42. RIFTING AND THE VOLCANIC-TECTONIC EVOLUTION OF THE IZU-BONIN-MARIANA ARC[1]

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ABSTRACT

This paper focuses on the processes of arc rifting in the context of the volcanic, structural, and sedimentologic evolution of the Izu-Bonin-Mariana arc-trench system. Middle and late Eocene supra-subduction zone magmatism formed a vast terrane of boninites and island arc tholeiites (>300 × 3000 km) that is unlike active arc systems but is similar to many ophiolites. A modern-style volcanic arc developed by the Oligocene, along which intense tholeiitic and calc-alkaline volcanism continued until 29 (Mariana) and 27 Ma (Izu-Bonin). The Eocene-Oligocene arc massif was stretched during protracted Oligocene rifting, creating sags and half graben in the forearc and backarc. Minima in arc volcanism (29–27 Ma in the Marianas and 23–20 Ma in the Izu-Bonins) occurred during early phases of backarc spreading in the Parece Vela and Shikoku basins, respectively. Western Shikoku Basin oceanic crust previously identified as formed during Subchrons 6C (25 Ma) to 6A, may instead have formed during Subchrons 6A (22 Ma) to 5D, with a spreading jump over the eastern 5D and 5E magnetic lineations, leaving only 6A lineations east of the axial 5B-5C lineations. Middle Miocene to Holocene Izu-Bonin volcanism developed a volcanic front oriented 3° counterclockwise from the Oligocene frontal arc and has increased in intensity to a Pliocene-Quaternary maximum. Neogene magmatism along the volcanic front has been focused on bimodally spaced (27 and 47 km), long-lived centers, but arc tholeiites have occasionally intruded the thermally cool forearc, and cross-chains of mostly submarine volcanoes occur in the backarc immediately west of the frontal arc volcanoes as well as further west, on the edge of the rifted Oligocene arc crust. The present rifting of the central Izu-Bonin arc began about 2 Ma. At 30° 55′N, in Sumisu Rift, 1.1 ± 0.4 km of subsidence of the inner rift basement and 1.1 ± 0.5 km of uplift of the rift flank are associated with the 2–2.5 km throw on the eastern border fault zone. A zigzag pattern of half-graben-bounding normal faults characterizes both the Oligocene and Quaternary rifts. Except for the greater extent (Basin and Range style) of the Oligocene structures, the two fault patterns appear similar and little-influenced by pre-existing structures. Many of the border faults and rift flank uplifts developed early in the rift history. Syn-rift sediments are pervasively faulted and often intruded. Both the Sumisu Rift at Sites 790 and 791 and the forearc basin at Site 793 are floored with syn-rift volcanics that are geochemically distinct from their contemporary frontal arc volcanics. The oldest (>1.1 Ma) to the youngest (Holocene) Sumisu Rift lavas are backarc basin basalts, whereas pre- and syn-rift arc volcanism is mostly low-K, subalkaline, rhyolite and andesite. The Oligocene forearc volcanics are dominantly high-Mg, low-Ti, two-pyroxene, basaltic andesites and andesites, similar to the Eocene volcanics of the outer arc high. Coarse volcanogenic sediments, derived from contemporaneous frontal arc volcanism, dominate both the Sumisu Rift and the Oligocene forearc basin fill. They were rapidly (>250 m/m.y.) deposited by turbidity currents and debris flows onto rift-floor sediment plains. Sedimentation patterns were directly influenced by the productivity of the proximal arc volcanoes, with volcanic lulls recorded by hemipelagic interbeds. Many arc segments go through a cycle of (1) frequent volcanism before and during rifting; (2) reduced and/or less disseminated volcanism during latest rifting and early backarc spreading, as new frontal arc volcanoes are being constructed and growing to sea level; and (3) increasingly vigorous volcanism during middle and late stage backarc spreading, and until the next rift cycle begins. Even within periods of intense volcanism, 100-km-long arc segments may be quiescent for periods of up to 400 k.y. The frontal arc volcanoes, because of their thicker crust and higher heat flow, create a linear zone of lithospheric weakness that controls the location of arc rifting. Differences in plate boundary forces at the ends, more than in the middle, of volcanic arcs may significantly influence their proclivity to rift.

INTRODUCTION

The Izu-Bonin-Mariana (IBM) arc-trench system is the type intra-oceanic example with which other older or less well-studied systems are compared. Marine geophysical studies, together with drilling on Deep Sea Drilling Project (DSDP) Legs 6, 31, 58, 59, and 60, have confirmed the essential tenets of Karig (1971) and Packham and Falvey (1971) that backarc basins, such as the Shikoku Basin, Parece Vela Basin, and Mariana Trough (Fig. 1), formed by seafloor spreading between the formerly contiguous remnant arcs (Palau-Kyushu and West Mariana ridges) and the active IBM arc. The objectives of Ocean Drilling Program (ODP) Legs 125 and 126 were to investigate some of the less understood aspects of this system, including (1) arc rifting, (2) arc/forearc magmatism and structure, (3) arc/forearc stratigraphy and vertical tectonics, and (4) forearc serpentinite seamounts. To this end, in the Izu-Bonin region, a transect of sites was drilled across the lower-slope serpentinite seamounts (Sites 783 and 784), the outer arc high (Sites 782 and 786), the forearc basin (Sites 785, 787, and 793), the frontal arc high (Site 792), the volcanic front between Sumisu Jima and Torishima (Sites 788 and 789), and the Sumisu backarc rift (Sites 790 and 791) (Figs. 2 and 3; Fryer, Pearce, Stokking, et al., 1990; Taylor, Fujioka, et al., 1990). Together with Site 296, on the Palau-Kyushu Ridge, and Sites 297 and 442–444 in the Shikoku Basin (Fig. 1; Karig, Ingle, et al., 1975; Kroenke, Scott, et al., 1980), these sites provide a drilling transect at 29°–33° N across the complete Eocene to Quaternary forearc-arc-backarc system.

This paper focuses on the processes of arc rifting in the context of the volcanic, structural, and sedimentologic evolution of the Izu-Bonin-Mariana arc-trench system. It is more than a synthesis of Leg 126 drilling results in that, in order to place these in context, the results of previous IBM drilling as well as geological and geophysical studies of the IBM land and submarine areas are incorporated. The paper is organized chronologically, beginning with the Eocene volcanic province (the basement that is later rifted) and progressing to the Quaternary. The development of the rifts in the Oligocene (both forearc and backarc) and Quaternary (dominantly backarc) is described and con-

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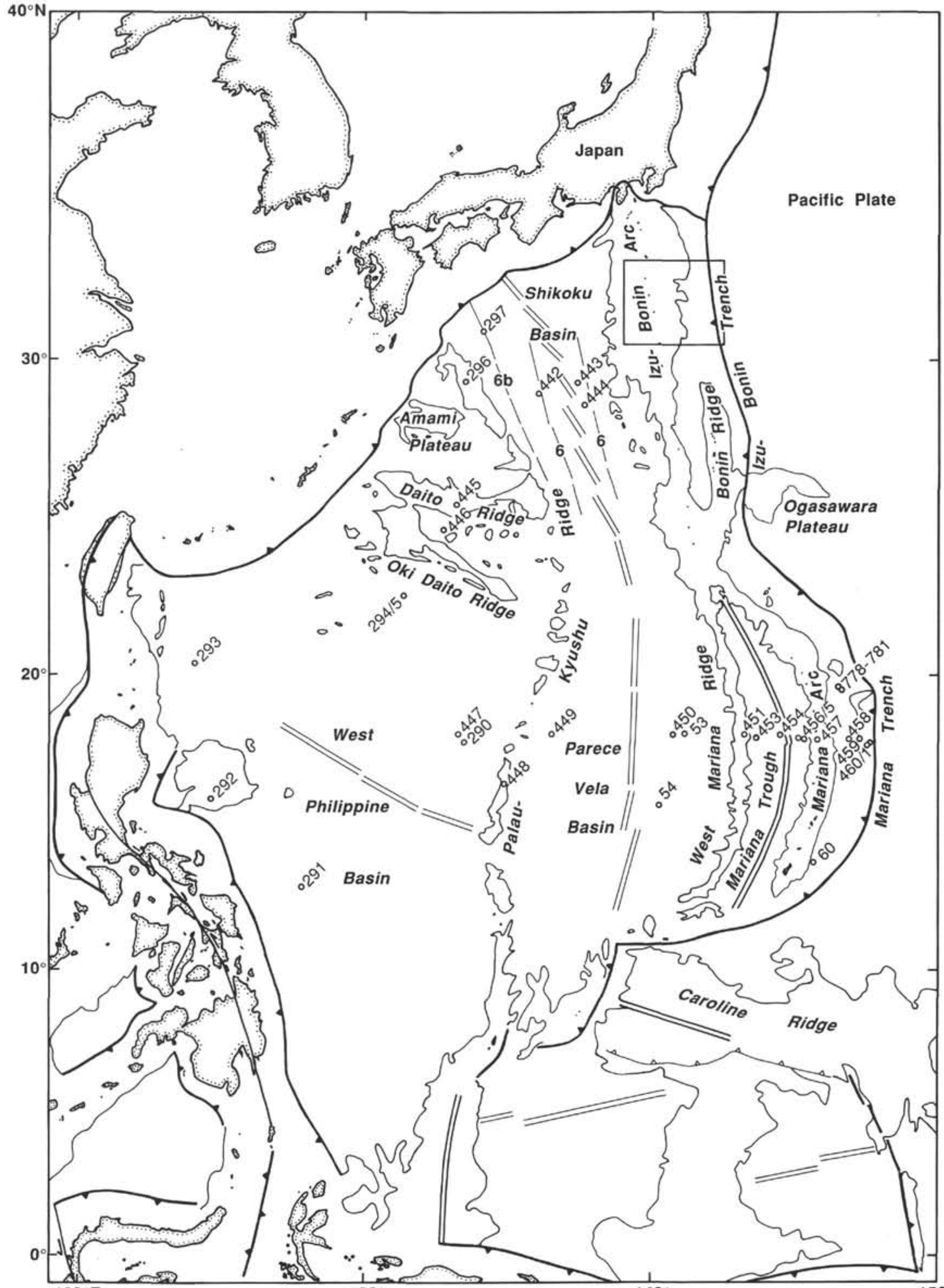

Figure 1. Active plate boundaries and relict spreading centers in the Philippine Sea region. Barbed lines locate subduction zones, medium double lines locate active spreading centers, and thin double lines locate relict spreading centers. Basins and ridges are outlined by the 4-km bathymetric contour, except for the Izu-Bonin, West Mariana and Mariana arcs, which are outlined by the 3-km contour. Magnetic anomalies 6 and 6b (Chamot-Rooke et al., 1987) are shown by thin lines in the Shikoku Basin. Numbered open circles locate sites drilled on the Philippine Sea Plate during Legs 6, 31, 58, 59, 60, 125, and 126, except those in the box, which are shown in Figure 2.

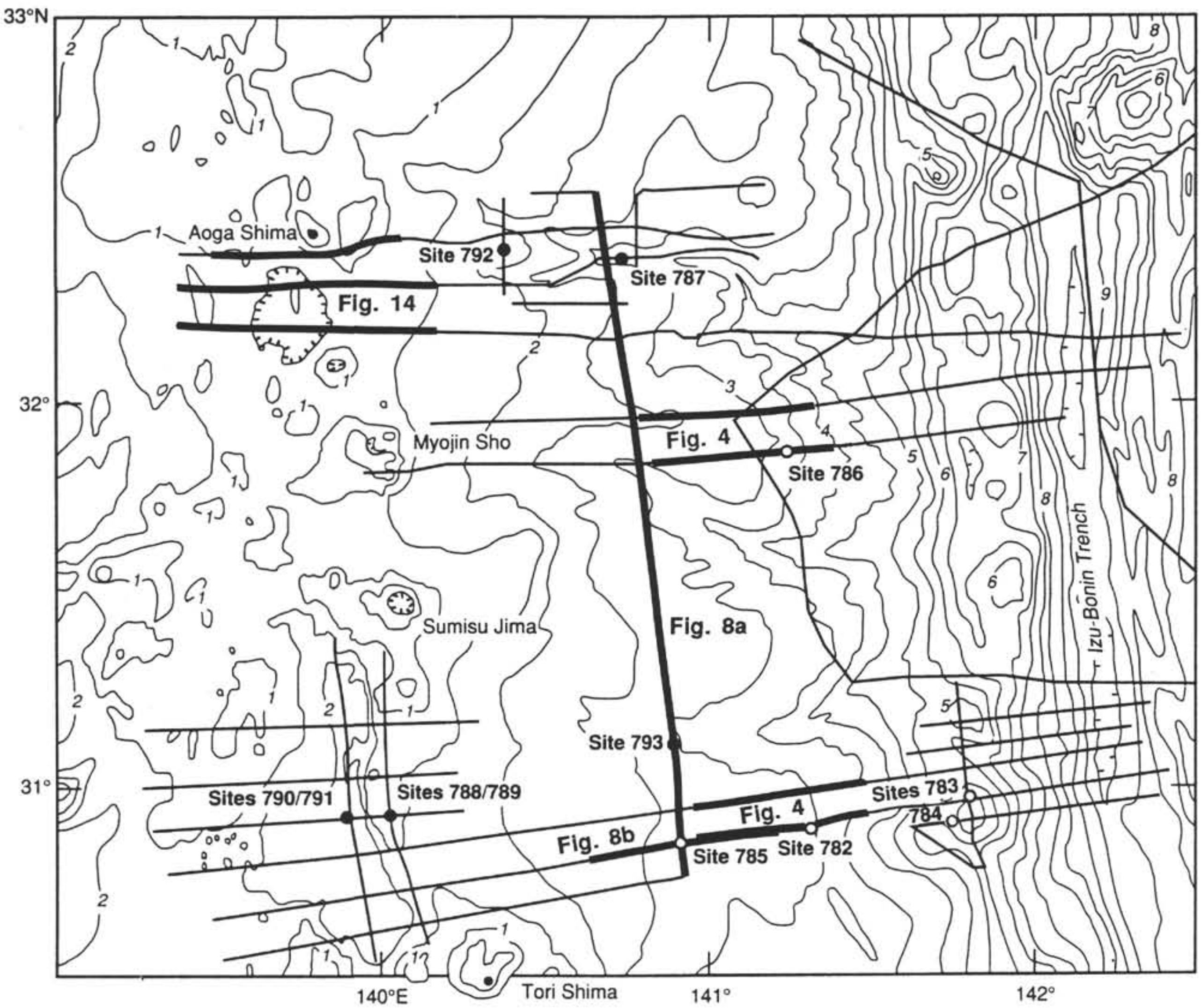

Figure 2. Locations of U.S. multichannel seismic profiles and Sites 782-786 (Leg 125) and 787-793 (Leg 126) in the Izu-Bonin region. The bathymetric base map is contoured at 500-m intervals and labeled in kilometers. Bold MCS profile segments are shown in Figures 4, 8, and 14.

trasted. As well as synthesizing the volcanic-tectonic evolution of the IBM arc, and proposing a revised spreading history for the Shikoku Basin, I provide some answers to the following questions:

1. What controls the locus and duration of arc rifting?
2. What is the nature of syn-rift faulting, volcanism, and sedimentation?
3. What is the temporal relationship between arc volcanism, rifting, and backarc spreading?

EOCENE VOLCANISM

The oldest (middle Eocene) island arc rocks in the IBM system are widely distributed, from the Palau-Kyushu remnant arc to the present outer arc high. Reconstructing the Eocene volcanic province, by closing the Parece-Vela and Shikoku basins, the Oligocene rift basins, the Mariana Trough, and the active Izu-Bonin rifts, defines a band of contemporaneous volcanism over 300 km wide. Eocene island arc tholeiite and boninite series (basalt to rhyolite) sheet flows, pillow lavas, dikes, breccias, and hyaloclastite have been sampled from the outer arc high at Sites 459, 782, and 786 and on the Bonin Islands (Hussong, Uyeda, et al., 1981; Umino, 1985; Dobson, 1986; Fryer, Pearce, et al., 1990), and from the frontal arc islands of Guam, Tinian, and Saipan (Ingle, 1975; Reagan and Meijer, 1984). The numerous basement protrusions seen on multichannel seismic (MCS) profiles of the outer arc high are probably volcanic edifices similar to those drilled at Sites 782 and 786 (Fig. 4; Pearce et al., in press). Geochemically similar lavas have been dredged from the inner wall of the IBM trench (Ishii, 1985; Bloomer and Hawkins, 1987). Eocene quartz diorites, andesites, and tonalites have been dredged from the northern Palau-Kyushu Ridge (Shiki, 1985).

