the rising serpentine has stopped protruding and/or stopped venting fluids, the density of the serpentine deposits increases. The physical properties of the deposits change with depth as well as with age. Documenting such changes and the study of the physical properties of the serpentine deposits allows us better to interpret similar deposits studied in subaerial exposures such as those of the basal Great Valley sequence in Napa County, California (Phipps, 1984).

The process of serpentinization of forearc materials was also investigated at Sites 783 and 784 on Torishima Forearc Seamount on the outermost part of the Izu-Bonin forearc region (Figs. 2 and 6). Swath-mapping of the lower slope terrace, which runs along the inner wall of the Izu-Bonin Trench (Taylor and Smoot, 1984) shows that this feature is not a simple linear structural ridge. It is composed of a series of seamounts spaced at intervals of 15–40 km, with summit depths between 4 and 7 km. Several dredges and one core from seamounts along this ridge have yielded serpentinized harzburgite, metamorphosed gabbro, dolerite, and basalt, and their sedimentary derivatives (serpentinite breccia, sandstone, and mudstone) (Ishii et al., 1981). SeaMARC II surveys of the three seamounts south of 32° N indicate sedimented slopes with some radial debris flows (B. Taylor, 1990, pers. comm.), and seismic reflection profiles along and across the seamounts reveal an acoustically chaotic basement with thin or no sediment cover (Horine et al., 1990). Most of the inner trench wall, both above and below the terrace, has been stripped of sediment, presumably by slumping. However, sediments showing complex unconformities, both turbidite deposits and pelagic sequences, are ponded behind the seamounts, drape their lower flanks, and fill the lows between them. Sites 783 and 784 are situated on the

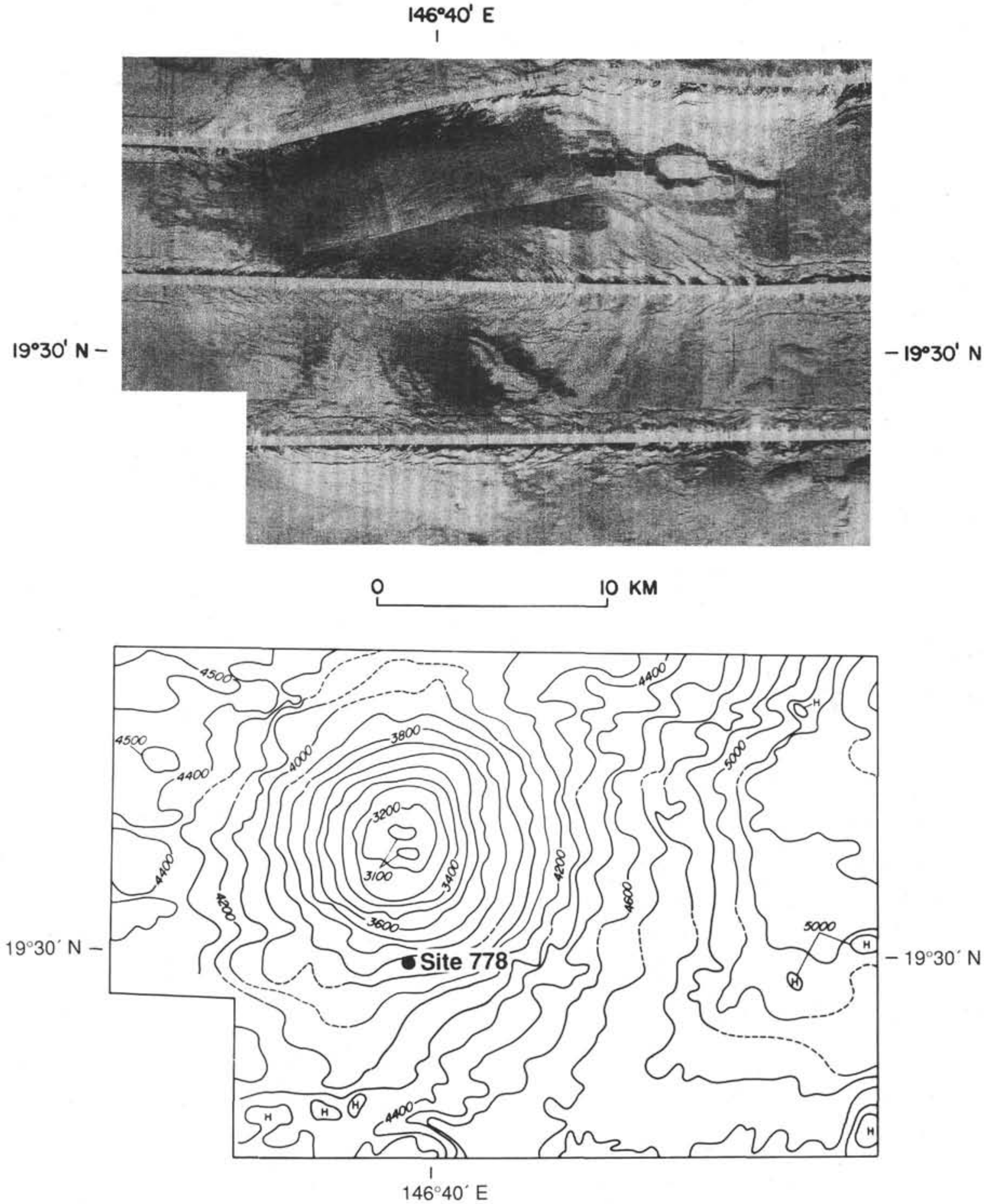

Figure 5. SeaMARC II side-scanning sonar image (top) and bathymetry (bottom) of Conical Seamount showing locations of Leg 125 Sites 778 through 781. Contours are in 100-m intervals. Side-scanning image shows regions of high backscatter as dark areas.

north and west flanks (respectively) of one of these seamounts, Torishima Forearc Seamount.

