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1. INTRODUCTION[1]

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OVERVIEW

The Izu-Bonin intraoceanic island arc is a product of the subduction of Pacific lithosphere since the Eocene. Ocean Drilling Program (ODP) Leg 126 focused on three important and poorly understood aspects of this arc system, namely:

1. the origin and evolution of the forearc, investigated by drilling a series of holes through the sediments and into the basement of the forearc basin (Sites 787 792, and 793);
2. the process and products of arc rifting, investigated by drilling holes into the center (Sites 790/791) and eastern footwall (Sites 788/789) of the Sumisu backarc rift; and
3. recycling of subducted lithosphere and evolution of the mantle, investigated indirectly from the composition of the volcanic rocks recovered from all sites.

TECTONIC SETTING AND EVOLUTION OF THE IZU-BONIN-MARIANA REGION

The present-day tectonic configuration of the Izu-Bonin-Mariana region (Fig. 1) comprises, from east to west, the trench; the forearc terrane, made up of an inner trench wall, an outer-arc high, a forearc basin, and a frontal-arc high (Fig. 2); the active Izu-Bonin and Mariana island arcs; the Izu-Bonin backarc rifts and the actively spreading Mariana backarc basin and its remnant arc, the West Mariana Ridge; the Shikoku and Parece Vela marginal basins; and the Palau-Kyushu Ridge, the westernmost remnant arc. Mesozoic Pacific oceanic lithosphere is being subducted to the west-northwest beneath the arcs at rates of 20 mm/yr in the south to 65 mm/yr in the north. The velocity at 31°N is 60 mm/yr along 288° (Seno et al., 1987).

The evolution of these arcs and backarc basins is thought to have begun in the early middle Eocene when westward subduction of Pacific lithosphere began beneath the Philippine Sea Plate (Karig, 1975). Development of the system continued throughout the early Oligocene, forming an intraoceanic volcanic arc on top of a 200-km-wide forearc composed of volcanic rocks primarily of tholeiitic and 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 Amami-Oki Daito province, a series of island arcs and intervening basins of Santonian to Paleocene age. Middle Oligocene rifting split the arc, and late Oligocene to early Miocene backarc spreading in the Shikoku and Parece Vela basins isolated a remnant arc (the Kyushu-Palau Ridge) from an active Izu-Bonin-Mariana arc (Kobayashi and Nakada, 1979; Mrozowski and Hayes, 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 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. 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 m.y. of spreading in the Mariana backarc basin isolated the active Mariana Arc from the West Mariana Ridge, a remnant arc, as well as increased its curvature with respect to the ridge (Karig et al., 1978; Hussong and Uyeda, 1981). Spreading in the Mariana backarc basin may now be propagating to the north, "unzipping" the Mariana Arc from the West Mariana Ridge (Stern et al., 1984). The Bonin Arc is still in the early rifting stage of backarc basin 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 one volcano near 29°N is surrounded by graben (Taylor et al., 1985). Volcanism is continuing along the active and the "remnant" arcs. Volcanic centers, with bimodal basalt-rhyolite composition, also have developed in the rift basins. The basalts have major and trace element abundances that resemble the basalts of the Mariana backarc basin rather than the basalts of the adjacent Izu-Bonin island arc (Fryer et al., 1985a; Hochstaedter et al., in press).

The backarc rifts are semicontinuous along strike, segmented by structural highs and chains of submarine volcanoes extending westward from the island-arc volcanoes (Taylor et al., 1985 and in press). Similar volcanic cross-chains are located west of the Mariana volcanoes, and older chains extend westward into the Parece Vela and Shikoku basins from the West Mariana Ridge and the Izu-Bonin Arc (Hussong and Fryer, 1983; Bloomer et al., 1989).