Both biostratigraphic and radiometric age dating indicate that the Izu-Bonin volcanism, along the outer arc high and on the Palau-Kyushu Ridge, began 48–49 Ma, whereas no evidence exists for Mariana volcanism, on the outer arc and frontal arc highs, older than 44–45 Ma (Hussong, Uyeda, et al., 1981; Meijer et al., 1983; Seno and Maruyama, 1984; Shiki, 1985; Dobson, 1986). Eocene volcanics from the southern Palau-Kyushu and West Mariana ridges, from the Izu-Bonin frontal arc high, and from beneath the forearc basin have yet to be penetrated. It appears that subduction began a few million years earlier along the Izu-Bonin segment than the Mariana segment. The latter may have begun as a transform fault but did not develop an arc until just before the change in Pacific Plate motion recorded by the Hawaiian-Emperor bend. The Izu-Bonin volcanism occurred

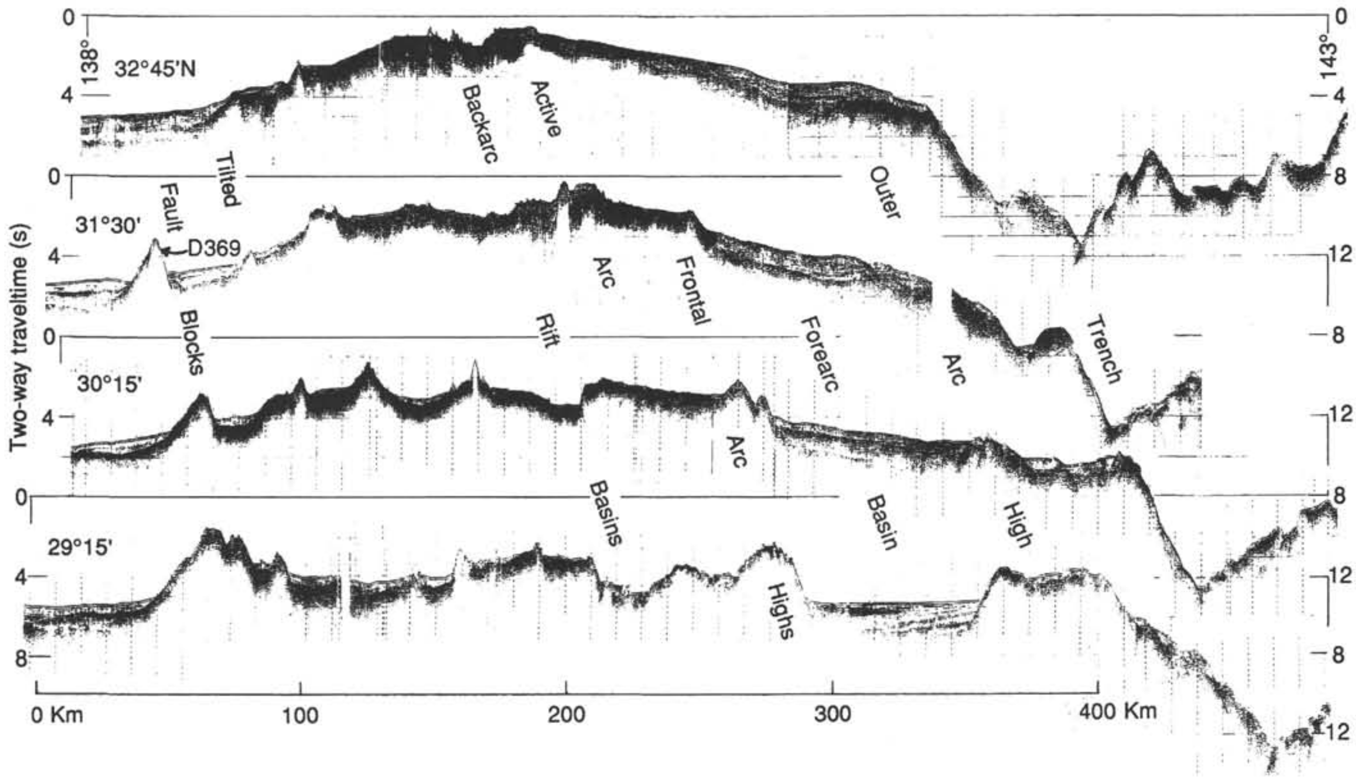

Figure 3. Geological Survey of Japan single-channel seismic profiles across the Izu-Bonin arc-trench system, from the Pacific Basin (143° E) on the right to the Shikoku Basin (138° E) on the left, provided courtesy of E. Honza (see locations and line drawings in Honza and Tamaki, 1985). The vertical exaggeration is 10. A dredge (D369) from the upper eastern scarp of the western tilted fault block at 31°30′N recovered siltstone and chlorite-white mica-quartz-albite schist (Yuasa and Yokota, 1982).

simultaneously over a wide region (e.g., on the Palau-Kyushu and Bonin ridges at 48 Ma) and continued for >10 m.y.

Which plate was initially subducted at the IBM trench is uncertain, however. Paleomagnetic data show that the Philippine Sea Plate has rotated up to 90° clockwise from equatorial latitudes in the middle Eocene (Keating and Helsley, 1985; Haston and Fuller, 1991; Koyama et al., this volume). Hence, the IBM arc initially faced north and the northward-moving Pacific Plate was retreating from it. To generate subduction beneath the Philippine Sea Plate, Seno and Maruyama (1984) proposed the existence of an intervening North New Guinea Plate, spreading southward from the Pacific Plate. This has the additional advantage of providing the high heat flow and volatiles, from the subduction of young lithosphere, that is required by petrogenetic models to explain the high temperatures (~1260° C) and shallow depths (<3 kb) of boninite magma segregation (Dobson and O'Neil, 1987; Pearce et al., in press; van der Laan et al., in press). The addition of water from subducted lithosphere to overlying young (hot) mantle of the Eocene West Philippine Basin might explain boninite magma-genesis in the Mariana region (Natland and Tarney, 1981) but can not account for boninites in the Izu-Bonin region, which formed adjacent to the older arc terranes of the Amami Plateau and Daito Ridge (Fig. 1).

Geological studies of the emergent parts of both the frontal arc, from Guam to Saipan, and the outer arc high, the Bonin Islands, show that these ridges formed volcanic highs in the middle and late Eocene. Some sections reached sea level, including volcanoes on and to the west of Guam and Saipan (Cloud et al., 1956; Tracey et al., 1964) and on Hahajima (Hanzawa, 1947), though Chichijima may not have been as shallow until the Oligocene (Dobson, 1986). Large foraminifers dredged from the Izu-Bonin frontal arc high at 29° 09′N indicate a shallow-water environment in the late Eocene (Nishimura, this volume). The ridges are subdivided into a series of fault blocks that have been variably tilted/rotated (Keating and Helsley, 1985) and differentially uplifted/downdropped, the frontal arc high by at least 1 km (Ingle, 1975; Kaiho, this volume) and the outer arc high by up to 3 km. Benthic foraminifers indicate that the basement at both Sites 782 and 786 (Fig. 4) has subsided 1.6 ± 0.5 km from a late Eocene depth of 1.3–2.1 km (Kaiho, this volume). Lagabrielle et al. (in press) argue from the clay mineralogy, clast weathering, and abundance of pyroclastic rocks that the volcanic edifice drilled at Site 786 actually reached close to sea level in the middle Eocene. In contrast, the Bonin Ridge and Islands have been uplifted several hundred meters since the early Miocene (Karig and Moore, 1975; Honza and Tamaki, 1985), whereas the Mariana outer arc high at Sites 458 and 459 has remained within 1 km of its present depth, just above and below the paleo-carbonate compensation depth (CCD), respectively (Hussong, Uyeda, et al., 1981). The data require major along- and across-strike variations both in the Eocene IBM arc elevations, as is observed in the modern arc, and in the vertical motion history.

The plutonic foundations beneath the Eocene extrusives are poorly sampled. The gabbros, hartzburgites, and lesser dunites incorporated in serpentinite seamounts drilled on Leg 125 (Fryer, Pearce, Stokking, et al., 1990) and dredged from the IBM trench inner wall have dominantly island arc characteristics (Bloomer, 1983; Bloomer and Hawkins, 1983; Ishii, 1985). Leucocratic plutonic rocks have been dredged from the northern Palau-Kyushu Ridge (middle Eocene quartz diorites, etc.) and the southern Mariana Trench and are found as angular xenoliths in rhyolite on Saipan (Bloomer and Hawkins, 1983; Shiki, 1985). No samples of the adjoining middle-late Eocene West Philippine Basin oceanic crust (Karig, Ingle, et al., 1975; Mrozowski et al., 1982) or Santonian-Paleocene Amami-Oki Daito island

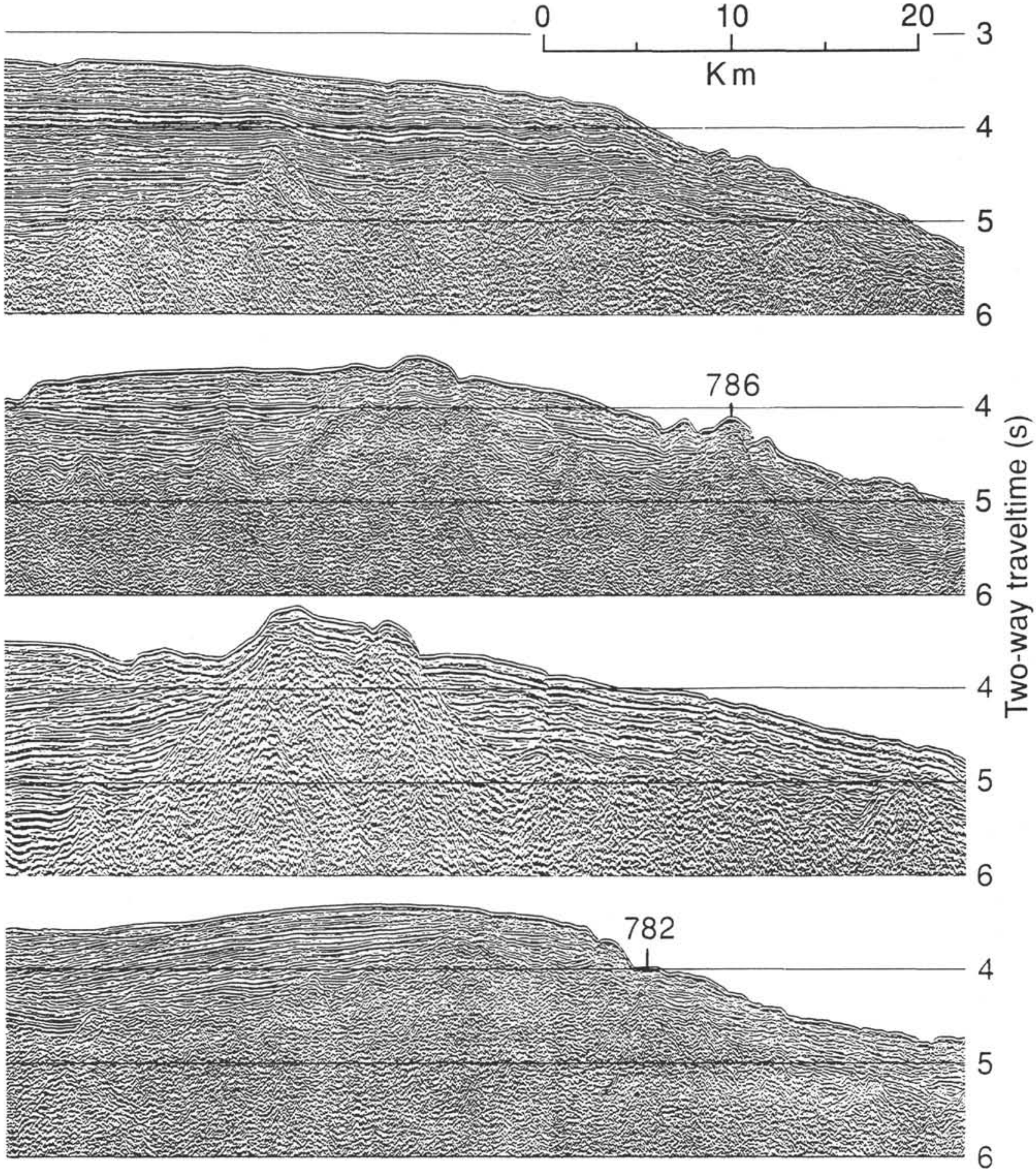

Figure 4. Hawaii Institute of Geophysics (HIG) migrated MCS profiles at 6.7 vertical exaggeration across the outer arc high near 32° N (top two profiles) and 31° N (bottom two profiles). See Figure 2 for location. Note the onlap of the forearc sediments onto the numerous basement protrusions, which I infer to be volcanic edifices similar to those drilled at Sites 782 and 786.

arc crust (Fig. 1; Klein, Kobayashi, et al., 1980; Shiki, 1985) have been reported from the IBM terranes.

Reconstructing the remnant arcs, frontal arc high, and outer arc high, which were dispersed by subsequent rifting and spreading, shows that contemporaneous middle and late Eocene arc tholeiite and boninite volcanism was occurring in a region over 3000 km long and over 300 km (up to 450 km) wide. The tholeiites and boninites are often interlayered, such as at Site 459, and regionally cannot be separated in time, although spatially the known occurrences of boninite do not extend further from the trench than Guam. There is no modern example of such extensive, contemporaneous, supra-subduction zone volcanism, which makes it one of the least understood aspects of the IBM system, and of the many ophiolites that have similar characteristics (Pearce et al., 1984; R. N. Taylor et al., 1991).

Tectonic Erosion/Accretion?

The extent of the Eocene volcanic province may have been even greater than at present, if significant tectonic erosion of the forearc has occurred. The evidence for tectonic erosion or accretion is controversial, however. Hussong and Uyeda (1981) argued for tectonic erosion because (1) island arc rocks form much of the trench inner wall, (2) the outer forearc is cut by high angle normal faults, and (3) Sites 460 and 461 were interpreted to show massive subsidence of the central Mariana outer forearc. Karig and Rankin (1983) argued to the contrary that relative uplift and arcward rotation of strata on the inner trench slope further south is more compatible with intermittent Neogene accretion. The displacement of the shallow-water Paleogene section at Sites 460 and 461 may be explained by slumping and canyon processes (Karig and Rankin, 1983), although Leg 60 participants dispute this. The relative uplift of the lower slope strata also can be explained, however, by the formation of serpentinite ridges and volcanoes similar to those drilled on Leg 125 (Horine et al., 1990; Fryer, Pearce, Stokking, et al., 1990).

The known vertical motion of the outer arc high, summarized previously, does not require tectonic accretion or erosion. There is seismic reflection evidence for minor accretion of sediments at the toe of the IBM trench (Mrozowski et al., 1981; Honza and Tamaki, 1985; Horine, 1989); however, this may be intermittent and short lived. The undisturbed deposition of hemipelagic silts and clays at or below the CCD since the middle Miocene onto the flank of the serpentinite seamount drilled at Sites 783 and 784 (Fig. 2; Fryer, Pearce, Stokking, et al., 1990) argues for the stability and lack of net Neogene tectonic erosion/accretion of the Izu-Bonin lower trench slope. The available data is compatible with little tectonic erosion or accretion of the IBM forearc since the middle Oligocene.

There is evidence from Lower Cretaceous radiolarian cherts and mid-ocean-ridge basalts (MORB) recovered from the Mariana forearc, from Upper Cretaceous foraminifers incorporated within the lower Oligocene volcaniclastic wedge at Site 290, and from alkali basalts dredged from the Mariana outer forearc, that some sedimentary and igneous material from the subducting plate was accreted into the Mariana Arc (Johnson et al., 1991). As yet there is no evidence for similar accretion in the region of initial subduction, along strike in the Izu-Bonin Arc. The accreted material was tectonically and/or magmatically surrounded by Eocene boninites, island arc tholeiites, and their plutonic roots, which now extend to the trench inner wall. Given the anomalous character of the widespread Eocene volcanism, including the probability of very shallow (<10 km) boninite magma-genesis, the amount of tectonic erosion necessary to produce these exposures is unknown, but could be quite small, perhaps on the order of 10–20 km. The conclusion remains, therefore, that the middle and upper Eocene IBM volcanic province was at least 300 km wide, with contemporaneous volcanism extending from what is now the Palau-Kyushu remnant arc to the inner trench wall, and with subaerial volcanoes along some segments of the frontal and outer arc highs.

OLIGOCENE ARC VOLCANISM

My interpretation of the biostratigraphic, radiometric, and sedimentologic data is that voluminous volcanism ceased on the outer arc high by the end of the late Eocene, but continued on the remnant arc/frontal arc high until 27–29 Ma (i.e., well into the rift phase before Shikoku and Parece Vela basin spreading). Determining the volcanic chronology is complicated by at least three factors: (1) redeposition of older fossil assemblages can increase apparent biostratigraphic ages; (2) K-Ar ages can be decreased by secondary alteration and/or argon loss, especially in K-poor, glassy rocks such as boninites (Walker and McDougall, 1982); and (3) intrusions much younger than the main phase of volcanism are common on the frontal arc high (in the middle Miocene Umatac and Fina Sisu formations on Guam and Saipan, respectively; Meijer et al., 1983), in the forearc basin (such as the post-15 Ma basalt sill at Site 792; Taylor, Fujioka, et al., 1990) and on the outer arc high (in the Pleistocene at Mariana Site 781; Marlow et al., in press).

I agree with Dobson (1986) that most of the young Bonin Island K-Ar dates, which range from 8 to 43 Ma (Tsunakawa,1983), are minimum ages. The interpillow sediments have middle Eocene faunal assemblages and there is one K-Ar date of 48 Ma (Dobson, 1986). Similarly, the 26–29 Ma K-Ar ages reported for the forearc basin basement at Site 793 by Taylor and Mitchell (this volume), are too young for the 31-Ma magneto-biostratigraphic age. There is some evidence, however, for early Oligocene outer arc-high magmatism at Sites 458 and 786. The nannofossil age of the overlying sediments and a "B-quality" $^{40}Ar/^{39}Ar$ age for the lavas at Site 458 are both 34 Ma (Hussong, Uyeda, et al., 1981; Ozima et al., 1983), and K-Ar dates on boninite and andesite intrusions within the basement at Site 786 also cluster around 34 Ma (Mitchell et al., in press). Even so, these may all be minimum ages, including the nannofossil age (Hussong, Uyeda, et al., 1981), given that Site 458 was drilled on a local basement high. The slow accumulation of dominantly pelagic Oligocene sediments at Sites 458, 459, 782, and 786 (Fig. 5) and of the Minamizaki limestone on the Bonin Islands (Umino, 1985) attests to the lack of major Oligocene volcanism along the outer arc high.

