44. GEOLOGICAL SUMMARY OF THE NORTH PHILIPPINE SEA, BASED ON DEEP SEA DRILLING PROJECT LEG 58 RESULTS

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INTRODUCTION

The North Philippine Sea is characterized by both topographic and tectonic complexities formed by the convergence of the Pacific and the Eurasian plates. This region contains an active trench and island arc (Bonin Trench, Bonin Islands), remnant arcs (Kyushu-Palau Ridge, Daito Ridge, Oki-Daito Ridge), and inactive back-arc and inter-arc basins (Shikoku Basin, Daito Basin, northwest Philippine Sea). The geological history of the area is also complex because of changing patterns of subduction (Hilde et al., 1977; Kobayashi and Isezaki, 1976; Kobayashi and Nakada, 1977, 1978; Watts and Weissel, 1975; Tomoda et al., 1975; Shiki et al., 1975; Mizuno et al., 1975, 1979).

Leg 58 of the Deep Sea Drilling Project concentrated on two areas of this complex region, the Shikoku Basin and the Daito Ridge and Basin province (Figure 1). Each is discussed in separate sections below.

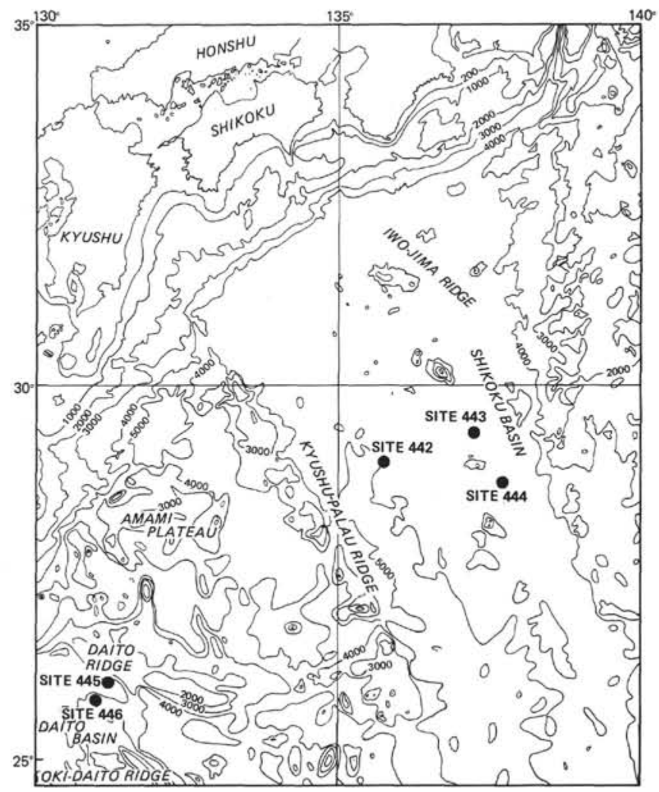

Figure 1. *General bathymetry, geographic features, and DSDP Leg 58 sites, north Philippine Sea.*

SHIKOKU BASIN

The Shikoku Basin is an inactive back-arc (or marginal) basin characterized by high heat flow (Karig, 1970, 1971; Watanabe et al., 1977) and a history of rifting by a sea-floor spreading process (Hilde et al., 1977; Kobayashi and Isezaki, 1976; Kobayashi and Nakada, 1977, 1978; Tomoda et al., 1975; Watts and Weissel, 1975; Karig, 1975; Shih, this volume.) The main evidence for rifting by sea-floor spreading comes from analysis of linear magnetic-anomaly patterns. The rifting is considered to be either symmetrical (Tomoda et al., 1975; Kobayashi and Isezaki, 1976; Kobayashi and Nakada, 1977, 1978; Watts and Weissel, 1975), asymmetrical (Shih, this volume), or single-limb (Watts and Weissel, 1975).