The differences in backarc evolution between the Mariana and Izu-Bonin systems are associated with corresponding differences in their forearcs. These differences are further accentuated by the fact that seamount chains and aseismic ridges on the subducting plate have collided only with the Mariana and southernmost Izu-Bonin Arc. Compared with the Mariana forearc, the Izu-Bonin forearc has experienced little deformation since subduction began (Honza and Tamaki, 1985). It has developed a broad forearc basin, filled with volcaniclastic and hemipelagic sediments, behind an outer-arc basement high (Fig. 2). Biostratigraphic dating of the strata that lap onto this high, both submarine and subaerial (Hanazawa, 1947), indicates that this high has been a positive topographic feature since the middle 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).

The Mariana forearc has a broadly similar structure, but it 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

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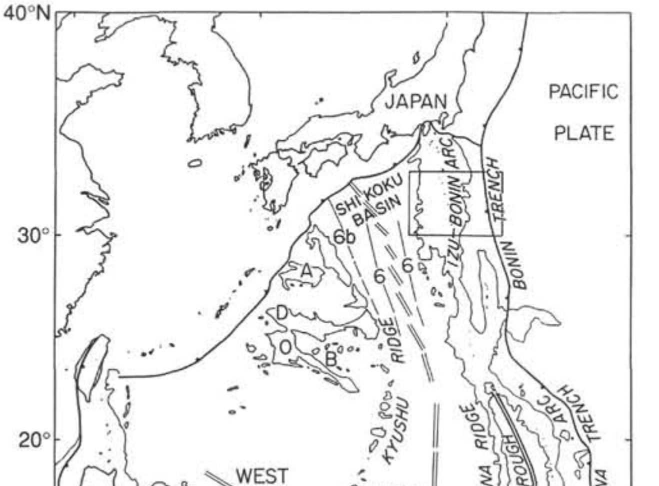

Figure 1. Active plate boundaries and relict spreading centers in the Philippine Sea region. Barbed lines locate subduction zones, medium double lines locate active spreading centers, and thin double lines locate relict spreading centers. Basins and ridges are outlined by the 4-km bathymetric contour, except for the Izu-Bonin, West Mariana, and Mariana arcs, which are outlined by the 3-km contour. Magnetic Anomalies 6 and 6B are shown by thin lines in the Shikoku Basin. A = Amami Plateau, B = Daito Basin, D = Daito Ridge, H = Halmahera, L = Luzon, M = Mindanao, and O = Oki Daito Ridge. The box shows the location of Figure 2.

in the configuration of the arc. These fractures have provided easy egress for serpentinite rising from the underlying mantle wedge. A broad zone of serpentinite seamounts, each 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. These seamounts are formed by the diapiric rise and protrusion of serpentinite bodies (Bloomer, 1983; Fryer et al., 1985b; Fryer and Fryer, 1987). In the Izu-Bonin forearc, a chain of serpentinite seamounts (up to 1500 m high and 20 km in diameter) is present <50 km from the trench axis. These seamounts are spaced at intervals of 15–60 km and, together with the sediments ponded around them, form a terrace on the lower slope of the trench inner wall. Serpentinite seamounts are inferred to result from the buoyant rise of mantle hydrated by water released from crustal materials subducted beneath igneous intraoceanic forearcs. Only very minor, and probably ephemeral, accretionary complexes occur at the bases of the inner walls of the Izu-Bonin and Mariana trenches (Horine et al., 1988; Mrozowski et al., 1981).

The Izu-Bonin Arc is being subducted to the north beneath Japan. Deformation of the northern Izu-Bonin Arc is focused on the leading edge of the downgoing plate where subduction-related thrusting at the Nankai Trough is stepping seaward to the south side of Zenisu Ridge, the northernmost volcanic cross-chain of the arc (Le Pichon et al., 1987). Terranes of Izu-Bonin Arc crust have been accreted onto southern Honshu during the last 15 m.y.; the latest terrane to be accreted was the Izu Peninsula in the early Quaternary (Matsuda, 1978; Huchon and Kitazato, 1985; Taira et al., 1989).