In contrast, volcanism continued into the late Oligocene along the remnant-arc/frontal arc high. The late Eocene to early Oligocene Alutom Formation on Guam is composed of volcanic breccias, tuffaceous sandstones, and lava flows, with calc-alkaline as well as arc tholeiitic and boninitic chemistries (Reagan and Meijer, 1984). K-Ar dates on the upper section of this formation range between 36 and 34 Ma, with sills intruded about 32 Ma (Meijer et al., 1983). Tholeiitic basalts, breccias, and tuffs drilled at Site 448 on the southern Palau-Kyushu Ridge (Fig. 1) document vigorous volcanism there at 34–29 Ma (Fig. 5; Kroenke, Scott, et al., 1980). Maximum sedimentation at the West Philippine Basin Site 447 (Fig. 1) also occurs at 34–29 Ma, associated with volcaniclastic breccia, conglomerate, and tuff from the Palau-Kyushu Ridge volcaniclastic apron (Kroenke, Scott, et al., 1980). Volcanic tuffs, lapilli tuffs, and sandstones drilled at Site 296 on the northern Palau-Kyushu Ridge (Fig. 1) indicate an overlapping but slightly later volcanic maximum, from 33 to 27 Ma (Fig. 5; Karig, Ingle, et al., 1975). Andesitic gravels in calcareous sandstone dredged from the surface of the frontal arc basement high at 29°09′N, 140°43′E (D731, 2640 m, Nishimura, this volume; see 29°15′ seismic profile in Fig. 3) gave K-Ar dates of 32.8 ± 2 Ma (Yuasa et al., 1988). If this is a true rather than a minimum age, then the associated shallow-water late Eocene foraminifers must be reworked. Rapidly deposited volcaniclastic turbidites and debris-flow deposits recovered at the Leg 126 forearc Sites 787, 792, and 793 (Figs. 2 and 5; Taylor, Fujioka, et al., 1990) document intense Izu-Bonin volcanism 31–27 Ma. Site 792 was drilled on one of the frontal arc highs and proved to be an Oligocene volcano (Figs. 2, 3, and 6). The basement, K-Ar dated at 33 Ma (Taylor and Mitchell, this volume), is composed of massive flows, with intercalated hyaloclastite and breccia layers, that are plagioclase-rich, two-pyroxene andesites and dacites with calc-alkaline affinities (Taylor, Fujioka, et al., 1990; Taylor et al., this volume). I interpret the frontal arc highs to be arc volcanoes of the Oligocene volcanic front and that, by the early Oligocene (≥ 33 Ma), the widespread Eocene volcanism that formed the IBM arc massif had evolved and focused into an arc system similar to the present (i.e., including volcanoes west of the volcanic front).

OLIGOCENE RIFTING

Determination of the nature of the basement and the origin of the forearc basin between the frontal and outer arc highs was a major objective of Leg 126. No previous leg had attempted to drill to basement through the thick sediments that typically fill intraoceanic forearc basins. Three main hypotheses had been proposed for the origin of the Izu-Bonin forearc basin: (1) it formed by forearc rifting

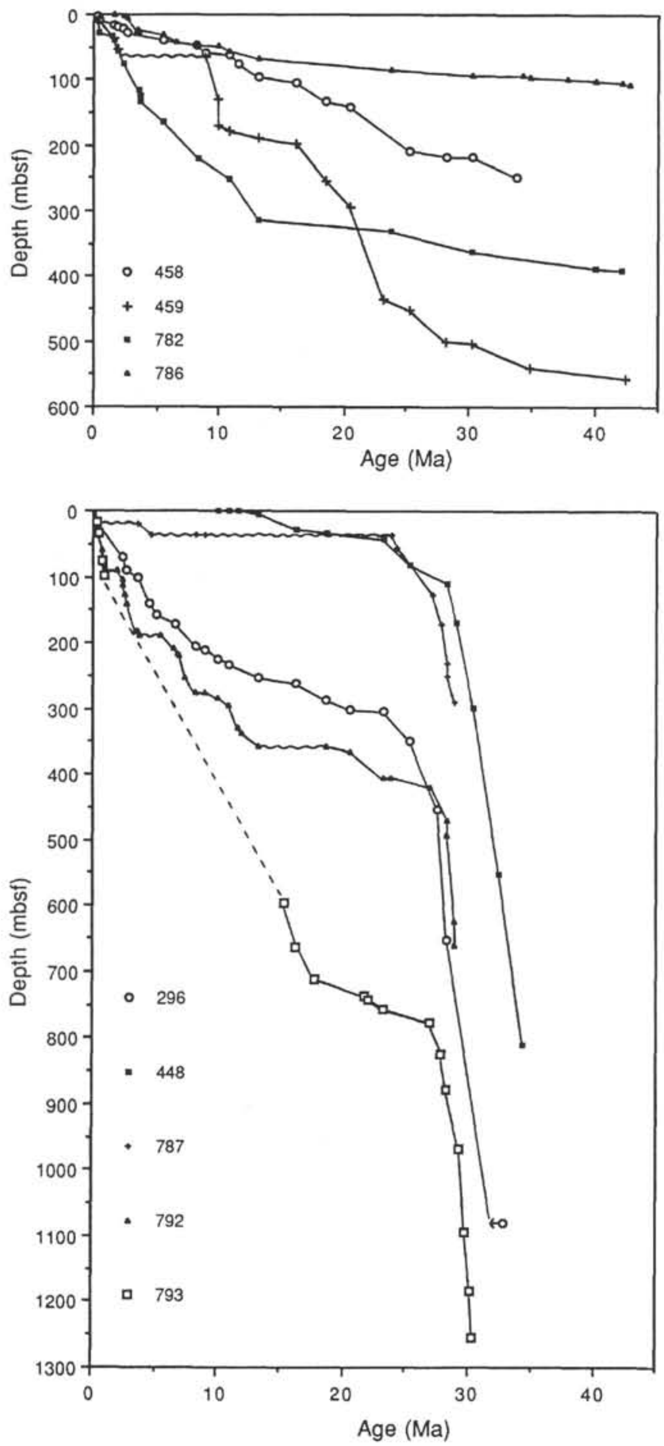

Figure 5. Age-depth plots for Izu-Bonin-Mariana outer arc high Sites 458, 459, 782, and 786 (top), remnant-arc Sites 296 and 448, and forearc Sites 787, 792, and 793 (bottom).

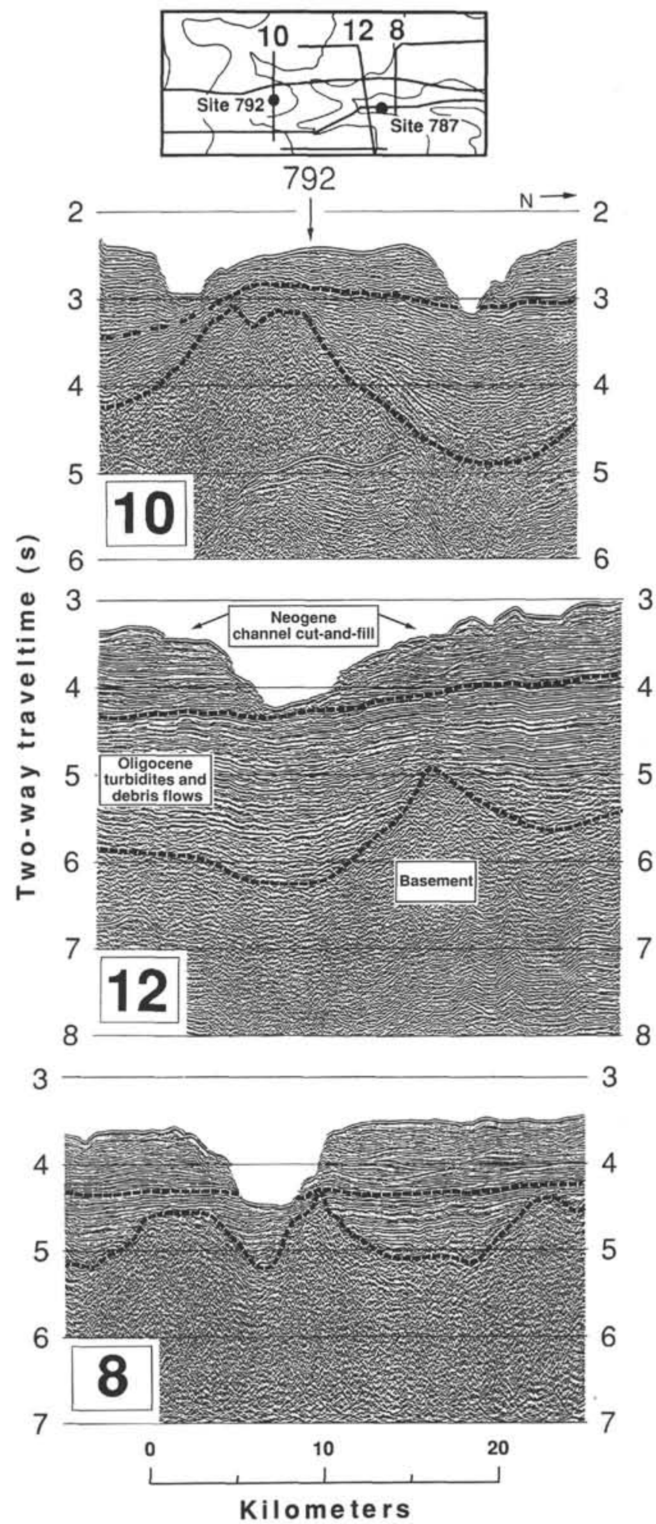

Figure 6. Migrated MCS profiles across Aoga Shima Canyon (Taylor et al., 1990b; Klaus and Taylor, 1991), illustrating the seismic stratigraphy of the Izu-Bonin forearc. Correlation of seismic horizons with drilling results at Sites 787 and 792 allows the identification of three major seismo-stratigraphic units: (1) high relief acoustic basement, characterized by incoherent reflections, (2) an Oligocene section dominated by unconfined turbidity and debris flows resulting in subparallel and continuous reflectors, offset by contemporaneous normal faults, and (3) Neogene sequences characterized by erosional surfaces and migrating sediment packages, indicative of pervasive channel cut-and-fill. Note that the numerous small-offset Oligocene normal faults, which are best evidenced on Profile 12, do not extend into the Neogene section.

or spreading that separated the once-contiguous frontal and outer arc highs; (2) the basin resulted from volcanic construction of the frontal and outer arc highs on preexisting crust (of the West Philippine Plate); or (3) the basin is a structural low in a continuous Eocene arc-volcanic province (Leg 126 Scientific Drilling Party, 1989). The Leg 126 results in the context of the regional seismic data confirm the first hypothesis.

Drilling at Sites 787 and 792 sought to recover the oldest basin sediments, which locally occur below an unconformity onto which laps the majority of the forearc basin fill (Fig. 6). Hole collapse prematurely ended drilling at Site 787 in 29-Ma volcaniclastics (Fig. 7). The unconformity was initially thought to have been crossed 53 m above basement at Site 792, with the basal sedimentary section being lower Oligocene (Leg 126 Shipboard Scientific Party, 1989). Subsequent identification of a CP19a nannofossil assemblage (28.2–30.2 Ma) only 19 m above basement (Firth and Isiminger-Kelso, this volume) and the possible presence of a normal fault at the basement-sediment interface indicate that the unconformity may not have been penetrated. Nevertheless, the 33-Ma K-Ar basement age at Site 792 (Taylor and Mitchell, this volume) is consistent with an early Oligocene age for the oldest basin sediments.

Drilling in the center of the forearc basin at Site 793 successfully penetrated the full sedimentary section and continued 278 m into volcanic basement (Figs. 7 and 8A), setting the DSDP/ODP record (1682 mbsf) for the deepest hole to reach basement. The basement consists of volcanic breccias, pillowed flows, and massive flows of dominantly high-Mg (but with some low-Mg), low-Ti, vesicle-poor (<5%), two-pyroxene basaltic andesites and andesites (Taylor, Fujioka, et al., 1990). Except for their less-radiogenic lead isotopes, they are very similar to the Mariana forearc Site 458 bronzite andesites and are geochemically intermediate between two Bonin Ridge lava suites (Chichijima boninites and Hahajima tholeiites; Taylor et al., this volume). Pyroxene geothermometry indicates crystallization temperatures of 1050°–1100° ± 50°K at pressures <10 kb (Lapierre et al., this volume).

The overlying 31 m of poorly sorted volcaniclastic breccia with sandy matrix at Site 793 contains plagioclase-porphyritic andesite clasts similar to the calc-alkaline andesites at Site 792, but not to the underlying volcanics. The base of the overlying coarse volcaniclastic sediments are magnetobiostratigraphically dated at 31 Ma (Taylor, Fujioka, et al., 1990) and, according to benthic foraminifer data, were deposited below the CCD in water depths of about 3.5–4 km (Kaiho, this volume). Significantly, no shallow-water or Eocene deposits were encountered, in contrast to drilling results from the frontal and outer arc highs on either side.

These data are incompatible with models of forearc basin formation that require pre-existing West Philippine Plate crust or a depression in Eocene arc crust (which should have collected Eocene sediments) to floor the basin. The data are compatible with the model of forearc rifting. In this model the lower Oligocene lavas at Site 793 would represent rift-related volcanism during or after the initial subsidence of the basin, which, once formed, filled rapidly with Oligocene debris flow deposits and turbidites produced by concurrent volcanism and erosion of the surrounding highs. An analogous evolution is documented below for the active Sumisu Rift. I prefer a model of forearc rifting rather than spreading, given the narrow and varying width (20–90 km) of the forearc depocenters, many of which are half graben (Figs. 8B and 9A–C).

Extension Structures

Figure 8B shows an example of the forearc basin floored by a low-relief basement surface, including small half-graben. The strong dipping reflectors within the basement (Fig. 8) may be from crustal detachment surfaces (Taylor et al., 1990b). The three MCS profiles in Figures 9A–9C show the more typical situation, with high-relief basement blocks bounding half graben or deep sags. Maximum basin depths commonly occur on the east, with adjacent footwall uplifts forming the western side of the outer arc high. Regionally, the depth of the forearc depocenters increases to the south, whereas the outer arc high shoals onto the Bonin Ridge. Consequently, the basement of the outer arc high is buried by onlapping sediments in the north but not in the south (Fig. 9).

The distance between the frontal and outer arc highs increases to the south (Figs. 9 and 10). The essential continuity of the outer arc high, and of the forearc basin, can be seen in the free air gravity and seismic data to extend from 33° to 22°N (Fig. 10, unpubl. data further south, and Honza and Tamaki, 1985). In contrast, the frontal arc highs (Figs. 3 and 6), like the volcanoes of the active arc, are spaced 20–80 km apart but cannot be identified south of 28°N, where they trend beneath the active arc. The frontal arc highs (the Oligocene volcanic front) trend 353° and bisect the Izu-Bonin arc massif, whereas the present volcanic front trends 350° and diverges westward from the frontal arc highs north of 28°. North of 33°N the forearc basement surface mimics the free air gravity; there is a gradually increasing slope trenchward without a well-developed forearc basin or outer arc high (Fig. 10; see seismic profiles in Honza and Tamaki, 1985).

Bathymetry, gravity, and seismic data indicate that the width of the Izu-Bonin arc massif (approximately bounded by the 3.5 and 6.5 km contours on the west and east, respectively) varies along strike from a minimum 300 km in the north to a maximum over 400 km near 28°N (Fig. 10). Assuming little Neogene tectonic accretion/erosion, as discussed previously, and noting the greater development of rift structures in the south, I infer that the amount of Oligocene rift-related extension increases to the south. The most marked increase occurs south of about 30°N and corresponds to a significant deepening of the arc massif as well as to the presence of major half graben rift basins in the backarc. Such sediment-filled half graben are present further north (Fig. 3), but are strikingly developed in the south. The largest of these is the Nishinoshima Trough, which occurs adjacent to the largest forearc basin segment, the Bonin Trough (Fig. 10).

Figures 9D–9E show seismic profiles across the Nishinoshima Trough and its western border fault blocks. The north-northeast-trending border fault forms part of Yuasa's (1985) "Sofu Gan Tectonic Line," an oblique tectonic boundary, which he inferred separates the northern and southern parts of the arc and possibly formed as a strike-slip fault during differential opening of the Shikoku and Parece Vela basins. Karig and Moore (1975) and Bandy and Hilde (1983) also noted en echelon NNE-NE arc structures and postulated that they may represent faults bounding rotated blocks resulting from collision of the Izu-Bonin Arc with Honshu. Rather than affecting the entire arc, deformation of the northern Izu-Bonin Arc appears to be 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 (Le Pichon et al., 1987). Repetition of this process has accreted terrains of Izu-Bonin arc crust to south central Honshu over the last 15 Ma (Taira et al., 1989).