The objectives of the Leg 58 drilling in the Shikoku Basin included:

1. Drilling to acoustic basement to determine the age of the oldest sediment to calibrate magnetic-anomaly ages and to determine which of the three spreading models characterizes the basin. (These findings are discussed in this paper.)
2. Examination of the mineralogy and petrology of the basaltic basement to permit a comparison of compositions of these back-arc-basin basalts with those of mid-ocean-ridge and island-arc basalts. (These findings are discussed in papers by Dick et al., this volume, and Wood et al., this volume.)
3. Determination of the sedimentary history of the basin and correlation of changes in sediment type with basin evolution. (This effort is reviewed in the sedimentological synthesis by White et al., this volume.)
4. Determination of the paleocirculation of the basin. (This effort is also reviewed by White et al., this volume.)

Topography

The Shikoku Basin is an elongate, fan-shaped back-arc basin oriented approximately north-northwest to south-southeast. The topography (Figure 2) of the basin is highly irregular, consisting of small-scale linear ridges and troughs and a series of seamounts, primarily in the eastern half. Seismic study of the basin reveals that the acoustic-basement topography is also rough (Karig, Ingle, et al., 1975; Murauchi and Asanuma, 1974, 1977; Kobayashi, this volume). Some of this rough topography has been covered with sediment, indicating an early history of infilling of topographic lows and subsequent basin-wide deposition of regional clastic wedges