Hydration of the crust and upper mantle of the forearc wedge is facilitated by the escape of fluids from the subducting Pacific plate (Fryer et al., 1985b; Fryer and Fryer, 1987), and thermal modeling suggests that large portions of the forearc wedge lie within the chlorite, greenschist, and blueschist stability fields. The mantle and lower crust of the forearc wedge can thus readily accommodate large volumes of fluids through metamorphic processes (Fryer and Fryer, 1987). Although Conical Seamount is the only forearc seamount where active protrusion of unconsolidated fine-grained serpentine is known to be occurring at present, under appropriate tectonic conditions, similar serpentine seamounts could be emplaced in any nonaccretionary forearc region. Forearc serpentine deposits have indeed been identified in the circum-Pacific, Mediterranean, and Caribbean areas (Lockwood, 1971; 1972).

Drilling at Conical and Torishima Forearc Seamounts enabled us to investigate (1) the mechanical properties of the serpentine deposits

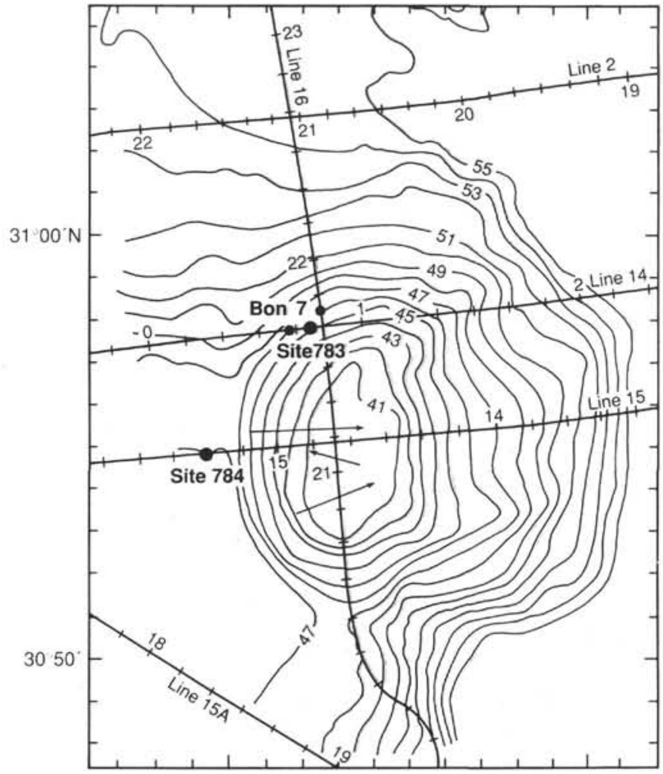

Figure 6. Bathymetry of Torishima Forearc Seamount showing locations of Leg 125 Sites 783 and 784 and dredges (arrows). Contours are in 100-m intervals.

and their emplacement mechanism, (2) the composition of the associated fluids and entrained metamorphosed xenoliths, and (3) the compositional and physical variability of the serpentine. While these immediate objectives are site-specific, they apply to the understanding of several larger questions. The two most obvious of these are the relationship of emplacement of serpentine bodies to the history of development of the forearc region of an intraoceanic arc system, and the geochemical mass balance of the subduction process. The seamounts provide "windows" through which we can observe the alteration and metamorphism of the forearc at depth by components derived from the underlying mantle or the subducting slab, and through which we can trace the changes in P-T and stress regimes of the deep forearc wedge.

SUMMARY OF LEG 125 DRILLING OBJECTIVES

The Izu-Bonin and Mariana regions are well-studied intraoceanic arc-trench systems. Yet fundamental questions about their evolution remained with regard to (1) arc rifting, (2) arc/forearc magmatism and structure, (3) arc/forearc stratigraphy and vertical tectonics, and (4) emplacement of serpentine seamounts in the outer forearc region. To address these questions, Leg 125 was designed with the following objectives:

Izu-Bonin Sites 782, 785, and 786 sought to determine:

1. The uplift/subsidence history across the forearc to provide information on forearc flexure and basin development as well as the extent of tectonic erosion;
2. The stratigraphy of the forearc with its record of (a) sedimentation, depositional environment, and paleoceanography and (b) the variations in intensity and chemistry of arc volcanism over time;
3. The nature of igneous basement forming the frontal arc, outer-arc high, and beneath the intervening basin, to answer questions concerning the initial stages of subduction-related volcanism, the origin of boninites, and the formation of the 200-km-wide arc-type forearc crust; and
4. The microstructural deformation and the large scale rotation and translation of the forearc.

Mariana Sites 778–781 and Izu-Bonin Sites 783 and 784 sought to determine:

1. The timing and mechanism of emplacement of the serpentinite seamounts, including their internal fabric, fracture patterns, and flow structures;
2. The chemistry and hence source of the associated fluids;
3. The conditions at depth in the outer forearc from the igneous and metamorphic petrology of the lower crust/upper mantle rocks;
4. The similarities and differences between the nature and genesis of greenschist facies metamorphism in the Mariana and Izu-Bonin forearc regimes; and
5. The differences between end-member processes of fluid flux in forearc regimes for application to investigations of geochemical mass balance in convergence zones.

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