The 20°–35° structures are matched by a set of 315°–330° structures, such as the fault block at the southern end of Nishinoshima Trough and the fault blocks bounding the outer arc high at 30.5°N (Figs. 9 and 10). I interpret both sets of structures as normal faults associated with the Oligocene rifting, rather than strike-slip faults. The border faults to the Oligocene rift basins form a zigzag fault pattern similar to the border faults of the Quaternary backarc rifts and of other rift basins, such as in East Africa (B. Taylor et al., 1991; Klaus et al., this volume; see below). Like the active Izu-Bonin rifts, the Oligocene rifts are characterized by numerous local depocenters, separated by structural highs (e.g., Figs. 6 and 8).

Sedimentation

The local depocenters filled rapidly with coarse volcanogenic sediments and formed a forearc basin plain by the middle Oligocene (Hiscott et al., this volume). The sediments older than 28 Ma at Sites 792 and 793 were deposited at undecompacted rates of 250–300 m/m.y. (Figs. 5 and 7). The sediments are (1) graded sandstones, pebbly sandstones and conglomerates deposited by turbidity currents; (2) up to 15 m thick structureless beds of similar material deposited by debris flows; and (3) 5%–10% mudstone interbeds. Between 27 and 29 Ma, paleocurrents flowed from north to south along the basin axis, with a small component of flow away from the western (arc) margin (Hiscott et al., this volume). Shallow-water limestone fragments, carbonate bioclasts, and wood fragments in the gravity-flow deposits at Site 793

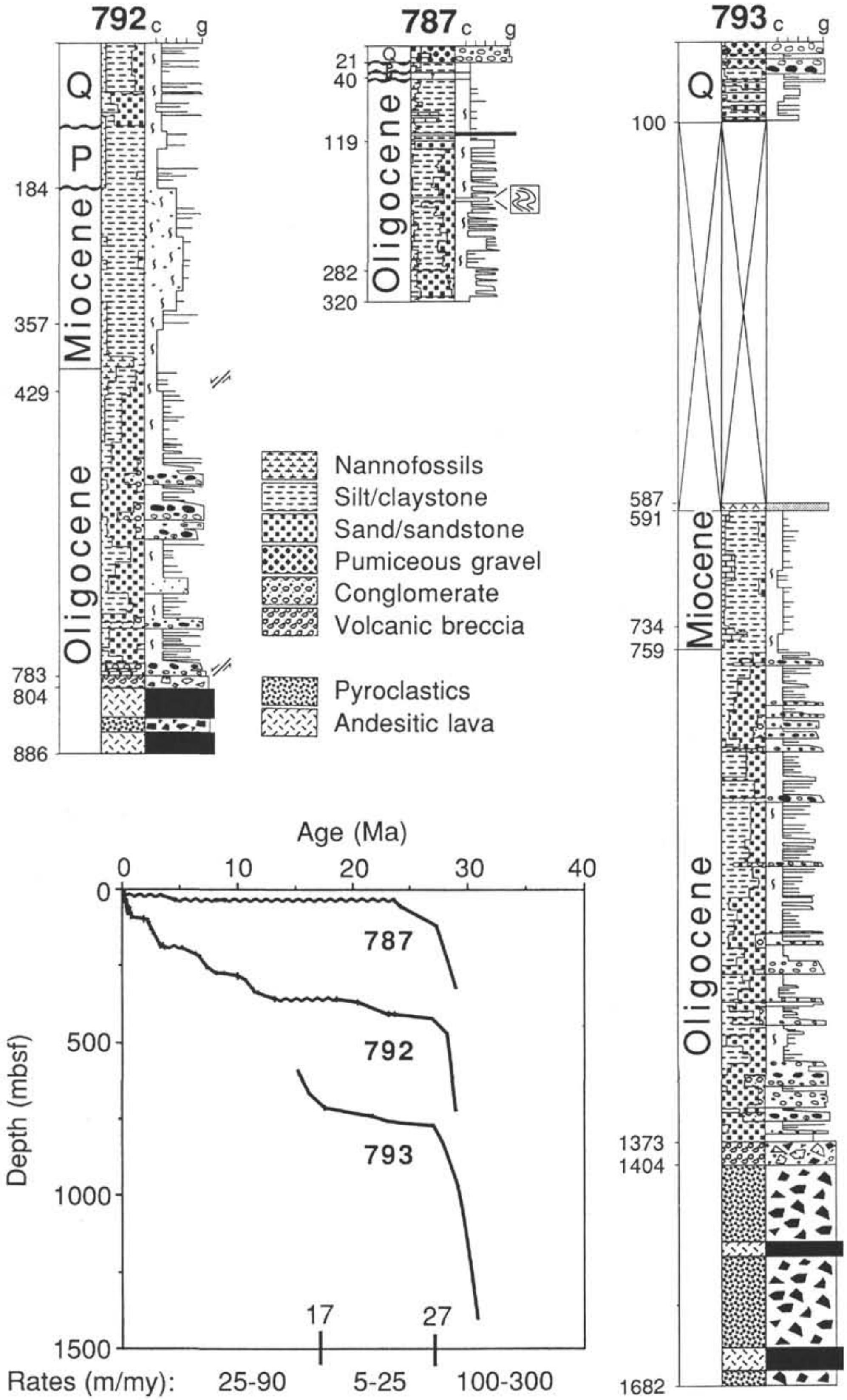

Figure 7. Lithostratigraphic summaries for Leg 126 forearc Sites 787, 792, and 793. The depths (mbsf) of unit boundaries are shown on the left of each column and a graphic sedimentological log displays the relative grain size on the right (from c = clay to g = gravel). An age-depth plot, showing three periods of distinct sedimentation rates, is shown on the bottom left.

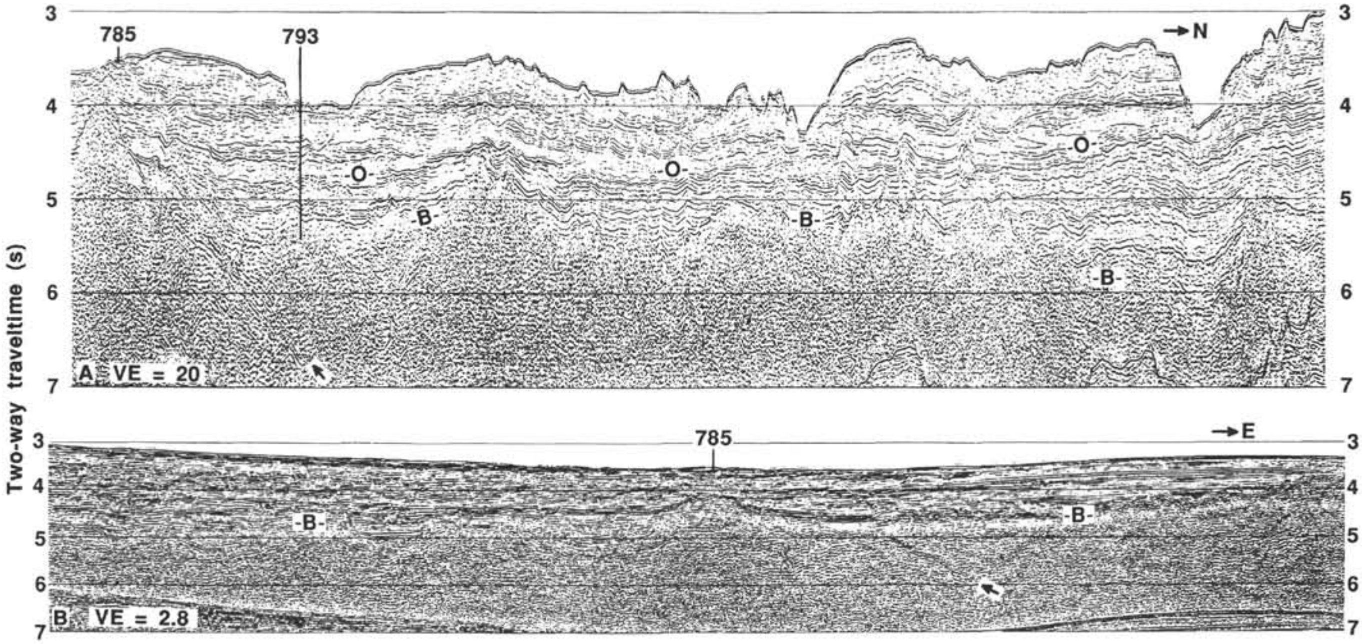

Figure 8. Migrated MCS profiles crossing Sites 785 and 793 (see Fig. 2 and Taylor et al. [1990b] for location). The 200-km-long Profile A (top) is a strike line along the approximate center of the forearc basin. The three seismo-stratigraphic units described in Figure 6 are divided by reflectors labeled B = basement/Oligocene and O = Oligocene/Neogene. The depth to Reflector O varies between 3724 m (at Site 793) and ~3500 m, from Sumisu Jima Valley to just south of Aoga Shima Canyon. At the northern end of the profile, this near-horizontal layer is tilted up to a depth of ~3000 m (Klaus and Taylor, 1991). The seismic stratigraphy indicates middle Miocene or younger uplift of the northern forearc. The 56-km-long Profile B (bottom) is a dip line showing a low-relief basement surface, including a small half-graben. The strong dipping events within basement on both profiles (arrowed) may be reflections from crustal detachment surfaces. VE = vertical exaggeration.

were probably derived from islands along the frontal arc (Nishimura, this volume). The unconfined mass flows created subparallel and continuous sedimentary sequences that filled the forearc basin between 30°–33°N to about the level of the outer arc high (Figs. 3, 4, 8, and 9), which benthic foraminifer data indicate was at depths between 1.3 and 3 km in the late Oligocene at Sites 782 and 786 (Kaiho, this volume); further south, the Bonin Trough remains unfilled (Figs. 3, 9, and 10). Seismic reflection data show that the Oligocene section is often pervasively faulted by small-offset (≤ 50 m), high-angle normal faults; they do not extend into the Neogene section (Fig. 6). Subvertical clastic injections, extension fractures, and vein structures observed in the forearc cores indicate that a mildly extensional environment continued from the upper Oligocene into the lower Miocene (Taylor, Fujioka, et al., 1990; Ogawa, this volume). However, the major forearc stretching phase, associated with the large-offset border faults (Fig. 9), was completed in the early Oligocene.

LATE OLIGOCENE-EARLY MIOCENE BACKARC SPREADING

Continued stretching of the Oligocene arc/backarc culminated in Shikoku and Parece Vela basin backarc spreading, which separated the Palau-Kyushu Ridge remnant arc from the IBM arc (Fig. 1; Karig, 1975). The initiation of this backarc spreading was not synchronous along the length of the Oligocene arc. Spreading began by 30 Ma (Magnetic Anomaly 10) in what became the central Parece Vela Basin (Mrozowski and Hayes, 1979; Kroenke, Scott, et al., 1980) and propagated north and south, giving the basin its bowed-out shape. A second spreading system began by 25 Ma (Magnetic Anomaly 6C reversed) in the northern Shikoku Basin and propagated south, producing a V-shaped basin (Fig. 11; Watts and Weissel, 1975; Kobayashi and Nakada, 1979; Chamot-Rooke et al., 1987). This diachronism is reflected in the delayed end to volcanism and rapid sedimentation on the northern vs. southern Palau-Kyushu Ridge, as recorded at Sites 296 and 448 (Fig. 5). By 23 Ma (Magnetic Anomaly 6B) the two basins had joined and they continued spreading along a common axis until spreading ceased, about 15 Ma. The magnetic anomaly identifications agree at Site 442 (drilled on Anomaly 6 west, Fig. 1) with the biostratigraphic determination of sediment age above basement (18–21 Ma, Klein, Kobayashi, et al., 1980).

Revised Shikoku Basin Spreading History

Identifying a symmetric set of magnetic anomalies in the Shikoku Basin has always been problematic (Watts and Weissel, 1975). Given the position of the relict spreading axis, approximately marked by the alkalic extrusions of the Kinan seamount chain, asymmetric accretion is required (Fig. 11). The extent of the asymmetry is only fully realized when the boundary of the rifted blocks of Oligocene arc crust is plotted, as in Figure 11. Chamot-Rooke et al. (1987) implicitly assumed that much of the asymmetry resulted from Neogene arc volcanism overprinting the former eastern edge of the basin. Although volcanism west of the arc front has occurred, with a few exceptions (such as Zenisu Ridge in the north), it has not extended substantially onto Shikoku Basin crust. The westernmost tilted fault blocks of the rifted Oligocene arc crust are still recognizable (e.g., Figs. 3 and 9), and their positions leave insufficient room, even at reasonably reduced asymmetric spreading rates, for an eastern equivalent to the oceanic crust previously identified as formed during magnetic Subchrons 6A to 6C (Fig. 11). Note the structural asymmetry of the rifted margins: most of the faults dip east on both edges of the basin.

As a possible solution to this space problem, I have postulated a failed spreading center within the "6A" sequence; changed the identification of anomalies 6C, 6B, and $6A^{1-4}$ to 6A, 6, and 5E-5D-5D-5E, respectively; and maintained similar spreading rates during the final spreading phase (5C-5B instead of 5E-5B). This is compatible with Shikoku Basin Sites 442-444 basement ages (Klein, Kobayashi, et al., 1980). Such a revised identification of the western anomalies, which would require only room for a 6A sequence east of the axial 5B-5C anomalies, is shown for three representative profiles at the base of

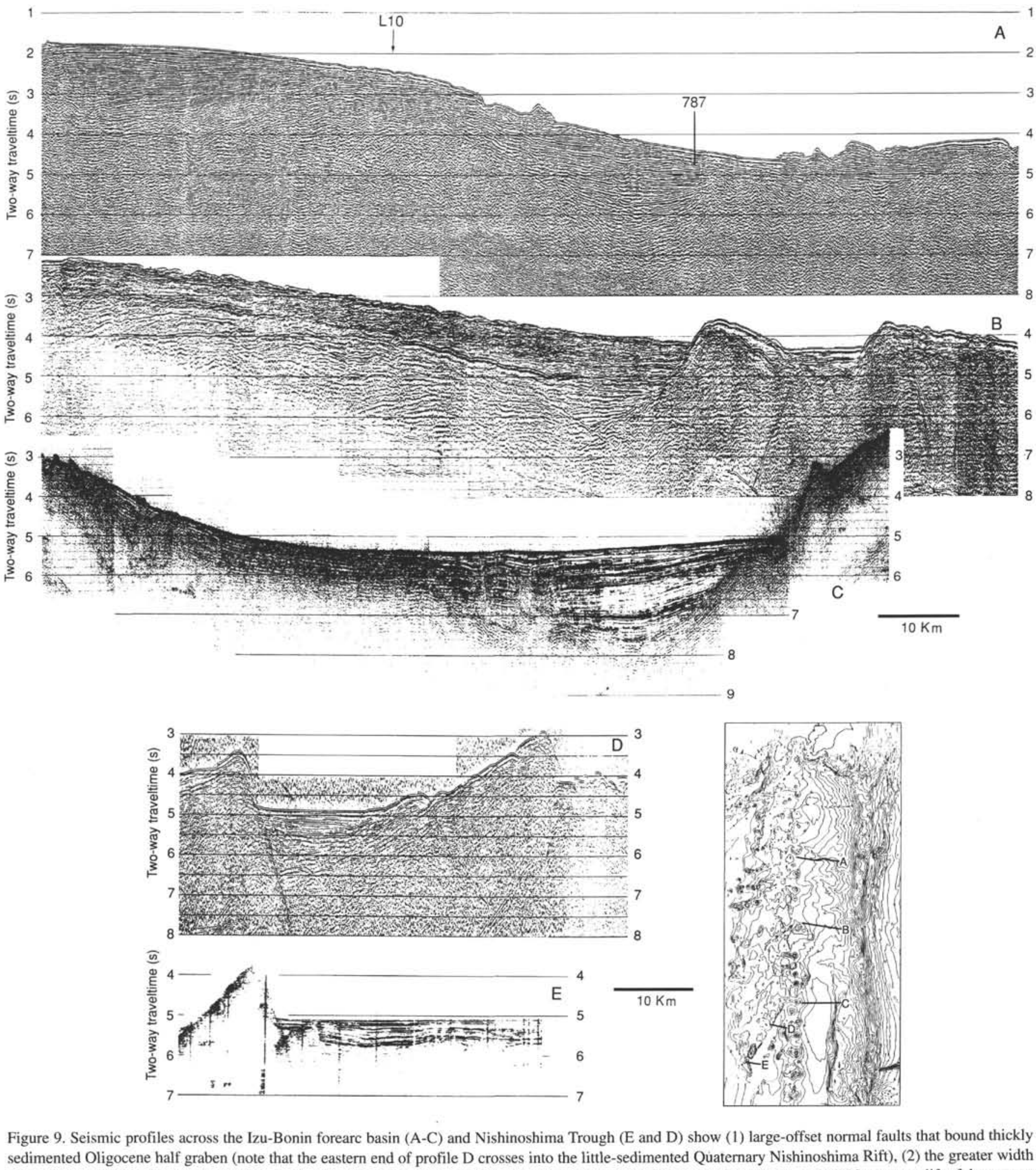

Figure 9. Seismic profiles across the Izu-Bonin forearc basin (A-C) and Nishinoshima Trough (E and D) show (1) large-offset normal faults that bound thickly sedimented Oligocene half graben (note that the eastern end of profile D crosses into the little-sedimented Quaternary Nishinoshima Rift), (2) the greater width of the forearc basin to the south (Profiles A-C), (3) a sill intruded into the forearc basin sediments in the center of Profile B, and (4) Neogene uplift of the eastern side of the Bonin Trough (Profile C). All profiles are plotted at a vertical exaggeration of 6.7. Profiles A (Taylor et al., 1990b) and C (Japanese DELP Research Group On Backarc Basins, 1989) are migrated MCS data; Profiles B (proprietary Japan National Oil Co. data) and D (Miyazaki et al., 1986) are stacked MCS data; and Profile E (Murakami et al., 1986) is single-channel data.