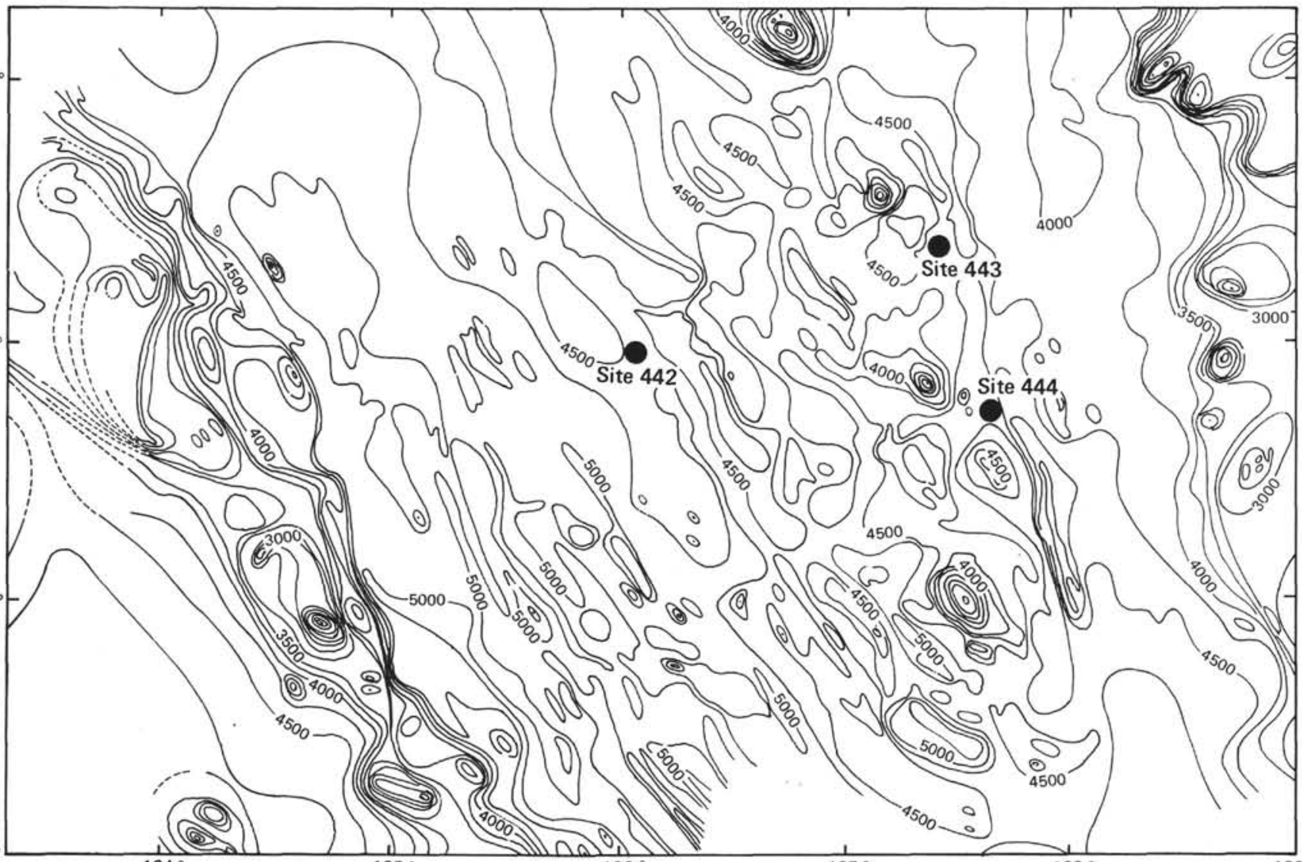

Figure 2. *Bathymetry of Shikoku Basin (from Kobayashi and Nakada, 1978). Contours in meters.*

(White et al., this volume). Basement topographic variations are masked by three clastic wedges, two of which merge in the western side of the basin, giving it a smooth appearance. The eastern part of the basin is characterized by an extremely rough, horst-and-graben type of topography, cut by a series of fracture zones.

The irregular topography owes its origin to a tensional, basin-and-range style of normal faulting, presumably associated with back-arc spreading. Seismic profiles (Murauchi and Asanuma, 1974, 1977; Karig, 1975; Karig, Ingle, et al., 1975; Kobayashi, this volume) indicate that the ridge-and-basin elements of the topography are offset and bounded by normal faults.

The irregular topography is independent of mapped magnetic-anomaly alignments (Tomoda et al., 1975; Watts and Weissel, 1975; Kobayashi and Isezaki, 1976; Kobayashi and Nakada, 1977, 1978; Shih, this volume). The rough topography has made correlation and identification of magnetic anomalies difficult in the Shikoku Basin (See also Lawver and Hawkins, 1978). The widespread sills in the basin indicate that the Shikoku Basin experienced off-ridge volcanism which characterized both the late stages of basin spreading and the post-spreading phase of its development (Dick et al., this volume; Klein et al., 1978). Such off-ridge volcanism contributed also to the irregular topography of the basin, particularly on its eastern side, and accounts in part for the difficulty in identification of magnetic anomalies encountered by past workers (See also Lawver and Hawkins, 1978).

Petrology and Stratigraphy of Volcanic and Intrusive Igneous Rocks

Igneous rocks recovered from the Shikoku Basin by drilling are basalts, which occur both as extrusive pillow-lava flows (assumed to have been emplaced during formation of the basin floor by sea-floor spreading) and intrusive sills (intruded very late in the formation of the basin, as well as after spreading ceased and emplaced during off-ridge volcanism). Sixty-four per cent of the basalts are aphyric, 20 per cent are plagioclase phyric, and 15 per cent are plagioclase and olivine phyric. Olivine occurs as phenocrysts, microphenocrysts, or groundmass. Some of the olivine has been replaced by calcite. Textures range from glassy to intersertal to intergranular and diabasic. Crystal forms and growth habits are similar to those reported from ocean-ridge basalts. The basalts show chemical affinities with mid-ocean-ridge basalts, although some island-arc-type basalts are present (Wood et al., this volume; Marsh et al., this volume).

Basalts from Site 442 are all phyric and extremely vesicular (Dick, this volume). Calcite has replaced olivine. Spinel, enclosed by pyroxene, is a common accessory mineral. The high vesicularity owes its origin to the abnormally hydrous nature of the basaltic magma source of the Shikoku Basin basalts (Dick, this volume).