ARC/FOREARC DEVELOPMENT: BACKGROUND TO SITES 787, 792, AND 793

With the exception of dredges from inner trench walls and large fault scarps (Bloomer and Hawkins, 1983; Bloomer and Fisher, 1987), our direct knowledge of intraoceanic forearc basement prior to ODP Legs 125 and 126 is based primarily on data from three island chains and two Deep Sea Drilling Project (DSDP) sites: the Mariana and 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); and DSDP Leg 60 Sites 458 and 459, which sampled Eocene arc tholeiites and lower Oligocene boninites and arc tholeiites, respectively, from the Mariana outer-arc high. Prior to Leg 126, basement beneath the thickly sedimented upper-slope basin between the frontal-arc and outer-arc high had never been sampled, nor had the deep forearc basement beneath the carapace of interbedded arc pillow lavas, flows, and sills been sampled. From the available data, it appears that the present 150–230-km-wide Bonin-Mariana forearc 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 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 highs could have originally been continuous and subsequently separated by forearc spreading; (2) the frontal-arc and outer-arc highs 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 forearc. The question remains: 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-subduction zone (SSZ) ophiolites (which have 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, for which the type locality is the Bonin Islands, commonly occur in SSZ ophiolites. They appear to require hydrous partial melting at shallow depth of refractory sources that are selectively enriched in light rare earth elements and certain high-field-strength elements, as well as the typical large-ion-lithophile-element arc component (Taylor and Nesbitt, 1988). These unusual conditions and component enrichments 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 Bonin forearc (Fig. 3) have revealed a complicated basement that is often seismically stratified and cut by dipping reflectors (see Taylor et al., this volume). These reflection characteristics imply 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 Amami Plateau (Taylor et al., 1988). Drilling in the forearc basin sampled the hitherto unstudied forearc basement to constrain some of these models for forearc evolution.