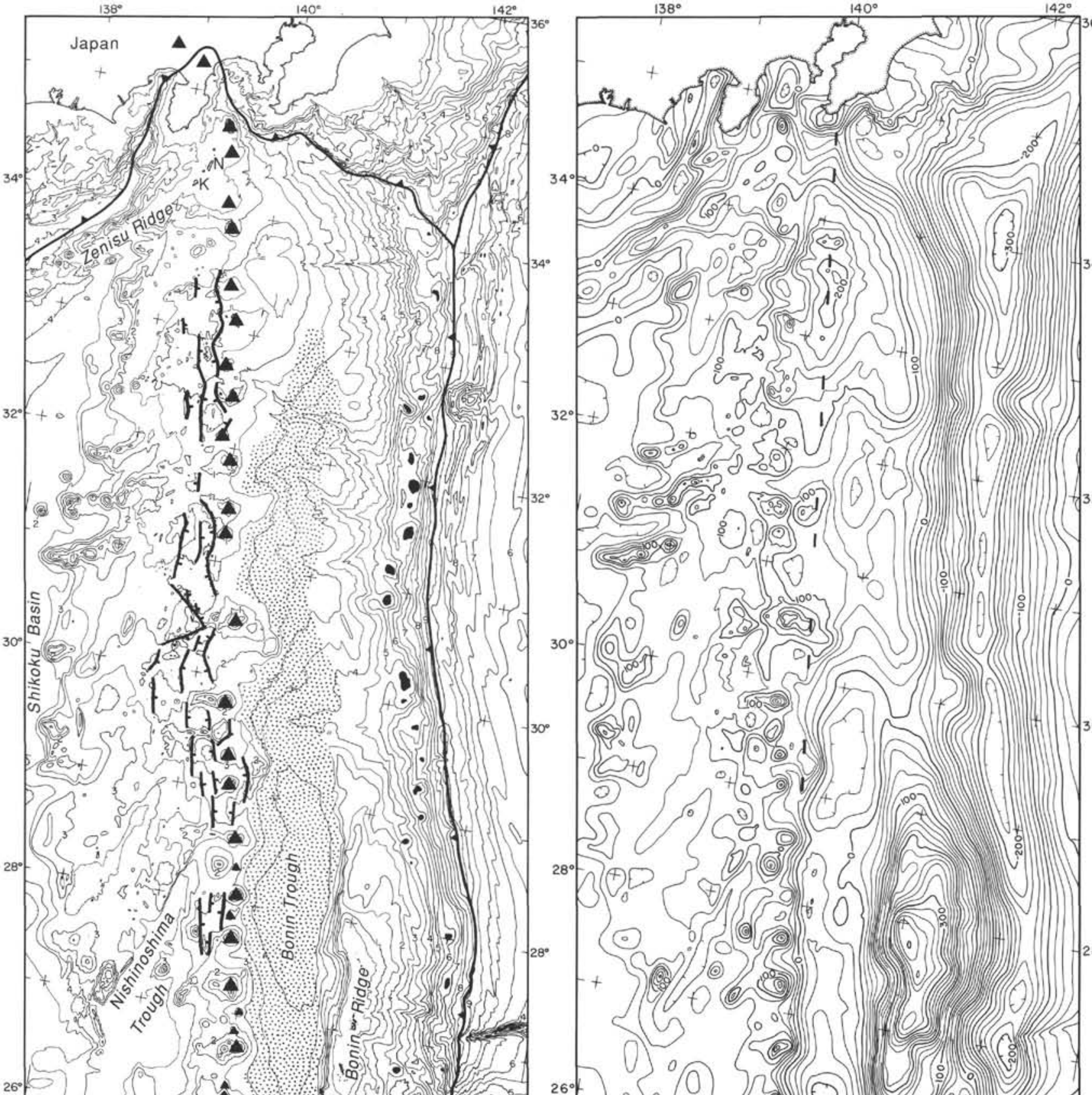

Figure 10. Bathymetry (left, at 500-m contour intervals, labeled every kilometer) and free-air gravity (right, 20-mgal contour intervals, labeled every 100 mgal) of the Izu-Bonin arc-trench system. On the bathymetric map, barbed heavy lines locate trench axes, filled bathymetric contours locate serpentinite seamounts on the trench inner wall, filled triangles locate frontal arc volcanoes, ticked heavy lines locate active normal faults, and the thickly sedimented forearc basin is stippled. N = Niijima and K = Kozushima. The dashed line on the free-air gravity map links frontal arc highs.

Figure 11. One implication of this revision is that the inferred age of initial Shikoku Basin spreading would decrease from 25 to 22 Ma, making it about 8 m.y. after the initial Parece Vela Basin spreading. This is not unreasonable, given the present 6-m.y. lead of central Mariana Trough spreading on the yet-to-spread Izu-Bonin rifts. Also, the two basins would not join until about 20 Ma (Anomaly 6), and the width of the crust generated since then in both basins would be more comparable than with the previous Shikoku Basin anomaly identifications.

Arc Volcanic Minimum

The period of final arc rifting and subsequent (initial) backarc spreading coincides with a major reduction in arc volcanic activity. Mariana arc volcanism decreased in intensity (31–29 Ma) and may have ceased (29–27 Ma) during initial spreading of the Parece Vela Basin (Kroenke, Scott, et al., 1980; Meijer et al., 1983). There is no record of volcanic ash in the Mariana system between 29–27 Ma, either on Guam (Meijer et al., 1983) or in the Leg 60 forearc sites

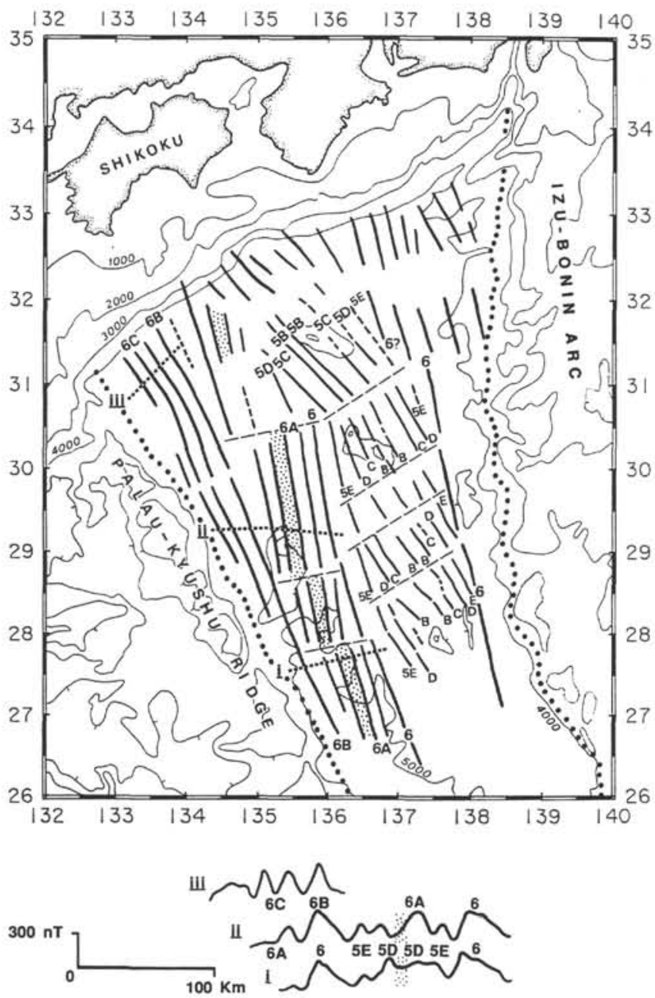

Figure 11. Magnetic lineation map of the Shikoku Basin, modified after Chamot-Rooke et al. (1987) and Chamot-Rooke (1989). Magnetic anomalies along Profiles i-iii, at the base of the figure, are identified according to the above authors (6C-6, top) and according to my alternate interpretation (6A-5D, bottom). The location of the failed rift that I infer at Subchron 5D is stippled and the boundary of rifted blocks of Oligocene arc crust is dotted. The position of the relict spreading center is between the 5B anomalies, as shown in Figure 1.

(Hussong and Uyeda, 1981); the insoluble residues from six samples of Maemong Limestone on Guam record volcanic input sometime during the late Oligocene-early Miocene (Hathaway and Carroll, 1964; Meijer et al., 1983), but the precise age of these samples is uncertain. A sharp decline in volcanogenic and epiclastic supply to the Izu-Bonin forearc and Palau-Kyushu remnant arc basins is recorded in the claystones, nannofossil claystones, and clayey nannofossil chalk that accumulated slowly (typically <10 m/m.y.) during the latest Oligocene and early Miocene (Figs. 5 and 7). The Legs 125 and 126 and Site 296 drilling results show that Izu-Bonin arc volcanism decreased in intensity at 27 Ma and was a minimum 23–17 Ma, with no record of volcanic ash 23–20 Ma during early spreading of the Shikoku Basin (Taylor, Fujioka, et al., 1990; Fujioka et al., this volume).

NEOGENE VOLCANISM AND SEDIMENTATION

Frontal Arc Volcanism

A significant increase in pyroclastic IBM arc volcanism began about 20 Ma in the Mariana and 17 Ma in the Izu-Bonin regions. Sites 449–451 and 459 near 18° N (Fig. 1) document explosive volcanism on the West Mariana Ridge from about 20 until 9 Ma (Kroenke, Scott, et al., 1980; Hussong, Uyeda, et al., 1981). Scattered ash in the upper lower Miocene Unit III at Site 793 heralds the renewed input at 20 Ma of pyroclastic material to the Izu-Bonin forearc (Taylor, Fujioka, et al., 1990). Volcanogenic input to the basin raised sedimentation rates at Site 793 to 70 m/m.y. between 17 and 15 Ma (Fig. 5). Site 792 records an increasing pyroclastic input since the middle Miocene, climaxing in the late Pliocene and Quaternary. The middle Miocene to Holocene pyroclasts are visually and chemically bimodal, with black basaltic-andesitic scoria and ash and white rhyodacitic pumice and ash (Fujioka, Matsuo, et al., this volume). Both form part of a mostly low-K, sub-alkaline arc series (Hiscott and Gill, this volume).

The Neogene Izu-Bonin volcanoes built on the stretched Eocene-Oligocene arc crust along a volcanic front oriented slightly counterclockwise (350°) from the Oligocene one (353°; Fig. 10). Unlike parts of the active Mariana, Tofua, and South Sandwich arcs (Taylor and Karner, 1983), they were not built on backarc basin crust. Partly as a result of the greater Oligocene stretching southward, the regional elevation of the arc massif on which the volcanoes sit deepens to the south (Fig. 12). South of 30° N most of the edifices are submarine. Whereas most of the high islands are basaltic or andesitic, most of the submarine or near-sea-level (e.g., Myojin Sho) edifices north of 31° N are rhyodacitic calderas (Taylor et al., 1990a; Yuasa et al., in press).

The volcanic centers north of 31° (from South Sumisu caldera to Oshima) form six pairs with an amazingly regular spacing (Figs. 10 and 12). The pairs of volcanic centers are separated by an average 74 km (total range 68–82 km) with the two volcanoes in each pair an average 27 km (24–33 km) apart. Torishima and Sofu Gan are not paired volcanoes. The next four submarine centers to the south are paired and similarly spaced, but this relationship breaks down further south (Fig. 12). Another unusual characteristic of the central Izu-Bonin arc, compared to northeast Japan or the Cascades, for example, is the small amount of Pliocene-Quaternary volcanism between the frontal volcanic centers. Only a handful of small (1–2 km diameter) vents are visible on 100% sidescan coverage of this area from 29° to 31.5° N (Taylor et al., 1988a, unpubl. data); no igneous material was encountered in drilling at Site 788 between Sumisu Jima and Torishima (Fig. 2; Taylor, Fujioka, et al., 1990). The Neogene magmatism along the volcanic front has been focused on regularly spaced, long-lived centers, by diapiric processes which are as yet imperfectly understood.

Backarc Volcanism

Neogene volcanism was not limited to the volcanic front but occurred in the backarc and forearc as well. Chains of mostly submarine volcanoes occur both immediately west of the frontal arc volcanoes (such as Sofu Gan) and on the western edge of the rifted Oligocene arc crust, particularly west of 139°E (Figs. 10 and 13). Thus, as in northeast Japan (Tatsumi, 1989), there is both a frontal and a rearward chain of arc volcanoes, both with cross chains. K-Ar dates on the calc-alkaline basalts and dacites dredged from the western chains are Pliocene (Ikeda and Yuasa, 1989). The longest arc volcanic cross chain on earth includes three islands (Niijima to Kozushima) southwest of the submarine caldera Omuro-dashi as well as the submarine edifices on Zenisu Ridge (Fig. 10), and is composed of mostly high-K andesites, dacites, and rhyolites (Isshiki et al., 1982; Hamuro et al., 1983). The western edifices were erupted along a fracture zone offset of Shikoku Basin magnetic anomalies (Lallemant et al., 1989).

Forearc Volcanism

The existence of volcanic flows or sills within the Izu-Bonin forearc sedimentary section was recognized before drilling from interpretation of MCS profiles. One such feature, seen in the center of Profile B (Fig. 9), is over 20 km across. An olivine diabase sill, not

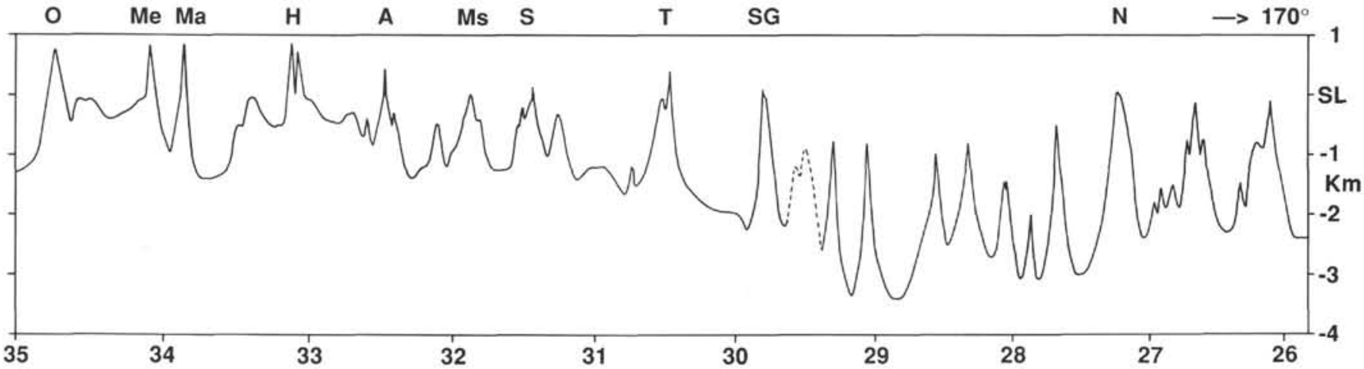

Figure 12. Silhouette profile of the topography and bathymetry of the Izu-Bonin volcanic front along a 25-km wide strip from O Shima (O) southward (170°) through Nishino Shima (N). Other subaerial volcanoes are labeled Me = Miyake Jima, Ma = Mikura Jima, H = Hachijo Jima, A = Aoga Shima, Ms = Myojin Sho, S = Sumisu Jima, T = Tori Shima, and SG = Sofu Gan. Basement highs that are not Quaternary volcanoes are dashed. The horizontal axis is labeled in degrees of northerly latitude. Note the bimodal spacing of volcanic centers north of 31° N. The profile is deepest between Nishino Shima and Sofu Gan, where both Oligocene arc stretching was a maximum and active rift basins cross the volcanic line. SL = sea level.

recognized on the site survey MCS data, was encountered at 586.5–591 mbsf at Site 793 (Taylor, Fujioka, et al., 1990). It is a basaltic andesite arc tholeiite and was intruded into 15 Ma sediments. A Pleistocene arc-tholeiite intrusion was drilled in the outer Mariana forearc at Site 781 (Fig. 1), adjacent to a contemporaneous serpentine volcano (Marlow et al., in press). The petrogenetic conditions that allow occasional "arc" volcanism in the thermally cool forearc are not understood (heat flow equals 54.6 and 24 mW/m^2, or 1.3 and 0.6 heat flow units, at Sites 792 and 784 [Fig. 2], respectively).

Sedimentation and Mass Wasting

In the region of Legs 125 and 126 drilling (Fig. 2), Oligocene sediments filled the forearc basin to about the level of low points in the outer arc high (Figs. 3, 4, and 9A). Three major submarine canyon/valley systems nucleated on these basement lows and incised the forearc basin (Fig. 2; Taylor and Smoot, 1984; Klaus and Taylor, 1991). The Neogene forearc sequences evidence pervasive channel cut and fill, characterized by migrating and unconformable seismic sequences (Figs. 6 and 8) and recorded at Site 792 by four lacunae (1–1.9, 3.5–6, 8–9, and 13–19 Ma; Taylor, Fujioka, et al., 1990). Except where ponded behind serpentinite seamounts, sediments on the lower forearc slope have slumped into the trench, exposing igneous basement (Fig. 3; Horine et al., 1990).

Extensive canyon formation since the early Miocene permitted sediment to bypass the forearc in canyon-confined mass flows (Klaus and Taylor, 1991). The upper 21 m drilled at Site 787 in Aoga Shima Canyon is scoriaceous and pumiceous sandy gravel and sand, <0.275 Ma in age (Taylor, Fujioka, et al., 1990), which I interpret to be volcaniclastic material, from a recent eruption, on its way to the trench. About 9500 km^3 of sediment has been eroded from the forearc basin between 31° and 32° 45′ N by the formation of the three large canyon/valley systems (Klaus and Taylor, 1991). Sediments presently in the adjacent trench, small accretionary prism, and lower slope terrace basin can account for <25% of this amount. Even ignoring sediments on the Pacific Plate or input by forearc bypassing, >3500 km^3 of sediment per 100 km of trench has been subducted and probably recycled into the mantle (Klaus and Taylor, 1991).

The Neogene forearc evolution varied to both the north and south of the region drilled. Seismic stratigraphy indicates that the Oligocene basin plain sediments north of 32.4° N were uplifted since the early Miocene (Fig. 8; Klaus and Taylor, 1991). The kilometer of total basement uplift at Site 792 (compared with 0.6 km of total basement subsidence at Site 793; Kaiho, this volume) is a record of this along-strike (rather than across-strike) variation in vertical motion history. The cause is unknown. This uplift and the less stretched forearc in the north combined to produce a steep forearc gradient, little influenced by either a forearc basin or outer arc high (see profiles in Honza and Tamaki, 1985). One result is that much narrower and straighter submarine canyons formed than in the central forearc (Fig. 10; Taylor and Smoot, 1984; Klaus and Taylor, 1991). Most of the canyons trend easterly into the Izu-Bonin Trench, indicating that they were initiated before northward bending of the forearc down into the Sagami Trough. South of 30° N the forearc basin is deeper and the outer arc high is higher so that no canyons have breached the outer arc high and sediments supplied to the forearc remain in the Bonin Trough (Figs. 9 and 10). The sediment supply is probably less than further north, however, given that most of the arc volcanoes are under water. Seismic stratigraphy indicates that the Bonin Ridge was uplifted in the Neogene (e.g., Figs. 3 and 9), before the more recent collision of the Ogasawara Plateau (Karig and Moore, 1975; Honza and Tamaki, 1985).

QUATERNARY RIFTING

Over a length of 700 km, from south of Mikura Jima to north of Nishino Shima, a series of basins bounded by normal faults parallels the volcanic front of the Izu-Bonin arc (Fig. 13). These rift basins occur on the west (backarc) side of the arc volcanoes, except near 29° N where they surround them. Following initial reconnaissance (Mogi, 1968; Hotta, 1970; Karig and Moore, 1975) and a systematic geophysical survey in 1979/80 (Honza and Tamaki, 1985) of the Izu-Bonin Arc, focused investigations of the active rift system by the Geological Survey of Japan and the Hawaii Institute of Geophysics began in 1984, with particularly intense studies of Sumisu Rift. These investigations include densely spaced, single-channel seismic profiling (Murakami, 1988; Klaus, 1991), SeaMARC II and SeaBeam swath-mapping (Brown and Taylor, 1988; Taylor et al., 1988a, 1988b, 1990a); sediment coring and heat flow measurements (Nishimura and Murakami, 1988; Yamazaki, 1988; Nishimura et al., 1988; Nakao et al., 1990); dredging and submersible rock sampling (Ikeda and Yuasa, 1989; Fryer et al., 1990; Hochstaedter et al., 1990a, 1990b; Urabe and Kusakabe, 1990); bottom photography and submersible observations (Taylor et al., 1990a; Smith et al., 1990); and multichannel seismic profiling (Taylor et al., 1990b; B. Taylor et al., 1991; Klaus, 1991; Klaus et al., this volume). In combination with drilling at Sites 788-791 (Taylor, Fujioka, et al., 1990), Sumisu Rift has become the most intensely and comprehensively studied intraoceanic arc rift segment. The following synthesis draws on all the above references, without repeated acknowledgments.

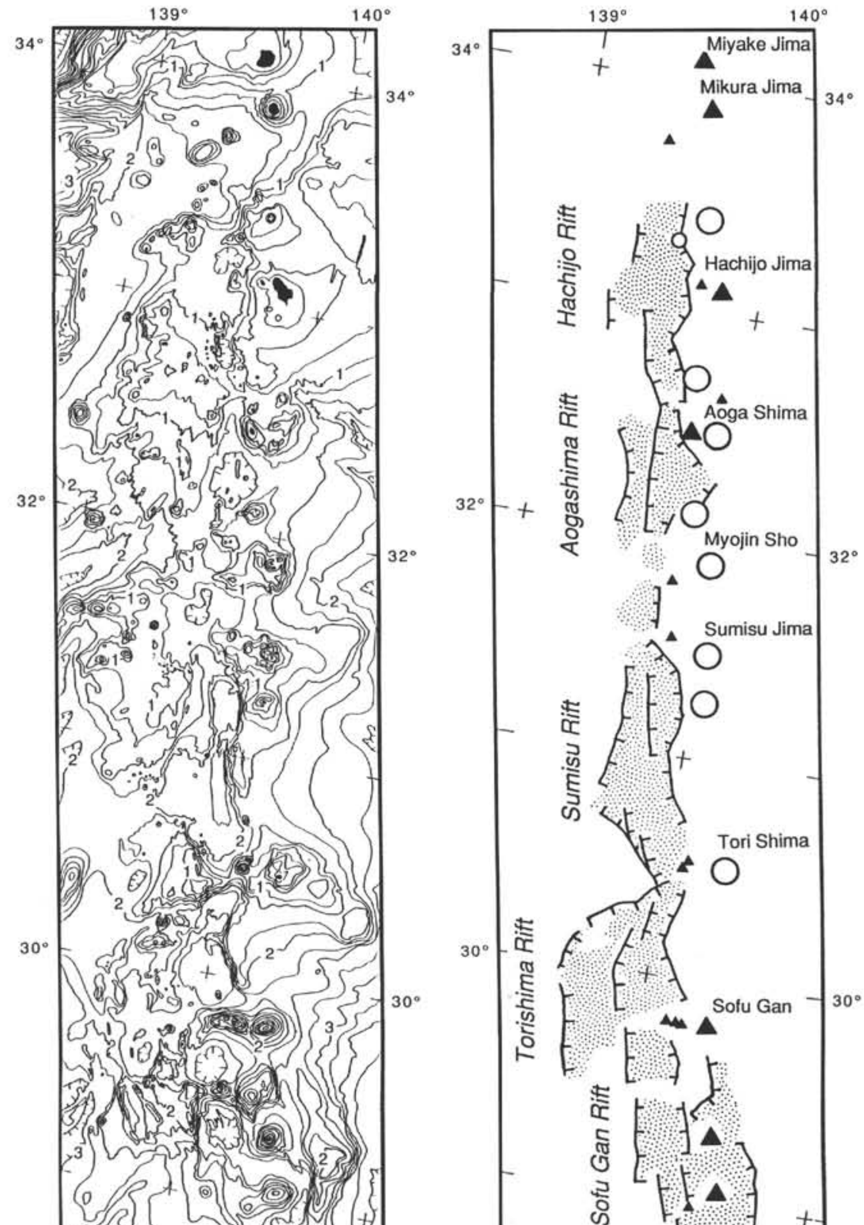

Figure 13. Bathymetry (left, at 250-m contour intervals, labeled every kilometer) and tectonic interpretation (right) of the Izu-Bonin Arc, 27° – 34° N. Solid triangles and open circles locate frontal arc volcanoes and calderas, respectively. Stippled areas locate rift basins and ticked lines mark major normal faults.

Nondrilling studies have shown that bimodal volcanism, normal faulting, rapid sedimentation, and hydrothermal circulation characterize the active rifting of the Izu-Bonin intraoceanic island arc, as outlined below.

Faulting

The rift basins are separated along strike by structural and volcanic highs and are bounded longitudinally by curvilinear border fault zones with both concave and convex dip slopes (Fig. 13). Some depressions are nearly equidimensional and only 20–30 km across; the least developed are sags with small-offset border faults. Sumisu Rift forms the longest (120 × 30–50 km), and Torishima Rift the widest (80 × 60 km), rift basin. The orientation of the zigzag pattern, in plan view, of the normal faults indicates that the extension direction is 080° ± 10°, orthogonal to the regional trend of the volcanic front. North of Sofu Gan, where the rifts do not surround arc volcanoes, normal faults divide the rifts into an inner rift on the arc side, which is the locus for maximum subsidence and sedimentation, and an outer rift further west (Figs. 13–17). The largest-throw (≥ 2 km) border faults alternate sides along the rift system, producing a varying structural asymmetry (Figs. 14–17). They formed during an initial half-graben stage. Antithetic faulting of their hanging wall rollovers, accompanied by basin widening through footwall collapse, produced the present, full graben stage. Near the seafloor, the faults are high angle, but in some locations the border faults are seen to become listric at depth, soling out on horizontal detachments only a few kilometers below the seafloor (Figs. 14 and 16). Uplift of the margin footwall blocks has accompanied rift basin subsidence. Flexural uplifts of the arc margin are a maximum where they are not suppressed by volcano loading, such as between South Sumisu and Torishima, and between Torishima and Sofu Gan (Figs. 13 and 15). Accommodation zones that link opposing border faults and rift flank uplifts further subdivide the rifts along strike. Volcano alignments and fault trends are arc-parallel within the accommodation zones (e.g., Fig. 17). The differential motion across these zones is accommodated by interdigitating arc-parallel normal faults rather than by oblique-slip faults. Presumably, such distributed strain can take up the oblique motion because the total offset is small. Total rift extension is estimated to be 2–5 km.

Rift Volcanism

Volcanism is often concentrated along the cross-rift transfer zones, rather than along the inner rift axes, and extends into both, but particularly the western, margins of the rifts. Volcanism is also concentrated on the highs between the rift basins; intrusions may be accommodating the extension there. A large (35 km diameter) shield volcano at 28.3° N fills the potential position of a rift basin (Fig. 13). Volcanism in the outer rifts has built 50–700 m high edifices, typically clustered along faults. A few multi-vent en echelon fissure ridges (the largest, just south of 33° N, is up to 600 m high and 25 km long) have formed in the inner rifts. The development of en echelon ridges is greater in other backarc rifts with more extension (southeast Manus > Okinawa > Sumisu). Continued extension in the Izu-Bonin rifts may concentrate volcanism in the inner rift, with eventual coalescing of the ridges into a backarc spreading system. The volcanism is dominantly basaltic, with K-Ar ages of 0.05–1.4 Ma. Taylor and Karner (1983) proposed that basalt compositions reflecting mantle sources little influenced by arc components can be present in the earliest stages of backarc opening. This was contrary to the then prevailing view that backarc basin basalts (BABB) evolve from island arc tholeiites (IAT) as the backarc spreading center moves away from its initial proximity to the arc (e.g., Tarney et al., 1981). The major and trace element geochemistry of the Sumisu and Torishima rift basalts is most similar to that of BABB found in other, more mature, backarc basins, consistent with the Taylor and Karner hypothesis (Fryer et al., 1990). Volatile concentrations (high H_2O/S, high δD, and low $\delta^{34}S$ ratios) distinguish Sumisu Rift and other BABB from IAT and MORB (Hochstaedter, Gill, Kusakabe, et al., 1990). $^{87}Sr/^{86}Sr$ and alkali and alkaline earth concentrations are higher in IAT > BABB > MORB. Rare earth element patterns and Pb and Nd isotopes indicate that the source of Sumisu Rift lavas is more enriched than that of the adjacent arc lavas (Hochstaedter, Gill, and Morris, 1990).

Hydrothermal Circulation

An elongate rhyolite dome and low temperature hydrothermal deposits occur at the en echelon step in the basaltic volcanic ridge located at the intersection of the 31° N transfer zone with the inner

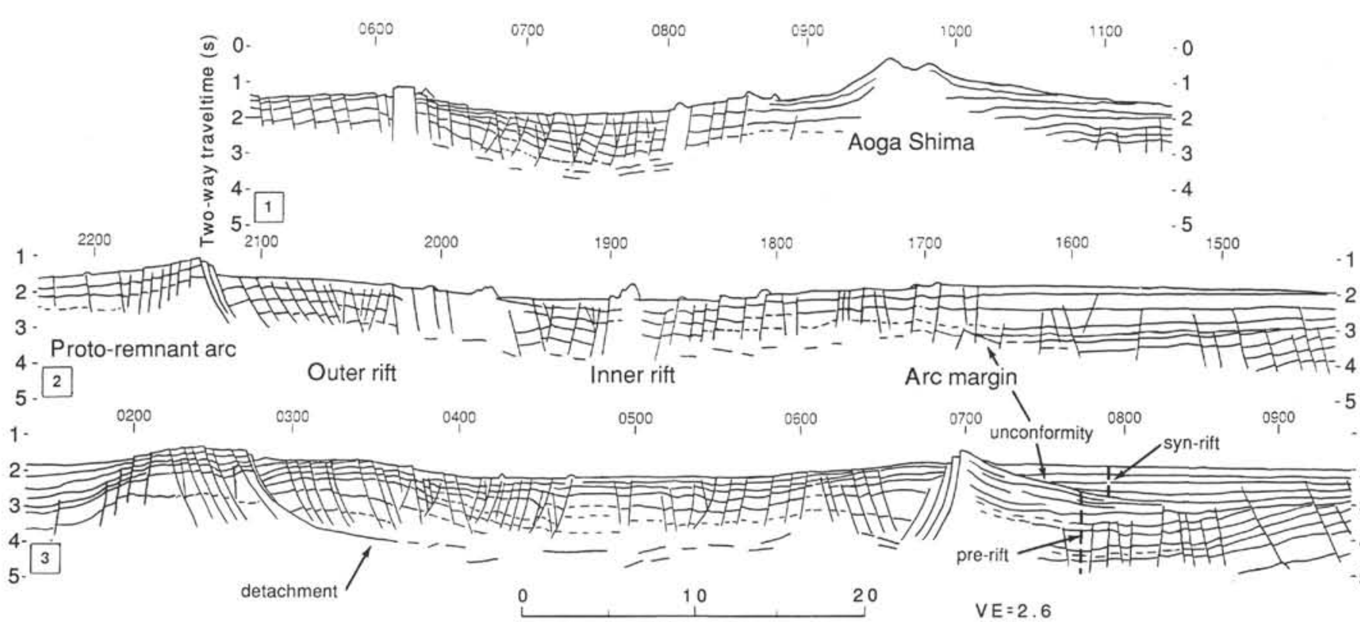

Figure 14. Line drawings of migrated MCS profiles across Aoga Shima Rift (see Fig. 2 for locations) after Klaus (1991). VE = vertical exaggeration.

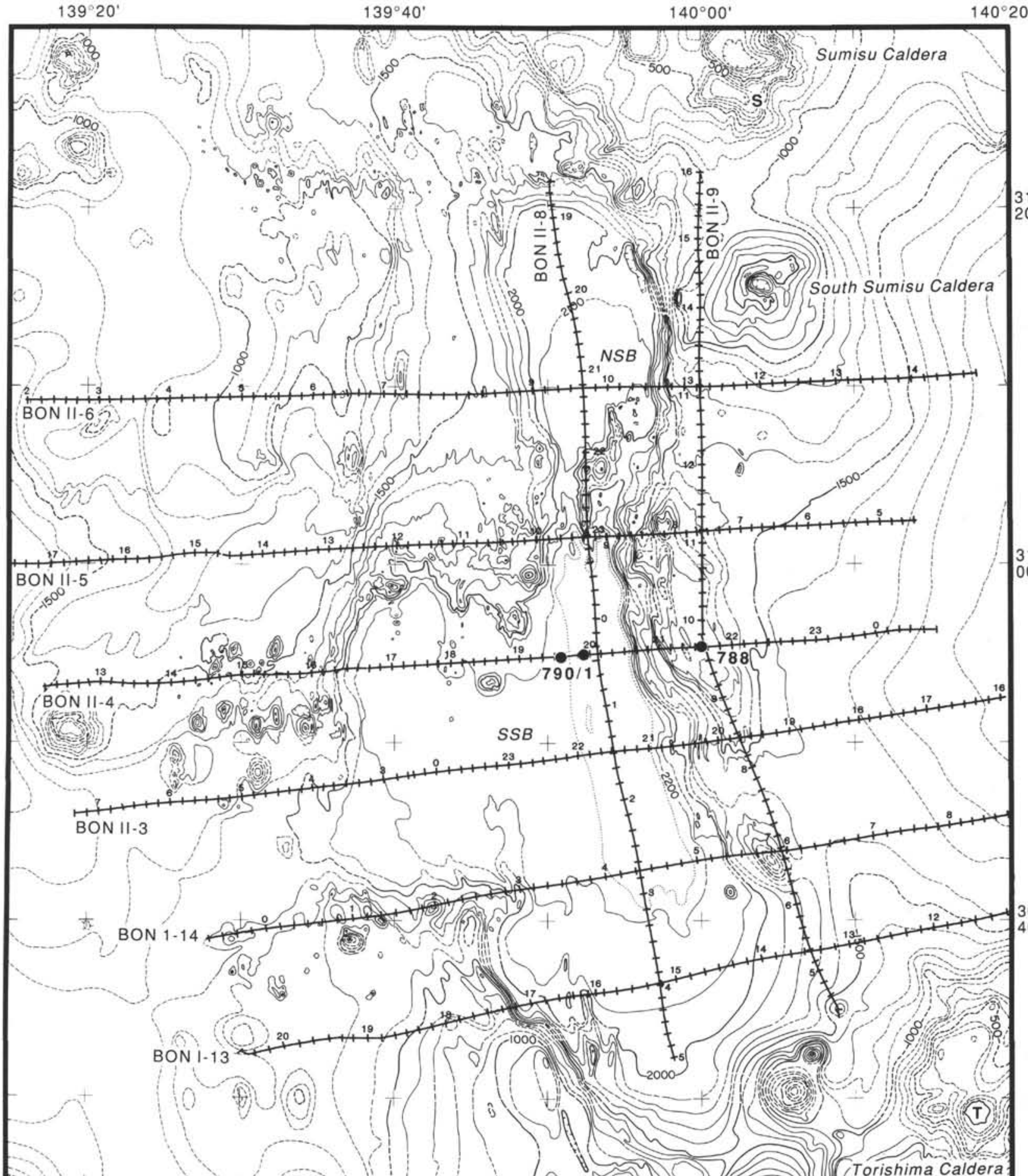

Figure 15. Bathymetry of Sumisu Rift, showing the location of *Fred Moore* 3505/07 MCS profiles (Fig. 16) and ODP Sites 788, 790, and 791. The contour interval is 100 m, except for the 2250-m contour, which is dotted. Ten-minute tick marks along the ship tracks are labeled every hour. S = Sumisu Jima and T = Torishima.