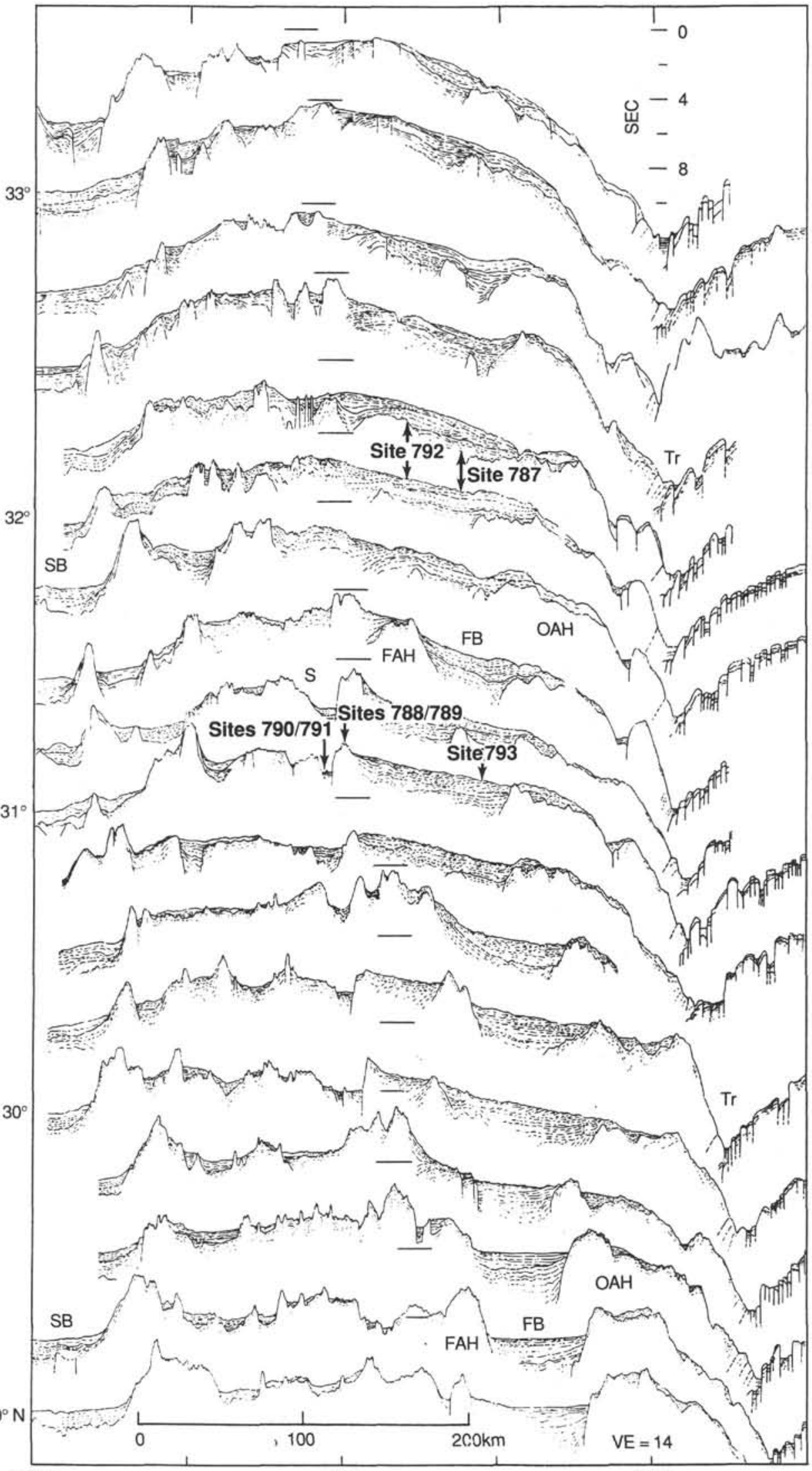

Figure 2. Line drawings of single-channel seismic profiles across the Izu-Bonin arc-trench system at 29°-33°N that show the location of drilled sites. Tr = trench, OAH = outer-arc high, FAH = frontal-arc high, FB = forearc basin, FAH = frontal-arc high; S = Sumisu Rift; SB = Shikoku Basin.