Sumisu Rift. The chimneys, veins, and crusts are composed of silica, barite, and iron oxide and are of similar composition to the ferruginous chert that mantles the Kuroko deposits (Urabe and Kusakabe, 1990). The association of barite-rich hydrothermal deposits on a fractured rhyolite dome in a basalt-dominated arc rift is a modern analog of the middle Miocene Hokuroku Basin in which the Kuroko sulfide deposits formed.

Heat flow measurements in the rift basins require hydrothermal circulation to explain the locally high, but widely variable, values that range from 12 to 700 mW/m^2 (Yamazaki, 1988; Nakao et al., 1989). Water-column bacterial biomass anomalies in the Sumisu inner rift at 31°08′N evidence active hydrothermal circulation (Mita et al., 1988). A 1.2-km transect of seven *Alvin* heat flow measurements at 30°48.5′N

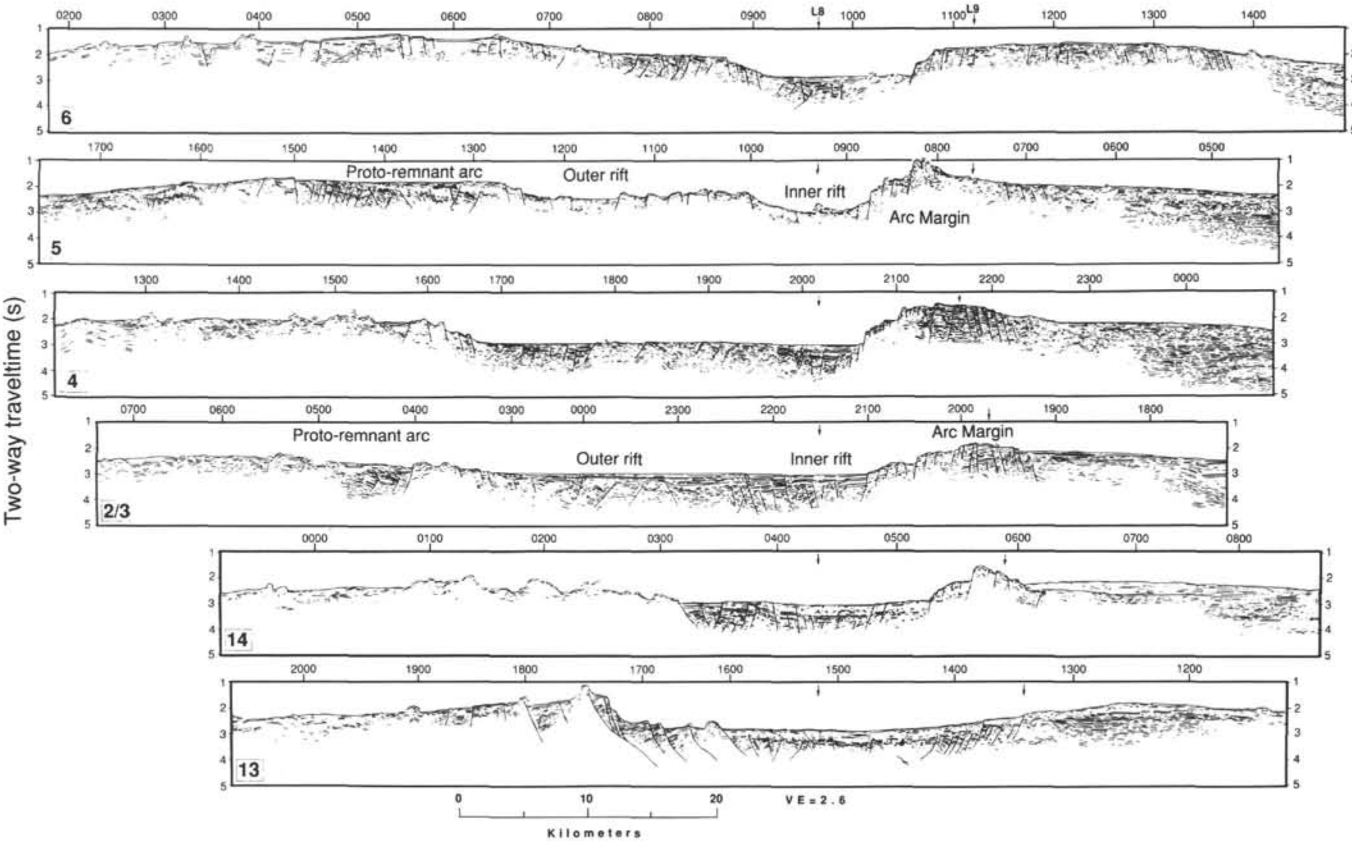

Figure 16. Line drawings of migrated MCS profiles across the Sumisu Rift (see Fig. 15 for locations) after Klaus et al. (this volume) and B. Taylor et al. (1991).

showed that the inner-rift-bounding faults may serve as water recharge zones, but that they are not necessarily areas of focused hydrothermal outflow, which instead may occur through the thick but permeable basin sediments (Taylor et al., 1990a).

Background to Sites 788 –791

The principal objectives of drilling into the floor and eastern flank of Sumisu Rift were to determine (1) the age of initial rifting and initial rift volcanism, (2) the nature of rift basement, (3) the differential uplift/subsidence history of the rift basin and adjacent arc margin, (4) the nature of volcanism and sedimentation in the rift and on the arc margin, and (5) the chemistry of fluids circulating in the rift basin (Taylor, Fujioka, et al., 1990). Figures 15–18 show the spatial relationships among the drill Sites 788, 790, and 791. Site 789 was abandoned after showing early signs of instability, before we learned that the advanced piston corer (APC) is the best drilling tool in pumiceous gravel.

Sites 788 and 792

Sedimentation and Vertical Motion

At Site 788 on the eastern Sumisu Rift flank, MCS profiles show a >1.5-km-thick stratified sequence uplifted above present depocenters and cut by active high-angle normal faults (Fig. 16; Taylor et al., 1990b; Klaus et al., this volume). Drilling to 374 mbsf recovered a Pliocene section of dominantly pumiceous and vitric gravel, sand, and silt, unconformably lain beneath 30 m of similar, but <0.275 Ma, material (Fig. 18; Taylor, Fujioka, et al., 1990). Benthic foraminifers from 4.0-Ma, finer grained material have been uplifted 1.1 ± 0.5 km (Kaiho, this volume).

I interpret the unconformity to record the flexural uplift of the rift flank (footwall) associated with isostatic rebound following removal of hanging wall material (unloading) during extension (Weissel and Karner, 1989). The date of this uplift should approximate the age of rift basin formation. Seismic stratigraphy indicates that the rift flank uplifts occurred rapidly and are approximately coeval with the oldest rift basin sediments (Figs. 14 and 16). The sediments immediately below the unconformity contain *Discoaster pentaradiatus*, which dates them as 2.35 Ma or older (Taylor, Fujioka, et al., 1990). Ages <2.9 Ma are consistent with the magnetobiostratigraphic dating and

Figure 17. Perspective block diagram of the Sumisu Rift, viewed from an elevation of 65°, looking 345°, and with a vertical exaggeration (VE) of 6 (after Klaus et al., this volume, and B. Taylor et al., 1991).

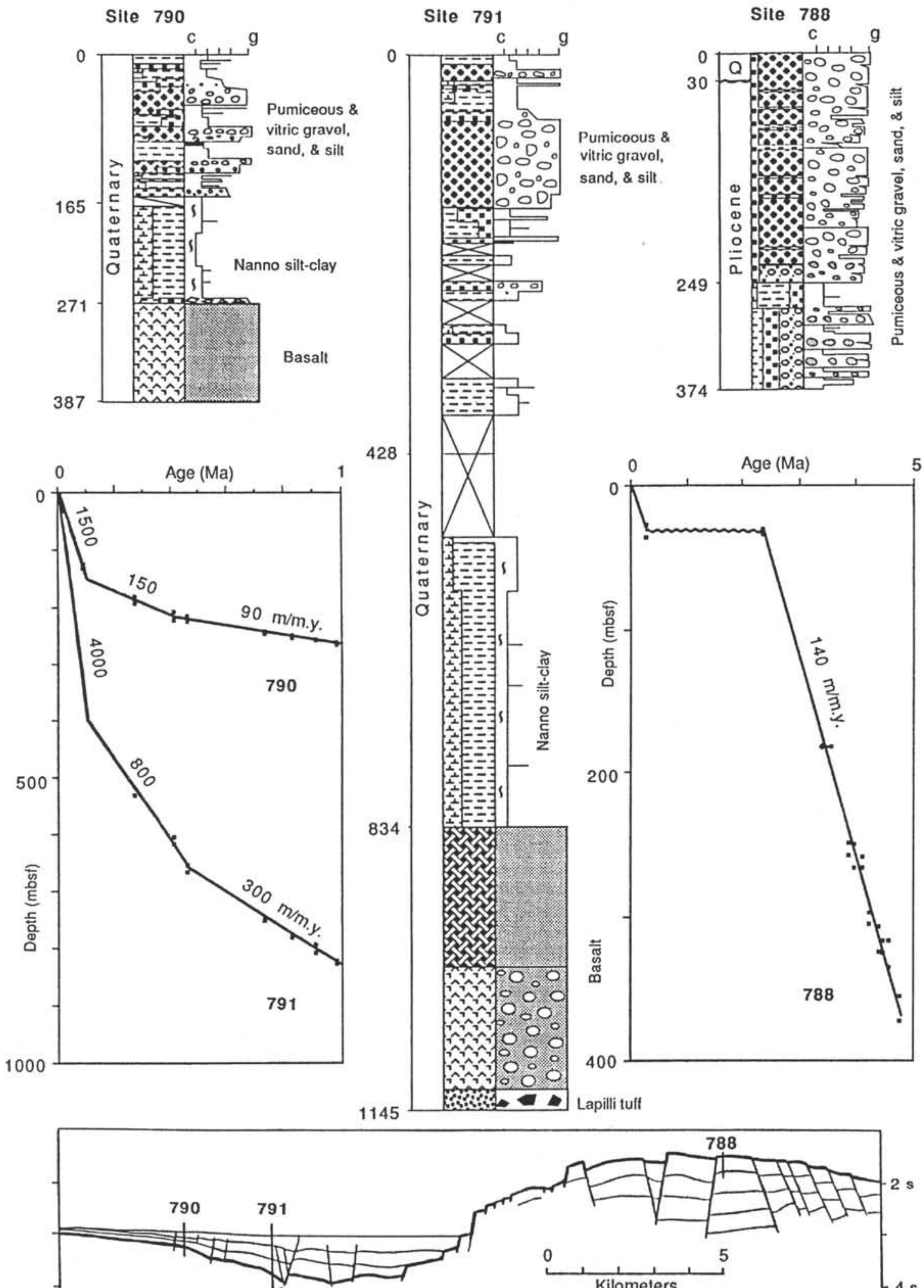

Figure 18. Lithostratigraphic summaries for Leg 126 Sumisu Rift Sites 788, 790, and 791. The depths (mbsf) of unit boundaries are shown on the left of each column, and a graphic sedimentological log displays the relative grain size on the right (from c = clay to g = gravel). Age-depth plots are shown in the center, with uncorrected sedimentation rates labeled in m/m.y. A simplified line drawing of MCS Profile 4 (Fig. 16) is shown with site locations at the bottom.

sediment accumulation rates of the older section at this site. The diagenesis of the sediments and the MCS data indicate that some late Pliocene section was removed by erosion (Marsaglia and Tazaki, this volume). Therefore, the 2.35–2.9 Ma age range is a maximum for the unconformity and rift flank uplift. Seismic correlation of drilled horizons at Site 792 to MCS Line 3 (Figs. 2 and 14), using a close grid of Geological Survey of Japan single-channel seismic profiles crossing the MCS lines, shows that the uplift of the arc margin of Aogashima Rift occurred about 1.9 Ma. The data are consistent with the near-synchronous initiation of rifting of the central Izu-Bonin arc, starting about 2 Ma.

Volcanism

The results from all Izu-Bonin sites, especially 788 and 792, show that Pliocene-Quaternary arc volcanism (i.e., immediately before and during backarc rifting) was dominantly silicic (subalkaline andesite-rhyolite) and at a Neogene maximum (Taylor, Fujioka, et al., 1990; Rodolfo et al., this volume; Fujioka et al., this volume). Even during this volcanic maximum, however, volcanic lulls lasting 300–400 Ka occurred between major Pliocene eruptions of rhyolitic pumice near 31°N.

Rare lithic clasts and glass shards similar in composition to the distinctive backarc rift magmas (enriched in Ta and light rare earth elements (LREE) relative to the known, LREE-depleted, frontal arc magmas) were found in the Site 788 section up to 1-m.y. pre-rifting, suggesting the presence of backarc magma types before rift extension (Gill, this volume; Hiscott and Gill, this volume). Volcanic ashes recovered at Site 792, however, show that both Ta- and LREE-enriched, and depleted, glasses were explosively erupted from shallow Izu-Bonin sources during the last 1 m.y. (Egeberg et al., this volume). Two andesitic sands from Sumisu Rift Sites 790 and 791 have flat REE patterns (Hiscott and Gill, this volume). It is uncertain whether the LREE-enriched glasses and andesitic sands represent eruptions of volcanoes along or behind the volcanic front. The former interpretation implies dual frontal arc magma source types; the latter, that the mantle sources are laterally zoned and that explosive eruptions occur behind the volcanic front (as occurs north of 34°N; Hamuro et al., 1983).

Sites 790 and 791

Volcanism

Like the Oligocene forearc rift basin at Site 793, the Sumisu inner rift basin at Sites 790 and 791 is floored with syn-rift volcanics (Fig. 18). Nannofossils from overlying and rare interlayered sediments constrain the age of volcanism to 1–1.6 Ma (Taylor, Fujioka, et al., 1990). With the possible exception of a pumpellyite-facies-metamorphosed tuff at the base of Site 791 (1119–1145 mbsf; Yuasa et al., this volume), no pre-rift arc volcaniclastics, such as those drilled at Site 788, were penetrated. The volcanics are scoriaceous basalt at Site 790, and basalt breccia, flows, "mousse," and diabase at Site 791, that are geochemically similar to the surficial BABB rift lavas (Taylor, Fujioka, et al., 1990). The oldest (>1.1 Ma) rift basalts have high water contents and were rapidly erupted in deep (~2 km) water, producing a 135-m-thick, mousse-textured, explosion breccia agglutinate (Gill et al., 1990; Gill, this volume). They are even more MORB-like in trace element and isotopic composition than modern Mariana Trough basalts, indicating that not only the present, but also the earliest, magmas erupted in the rift differ from the arc magmas. The rift lavas may reflect decompression melting of the shallow mantle, above the deeper mantle source of the arc diapirs. The high water contents of the shallow mantle are subduction related, but the shallow mantle has not inherited all the slab-derived geochemical signatures, such as Ba-enrichment, of the arc diapirs that pass through it.

Sedimentation and Vertical Motion

Though only 2.4 km apart, there is a factor of 3 difference in the sediment thicknesses and sedimentation rates at Sites 790 and 791 in essentially time-equivalent sections (0–1.0 and 1.1 Ma, respectively; Fig. 18). The rapid sedimentation has maintained a flat basin floor in the inner rift; however, MCS profiles show that fault offsets and reflector dips increase with depth, indicating differential subsidence associated with syndepositional faulting (Taylor et al., 1990b). The bedding is subhorizontal at Site 790, but at Site 791 the dip gradually increases to 15°–20° near 600 mbsf and 45° by 800 mbsf (Taylor, Fujioka, et al., 1990). I infer that the west-dipping normal fault just east of Site 791 is listric.