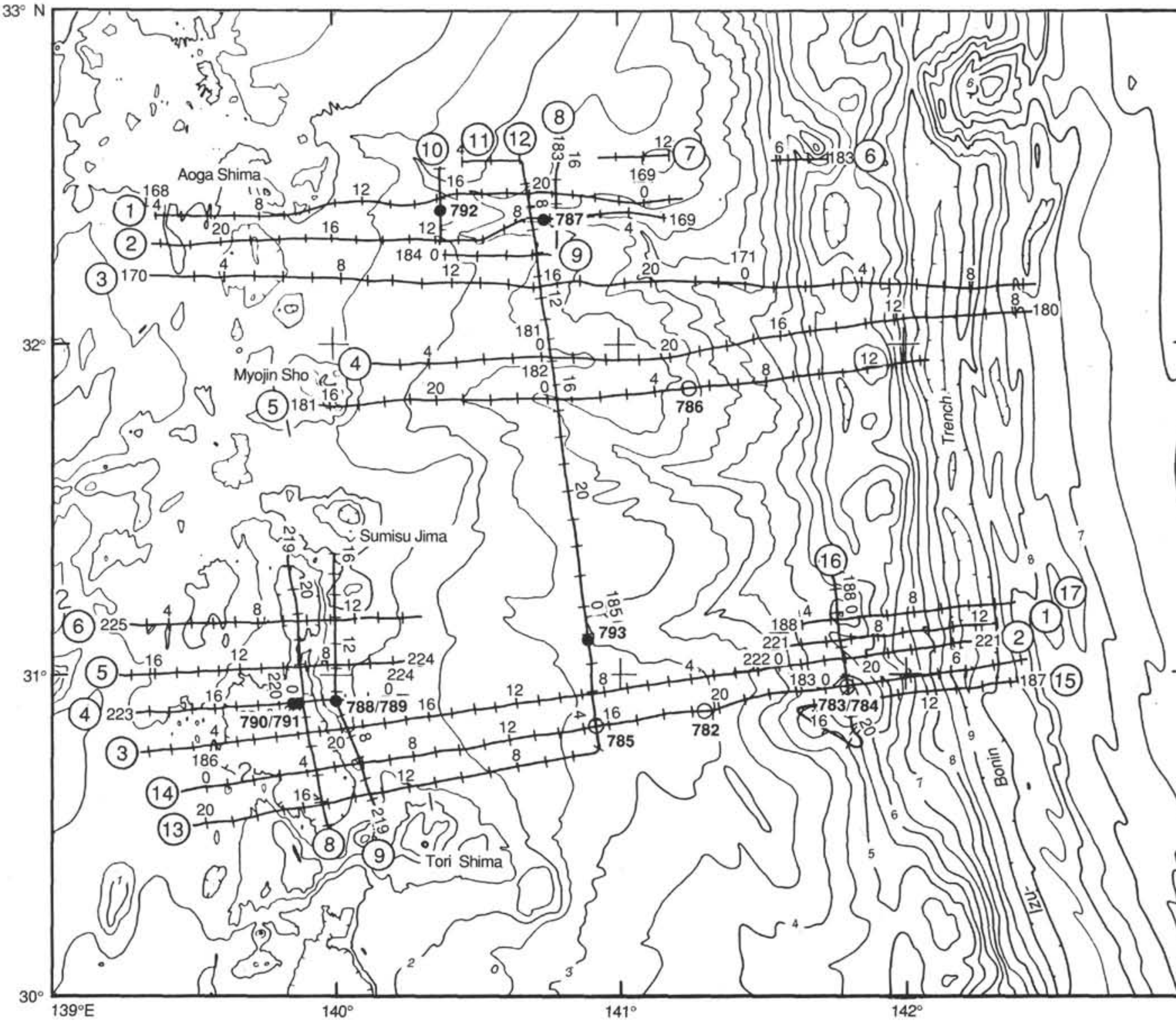

Figure 3. Locations of MCS profiles and Sites 782–786 (Leg 125) and 787–793 (Leg 126) in the Izu-Bonin region.

The presence of arc igneous rocks near the trench, together with observations of normal faulting in the forearc and interpretations of outer-arc subsidence, have been cited as evidence for large-scale removal of Mariana forearc material by tectonic erosion since the late Eocene (Hussong and Uyeda, 1981). This analysis has been questioned by Karig and Ranken (1983), who infer that the Mariana forearc has not undergone significant tectonic subsidence or erosion. Likewise, in the Bonin forearc, the presence of shallow-water Eocene fossils on the Bonin Islands, and of a well-developed submarine canyon system and lower-slope terrace elsewhere in the forearc, indicate that fairly stable conditions have prevailed since the anomalous Eocene phase of arc-basin development. This hypothesis will be tested by determining the uplift-subsidence history across the forearc by means of backstripping techniques on cored/logged holes and seismic stratigraphic analyses of interconnecting MCS profiles. Microstructures in the drill cores helped determine the intensity of faulting in space and time across the forearc terrane. Furthermore, we do not know (1) if the frontal-arc and outer-arc high developed by igneous construction or by differential uplift; (2) if the upper-slope basin between them is caused by forearc spreading or differential subsidence; and (3) if flexural loading by arc volcanoes or by coupling with the subducting plate is an important process. Determining the forearc vertical displacement field should provide some of the information on forearc flexure and basin development necessary to evaluate these hypotheses.

The forearc stratigraphy also 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 rates. On the other hand, Scott and Kroenke (1981) hypothesized that initial periods of backarc spreading coincide 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 arc rifting produced drastic subsidence of the arc volcanoes, which resulted in turn in deep-water eruptions with limited lateral transport of volcanic material. Studies of the chronology and geochemistry of tephra deposits in the forearc-basin drill cores will contribute to the evaluation of these various models. Such studies will 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 forearcs and from Palau have indicated clockwise rotation since the Eocene from 30° to >90° (Larson et al., 1975; Keating et al., 1983; Haston et al., 1988). These data, in conjunction with paleopoles estimated from Eocene marine magnetic anomalies in the West Philippine Basin (Louden, 1977; Shih, 1980), indicate that a general clockwise rotation characterizes the motion of the Philippine Sea Plate in the Tertiary. However, other studies have interpreted easterly declinations along the plate margin in terms of local rotations that arose from oblique subduction of the Pacific Plate (Kodama et al., 1983) or from the collisions of island arcs, rifted continental fragments, and aseismic ridges with the margin (McCabe, 1984). If the deflected declinations represent plate-wide motion, much of the clockwise rotations endemic to at least the southern parts of the Philippine Archipelago (McCabe et al., 1987) might serve as evidence for their attachment to the Philippine Sea Plate earlier in the Tertiary.

Magnetic inclination data from submerged and subaerial strata, including volcanic rocks from the Bonin Islands, also indicate significant (>20°) northward motion of the Philippine Sea Plate as well as the Philippine Islands during the Tertiary (Louden, 1977; Kinoshita, 1980; Bleil, 1981; Keating et al., 1983; Fuller et al., in press). Karig and Moore (1975) and Ogawa and Naka (1984) hypothesized that the Bonin Islands might be an exotic terrane introduced from the south by oblique motion; however, marine geophysical data indicate their structural continuity with the outer-arc high (Honza and Tamaki, 1985). However interpreted, the magnetic inclination and declination data are essential parameters for reconstructing the initial geometry of the Philippine Sea Plate and its relationship to surrounding plates, and for understanding the conditions that lead to initial subduction along the Izu-Bonin-Mariana Margin and Philippine Sea Plate evolution. The area of Leg 126 drilling is north of all previous Philippine Sea Plate paleomagnetic sampling sites and is unaffected by collision tectonics. Therefore, paleomagnetic studies of the recovered cores provide critical tests of the hypothesized plate-wide motions vs. local tectonic effects, particularly since azimuthal orientations can be obtained through the use of the formation microscanner (FMS).

RIFTING OF THE IZU-BONIN ARC: BACKGROUND TO SITES 788–791

The processes associated with the rifting and subsequent separation of continental lithosphere have been a major research focus and drilling objective for some time. In contrast, the rifting of arc lithosphere prior to backarc spreading has, until recently, received almost no attention, despite the fact that similar processes and questions are involved (e.g., the extent and nature of crustal stretching, the duration of rifting, and the interaction between vertical tectonics, rift sedimentation, and volcanism). These processes may best be observed in active rifts before the syn-rift sediments are buried by arc-volcaniclastic rocks. To date, no seaward-dipping seismic reflectors, interpreted to represent massive outpourings of volcanic material, have been recognized in backarc basins. However, SeaMARC II surveys in the Izu-Bonin region have revealed widespread syn-rift volcanism, not only on the active and "remnant" arcs but in the rift basins as well (Brown and Taylor, 1988). Most dredged samples are basalts, but andesites, dacites, and rhyolites have also been recovered. The fact that the basalts are similar to Mariana Trough basalts means that mantle little modified by a subduction component is melted even during the initial stage of backarc opening (Fryer et al., 1985a; Hochstaedster et al., in press).