Benthic foraminifers indicate similar paleowater depths to the present (~2250 mbsl) at both sites since 0.7 Ma (Kaiho, this volume), with a maximum possible range of 1300–2600 mbsl (Kaiho and Nishimura, this volume). Kaiho (this volume) records the presence of a different faunal assemblage, associated with an open-ocean rather than ocean-margin water mass, before 0.7 Ma at Sites 790, 791, and 792. Based on the Holocene data of Kaiho and Nishimura (this volume), he suggests a >2300 mbsl paleowater depth at Sites 790 and 791 before 0.7 Ma, but the data from Site 792 show that, in the open-ocean water mass, this assemblage could occur as shallow as 1800 mbsl. I infer that the inner rift water depths were about the same over the last 1.1 m.y. (1800–2600 mbsl) as at present. Given the 1.1-km syn-rift section drilled at Site 791, and recalling that Site 788 has been uplifted 1.1 ± 0.5 km, the 2–2.5 km throw on the eastern border fault zone may be apportioned approximately equally between subsidence of the inner rift basement and uplift of the rift flank.

Nannofossil-rich clay, silty clay, and clayey silt, with thin ash beds and scattered pumice and scoria clasts, accumulated in the inner rift basin at Sites 790 and 791 from 1.1 to 0.15 Ma (Taylor, Fujioka, et al., 1990). This fine-grained sediment records another lull in nearby arc volcanism. It shows that models of backarc rift basin sedimentation that predict initial coarse volcaniclastic fill may be locally errant, depending on the amount of proximal volcanism.

More than half the rift sediments were deposited during the last 150 k.y., following a dramatic increase in volcanic activity. Four cycles of explosive, rhyolitic volcanism deposited thick sequences of coarse pumiceous tephra and sand- to silt-sized ash (Nishimura et al., 1991, this volume). The three submarine calderas (Sumisu, South Sumisu, and Tori Shima) on the eastern margin of the rift (Fig. 15) are likely source areas of the rhyolitic pumice. Intervening quiescent intervals, each lasting about 30 k.y., are represented by thin beds of clay-nannofossil hemipelagites with minor ash intercalations. A large proportion of the pyroclastic and pelagic materials were (re)deposited in the rift basin by submarine mass flows. Sedimentation rates increased exponentially from 90 and 300 m/m.y at 1 Ma to 1500 and 4000 m/m.y. since 100 ka at Sites 790 and 791, respectively (Fig. 18).

Hydrothermal Circulation

Two measurements of heat flow, 500 m apart and surrounding Site 791, recorded 13 and 27 mW/m^2 (T. Yamazaki, unpubl. site survey data). Another measurement, 1 km west of Site 791 (1.4 km east of Site 790), recorded 397 mW/m^2. These and other widely varying heat flow values in Sumisu Rift indicate that hydrothermal circulation is occurring through the thick basin sediments (Yamazaki, 1988). The pore-fluid geochemistry at Sites 790 and 791, however, showed no indication of fluids other than seawater. I infer that hydrothermal upflow zones are narrowly focused and that seawater drawdown was probably occurring at the two sites drilled.

DISCUSSION

Locus and Duration of Rifting

The Izu-Bonin volcanic front has thicker crust and higher heat flow than the forearc or backarc (Hotta, 1970; Honza and Tamaki, 1985; Japanese DELP Research Group on Back-arc Basins, 1989; Katao et al., 1990). Total crustal thickness varies between 10 and 15 km in the forearc (east to the outer arc high and north of 28° N), but may reach 20 km beneath the arc. Thicker crust (which is rheologically weak compared to the mantle) and higher heat flow have been shown to weaken the lithosphere (Vink et al., 1984; Steckler and ten Brink, 1986; Kuznir and Park, 1987). I therefore infer that the frontal arc volcanoes create a linear zone of lithospheric weakness that controls the location of rifting (B. Taylor et al., 1991; Klaus et al., this volume). The large relict Oligocene rift structures do not control the Quaternary rift structures, which subparallel the active arc and cross-cut the former (Fig. 13). Given that crustal thickness and heat flow control lithospheric strength, rifting might occur on either side of the volcanic front, but may more often occur on the backarc side where there is additional (cross-chain) arc volcanism. This is the pattern observed in the IBM and other volcanic arcs (Taylor and Karner, 1983). The Mariana Trough and Lau Basin appear to be examples of forearc spreading; the Miocene arcs form the remnant arcs (West Mariana and Lau ridges, respectively) and the modern Mariana and Tofua arcs are built near the juncture of backarc basin and rifted arc crust (Taylor and Karner, 1983; Bloomer et al., 1989). The majority of the Izu-Bonin rifts are backarc, but at 29° N the rifts surround an arc volcano (Fig. 13).

The above arguments would suggest that rifting should initiate adjacent to individual arc volcanoes, but just the opposite is observed (Fig. 13). The rifts generally are wider and more subsided between, rather than adjacent to, the arc volcanoes. This may result from arc magmatism accommodating some of the extension, intrusions rather than faulting taking up the strain adjacent to the arc volcanoes (Klaus et al., this volume; B. Taylor et al., 1991). The large submarine shield volcano at 28.3° N may have suppressed or overprinted rift basin development between the Sofu Gan and Nishinoshima rifts (Fig. 13).

Evidence from the Mariana region indicates that arc rifting (from initiation to spreading) requires only a few million years at any one place, but that rift propagation along the arc system may take more than 6 m.y. (Hussong and Uyeda, 1981; Stern et al., 1984). The initial Izu-Bonin rifting lagged behind central Mariana rifting by ~6 m.y. If the Izu-Bonin rifting progresses to spreading, the two systems will meet near 24° N, at approximately the same position along the IBM arc, and with the same time lag from initial to through-going spreading, as the Parece Vela and Shikoku basin systems (Fig. 1). The causes of the time lag between Mariana and Izu-Bonin backarc spreading and of the "strong" arc segment near 24° N are speculative. The relative subduction rates (Mariana faster than Izu-Bonin) as well as the curvature of the IBM arc at 18° N (convex east) and 24° N (concave east) have reversed sense between the Oligocene and Quaternary, and so cannot be critical factors. Mesozoic lithosphere with similar thermal and density properties is being subducted all along the IBM arc. The present subduction of the Ogasawara Plateau near 26° N does not explain the repetition of the constriction in the Miocene as well as the Quaternary. The arcs and basins of the Amami Plateau-Oki Daito province differ from the deep oceanic crust of the West Philippine Basin, but it is not clear how this would affect Quaternary tectonics (Fig. 1). Present tectonic differences at the ends of both systems (a transform boundary and subduction of the Caroline Ridge in the south, vs. subduction of the Izu-Bonin Arc beneath Japan in the north) may have had Miocene counterparts (interaction with the Caroline Plate in the south, vs. a transform boundary in the north; Hibbard and Karig, 1990) and may be the most significant influence on the proclivity for the arc to rift. Certainly the active Izu-Bonin rifts end along strike to the northeast from the "South of Zenisu" Ridge, the seaward limit of present collisional deformation (Lallemant et al., 1989; Fig. 10). To the south, the Quaternary rifts terminate in the inferred region of greatest Oligocene arc stretching. Thinner crust may cause the extra strength of the lithosphere there.

Unlike the active arc, the Oligocene Izu-Bonin Arc experienced widespread and protracted rifting, from the outer arc high to the now remnant arc, and from the early to late Oligocene. I hypothesize that the different style of rifting was related to the different development of the arc basement. Voluminous Neogene volcanism was focused along the modern volcanic front and developed a thick, localized crustal root along which the active rifts nucleated. The Eocene volcanism, in contrast, was distributed over a broad region and formed a >300-km-wide arc massif. Although Oligocene volcanism became concentrated along the (now) frontal arc high, it may not have had time to develop a thick, localized crustal root before rifting began. Consequently, the entire arc massif was stretched (Basin and Range style) before spreading finally propagated through the western side. The southern Izu-Bonin Arc (forearc and backarc) may have been extended more than the north because of a longer rift phase as spreading propagated from north to south.

Syn-rift Faulting, Volcanism, and Sedimentation

A zigzag pattern of half-graben-bounding normal faults characterizes both the Oligocene and Quaternary rifts. Except for the greater extent of the Oligocene structures, their patterns appear similar. Many of the border faults and rift flank uplifts develop early in the rift history. Syn-rift sediments are pervasively faulted and often intruded. Both the Sumisu Rift at Sites 790 and 791 and the forearc rift basin at Site 793 are floored with syn-rift volcanics. Both volcanic suites are geochemically distinct from their contemporary frontal arc volcanics. The Oligocene forearc volcanics are similar to the Eocene volcanics of the outer arc high, but not to the Neogene forearc sill. Coarse volcanogenic sediments, derived from contemporaneous frontal arc volcanism, dominate both the Sumisu Rift and the Oligocene forearc basin fill. They were rapidly (>250 m/m.y.) deposited by turbidity currents and debris flows onto rift-floor sediment plains. Sedimentation patterns were directly influenced by the productivity of the proximal arc volcanoes, with volcanic lulls recorded by hemipelagic interbeds.

Arc Volcanism and Rifting-Spreading

The temporal relationship between arc volcanism, rifting, and backarc spreading is an important but controversial feature of many models of arc development. Karig (1975 and 1983) proposed that periods of backarc spreading and intense arc volcanism are nearly synchronous. The participants in Leg 59 concluded that backarc spreading in the Parece Vela Basin and Mariana Trough initiated during relative minima in the intensity of Mariana arc volcanism (Kroenke, Scott, et al.,1980). Hussong and Uyeda's (1981) synthesis of Leg 60 drilling results postulated that Mariana arc volcanism has probably been continuous since the Eocene, but that syn-rift subsidence of arc volcanoes limited explosive eruptions and lateral transport of volcanic material.

The evidence from the Oligocene and early Miocene IBM arc, discussed previously, is consistent with a syn-rift volcanic maximum followed by a short period of quiescence during early backarc spreading, both periods occurring earlier in the Mariana Arc than the Izu-Bonin Arc. The early Miocene volcanic quiescence observed at Site 792, drilled on an Oligocene frontal arc volcano, is not consistent with Hussong and Uyeda's (1981) rift subsidence explanation for reduced volcanism. Rather, it appears that the Izu-Bonin Oligocene frontal arc volcanoes were replaced by Neogene volcanoes built along a new front (Fig. 10), and that the short period of quiescence corresponds to the time of initial construction of the new arc.

The volcanic history in the late Miocene, before central Mariana Trough backarc spreading, was somewhat different. A volcanic minimum occurred in central Mariana arc volcanism between 9 and 5 Ma, followed by a Pliocene-Quaternary maximum (Kroenke, Scott, et al., 1980; Hussong and Uyeda, 1981). From the lack of primary volcanic material in the insoluble components of the Alifan Limestone on Guam (~11 Ma; Hathaway and Carroll, 1964; Ingle, 1975) and the decrease in the depositional rate of volcanic material at Sites 53 and 450 between 13 and 9 Ma, Karig (1983) argued that West Mariana Arc volcanism began to wane as early as 13 Ma. Thus, the rifting, and initial spreading (6 Ma), in the central Mariana Trough was accompanied by less intense arc volcanism. The new volcanoes formed very quickly, however, so that the majority of the spreading history, and the rifting in the northern Mariana arc, coincided with a regional volcanic maximum. Nevertheless, volcanoes have yet to build above sea level in the region of active Mariana arc rifting, between 22° and 24° N (Bloomer et al., 1989). Drilling results from Legs 125 and 126 show that the Quaternary rifting of the central Izu-Bonin Arc was preceded and is accompanied by voluminous silicic arc volcanism.

There does not appear to be a universal temporal relationship between arc volcanism, rifting, and backarc spreading. Volcanism is vigorous along the Izu-Bonin and New Hebrides arcs during the present backarc rifting, as it was during Oligocene rifting of the IBM arc. Note, however, that the Izu-Bonin arc maximum (>27 Ma) overlapped the Mariana arc minimum (27–29 Ma) as a result of the different time of rifting along strike. Furthermore, when central Mariana Trough rifting began in the late Miocene, Mariana arc volcanism was at a minimum. Likewise, the southern Ryukyu Arc is in a quiescent phase during the current rifting in the Okinawa Trough, though along strike to the north where the trough is less extended, arc volcanism is more active (Sibuet et al., 1987).

It is possible that many arc segments go through a cycle of (1) frequent volcanism before and during rifting; (2) reduced and/or less disseminated volcanism during latest rifting and early backarc spreading, as new frontal arc volcanoes are being constructed and growing to sea level; and (3) increasingly vigorous volcanism during middle and late-stage backarc spreading, and until the next rift cycle begins. This is not a universal relationship, however, as it does not match the late Miocene central Mariana volcanic minimum. Also, because initial rifting and spreading are spatially diachronous (rifts propagate), at any one time adjacent arc segments may be in different stages of this cycle, so that a local volcanic minimum may be overprinted by volcanism from along strike. Lastly, drilling results from Site 788 indicate that, even within periods of intense volcanism, 100-km-long arc segments may be quiescent for periods of up to 400 k.y.

CONCLUSIONS

Middle and late Eocene boninites, island-arc tholeiites, their differentiates, and their plutonic roots formed an enormous province (>300 × 3000 km) of contemporaneous IBM supra-subduction zone magmatism, unlike any active system today but similar to many ophiolites. Some sedimentary and igneous material from the subducting plate was accreted into the Mariana Arc (Johnson et al., 1991), but little tectonic accretion or erosion of the IBM forearc has occurred since the middle Oligocene.

Intense tholeiitic and calc-alkaline volcanism occurred along an Oligocene arc (the present frontal arc high and remnant arc) until 29 Ma (Mariana) and 27 Ma (Izu-Bonin). Widespread and protracted Oligocene rifting stretched the Eocene-Oligocene arc massif, creating tilted fault blocks and rift basins between the now remnant arc and outer arc high. The greatest stretching occurred near 28° N. Syn-rift, dominantly high-Mg, low-Ti, two-pyroxene, basaltic andesites and andesites floor the forearc basin at Site 793. The basin filled rapidly with Oligocene debris-flow deposits and turbidites produced by concurrent volcanism and erosion of the surrounding highs.

Minima in arc volcanism occurred 29–27 Ma in the Marianas and 23–20 Ma in the Izu-Bonins, during early phases of backarc spreading in the Parece Vela and Shikoku basins, respectively. Western Shikoku Basin oceanic crust previously identified as formed during Subchrons 6C (25 Ma) to 6A may instead have formed during Subchrons 6A (22 Ma) to 5D, with a spreading jump over the eastern 5D and 5E magnetic anomalies leaving only the 6A anomalies east of the axial 5B-5C anomalies.

Middle Miocene to Holocene Izu-Bonin frontal arc volcanism is bimodal (basalt-andesite and rhyo-dacite) and mostly low-K and subalkaline; it has increased in intensity to a Pliocene-Quaternary maximum. Neogene magmatism along the Izu-Bonin volcanic front has been focused on bimodally spaced (27 and 47 km), long-lived centers, oriented in a line 3° counterclockwise from the Oligocene frontal arc.

Neogene arc tholeiites have occasionally intruded the thermally cool forearc. Cross-chains of mostly submarine volcanoes occur in the backarc both immediately west of the frontal arc volcanoes and further west, on the edge of the rifted Oligocene arc crust.

The upper forearc north of 32.4° and the Bonin Ridge (outer arc high south of 30°) were both uplifted in the Neogene, the basement at Site 792 by 1 km. This, together with the greater Oligocene arc stretching in the south than in the north, produced three geomorphological provinces along strike in the Izu-Bonin forearc, with contrasting Neogene sedimentation and drainage patterns. Pervasive channel cut-and-fill and large submarine canyon/valley systems characterize the central, drilled province.

The present rifting of the central Izu-Bonin Arc began about 2 Ma. At 30° 55′ N, in the Sumisu Rift,

1. the 2-2.5 km throw on the eastern border fault zone is associated with 1.1 ± 0.4 km of subsidence of the inner rift basement and 1.1 ± 0.5 km of uplift of the rift flank;
2. the oldest (>1.1 Ma) to the youngest rift lavas are BABB, unlike the adjacent arc magmas which rise diapirically through the shallower mantle source of the BABB;
3. hydrothermal upflow is narrowly focused (<1 km) between Sites 790 and 791; and
4. rhyolite pumice dominates the pre- and syn-rift sedimentation, which includes pyroclastic and pelagic materials (re)deposited in the rift basin by submarine mass flows.

A zigzag pattern of half-graben-bounding normal faults, little influenced by pre-existing structures, characterizes both the Oligocene and Quaternary rifts. Oligocene rifting of the >300-km-wide Eocene arc massif was widespread and protracted (basin and range style) in contrast to the narrow rift mode of the Quaternary rifting of the active arc.

The frontal arc volcanoes, because of their thicker crust and higher heat flow, create a linear zone of lithospheric weakness that controls the location of arc rifting. Differences in plate boundary forces at the ends, more than in the middle, of volcanic arcs may significantly influence their proclivity to rift.

I suggest that many, but not all, arc segments go through a cycle of (1) frequent volcanism before and during rifting; (2) reduced and/or less disseminated volcanism during latest rifting and early backarc spreading, as new frontal arc volcanoes are being constructed and growing to sea level; and (3) increasingly vigorous volcanism during middle and late stage backarc spreading, and until the next rift cycle begins. Even within periods of intense volcanism, 100-km-long arc segments may be quiescent for periods of up to 400 k.y.

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