The best-studied area of Izu-Bonin Arc rifting is the Sumisu Rift, located between the active arc volcanoes Sumisu Jima and Tori Shima (Fig. 3). It is a graben bounded by high-angle normal faults, in which the locus of maximum subsidence lies within an inner subgraben on its eastern side (Murakami, 1988). Faulting occurs along north-northeast-trending doglegs that form an orthorhombic fabric similar to that found in continental rifts (Brown and Taylor, 1988). The surface sediments in the rift basin include hemipelagic muds and volcaniclastic turbidites, with ash and pumice layers (Nishimura and Murakami, 1988). Whether the basement of the graben is formed of stretched, subsided arc crust, recently intruded crust, or some combination of the two, was unknown prior to Leg 126, as was the duration of rifting. The K/Ar dating of samples collected during a 1987 ALVIN program in the rift axis and on the eastern wall indicate that rift-axis volcanism began more than 0.6 Ma (Hochstaedter et al., in press). Drilling in the center and on the eastern flanks of the graben allowed us to determine if rifting began at the same time as, or subsequent to, rifting in the Mariana backarc basin (~10 Ma), if arc volcanism continued throughout its development, and when the extrusion of backarc-type basalts began.

The locus of maximum uplift and backtilting of the horst blocks that bound the basin varies back and forth along the strike between the eastern and western sides of the graben. This locus lies on the western side adjacent to the arc volcanoes and on the eastern side between them. Perhaps volcano loading suppresses the uplift. There is also some evidence of half-graben tectonics, with a master normal fault marking the edge of the dominant horst block and smaller antithetic normal faults on the other side forming the graben. However, the transfer zones linking the opposed master faults are relay zones of overlapping normal faults rather than strike-slip faults. Site survey multichannel seismic profiles have not been able to determine if the master faults are listric at depth (see Taylor et al., this volume). The uplifted footwall blocks are isolated from recent submarine volcaniclastic flow deposits and therefore were good drilling sites (1) to determine the differential vertical tectonics with respect to the graben and (2) to penetrate into the pre-rift arc basement. The nature of the frontal-arc basement between the arc volcanoes is unknown at present. Analogy with land sections such as in Japan or the Cascades would suggest that there should be numerous vents and flow fields between the large volcanic edifices. However, potential field and sidescan marine geophysical data indicate that this may not be the case in the central Izu-Bonin intraoceanic arc.

The tectonic setting and volcanic associations of the Izu-Bonin rifts are similar to those of the Hokuroku district in Japan during its ore-forming period at about 13–14 Ma (Cathles et al., 1981; Fujioka, 1983). Silica/barite/iron oxide deposits sampled with ALVIN from the rhyolite domes on the basalt ridges in the Sumisu Rift have similar trace metal abundances to the iron chert (*Tetsusekiei*) that overlies the Kuroko massive sulfide deposits (Taylor et al., in press; Urabe, in press). The chemistry of the fluids responsible for precipitating these deposits, and presumably sulfide deposits at depth, is unknown. Heatflow measurements in the rift basin require hydrothermal circulation to explain the locally high, but widely variable, values that range from 12 to 700 mW/m^2 (Yamazaki, 1988; T. Yamazaki, pers. comm., 1988). Drilling in the Sumisu Rift was designed to enable us to investigate the metallogenic implications of arc rifting by sampling the formation fluids.

DRILLING OBJECTIVES

The Izu-Bonin and Mariana regions are the best-studied intraoceanic arc-trench systems. They are the type examples with which other older or less well-studied systems are compared. Yet fundamental questions about their evolution remain with regard to (1) arc rifting, (2) arc/forearc magmatism and structure, and (3) arc/forearc stratigraphy and vertical tectonics. To address these questions, Leg 126 drilling in the Izu-Bonin Arc had the following objectives:

1. In the arc-backarc region (Sites 788–791), we sought to determine (1) the differential uplift/subsidence history of the rift basin and adjacent arc margin; (2) the nature of volcanism and sedimentation in the rift and on the arc; (3) the duration of rifting and the nature of the rift basement; and (4) the chemistry of fluids circulating in the rift basin.

2. In the forearc region (Sites 787, 792, and 793), we 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 sedimentation, depositional environment, and paleoceanography, as well as the variations in intensity and chemistry of arc volcanism over time; (3) the nature of the igneous basement that forms the frontal-arc high and underlies the forearc 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.

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