All three Shikoku Basin sites contain massive basalt cooling units underlying sediment, and at two sites sediment interbeds were found within the basalt sequence. On the basis of subtle changes in lithology and the location of chill zones in the sequence, 38 cooling units can be identified at the three drill sites. The units range from 24 meters to less than 1 meter in thickness, averaging 5.8 meters. At Site 442, 69 meters of massive basalt (16 subunits) are underlain by 102 meters of pillow basalt with two interbeds of massive basalt. These cooling units are petrographically typical of mid-ocean-ridge pillow basalts.

The pillow basalts are interpreted as having been extruded during active basin spreading, whereas the massive units are interpreted as either sub-sediment flows or intrusive sills emplaced by post-spreading, off-ridge volcanism (Dick et al., this volume; Klein et al., 1978).

Evidence bearing on the timing and duration of volcanism in the Shikoku Basin is provided by the stratigraphy at the various sites, and by K–Ar age determinations of the youngest pillow lava at Site 443 (Tables 1 and 2) and the sill intruding the sediment section at Site 444 (McKee and Klock, this volume). At Site 442, sediment overlying massive basalt is approximately 15 to 17 m.y. old, whereas that below the massive basalt and above the youngest pillow lava is 18 to 21 m.y. old. At Site 443, the youngest pillow basalt is 17.2 ± 3.2 m.y. old (Tables 1 and 2), and at Site 444, the sill intruding sediment is 14.7 ± 2.1 m.y. old (McKee and Klock, this volume). Thus, the massive basalt intrusives represent post-spreading, off-ridge volcanism that occurred during the latest stage of ocean floor spreading and post-spreading igneous activity.

Stratigraphy and Age Relations

Sediments recovered from the Shikoku Basin consist of a succession of turbidites and hemipelagic clays at Site 297 (Karig, Ingle, et al., 1975), and hemipelagic clays from the distal portions of clastic wedges at Sites 442, 443, and 444. These hemipelagic clays appear to have been derived from the Japanese Islands, the Kyushu–Palau Ridge, the Iwo Jima Ridge and the Asiatic mainland (Chamley, this volume).

TABLE 1
Magnetic Anomaly, Paleontological, and K–Ar Ages for Oldest Sediments and Basaltic Basement at Shikoku Basin Sites[a]

Site	Magnetic Anomaly	Magnetic Anomaly Age[a] (m.y.)	Paleontological Age of Oldest Sediment (m.y.)	K–Ar Age (m.y.)	Remarks
442	6[b,c]	19–20.5	19–21	–	–
443	6A[b] 5D–5C[c]	20.5–21.0 16.0–17.0	14–15	17.2±3.2	K–Ar age on uppermost pillow basalt[d]
444	6A[b] 5D[c]	20.5–21.0 17.0–17.5	14–15	14.7±2.1	K–Ar age on sill intruding sediments[e]

[a]Magnetic time scale after LaBreque et al. (1977).
[b]Magnetic-anomaly identification from Tomoda et al. (1975), Kobayashi and Isezaki (1976), Kobayashi and Nakada (1977, 1978), and Watts and Weissel (1975).
[c]Magnetic-anomaly identification from Shih (this volume).
[d]K–Ar age from 443-57-2, uppermost pillow basalt (E. H. McKee, pers. comm.; Table 2).
[e]K–Ar age on sill intruding sediment at Site 444 (from McKee and Klock, this volume).

TABLE 2
K–Ar Age of Sample from 443-57-2[a]

Procedure: Whole rock basalt, crushed, sieved (60–100 mesh), and treated in HF and HNO_3 solutions. Argon analyzed by isotope dilution with Neir-type mass spectrometer. K analyzed by flame photometer, using Li as standard.

Decay Constants: $\lambda_e + \lambda_e^1 = 0.581 \times 10^{-10}\ \mathrm{yr}^{-1}$
$\lambda_\beta = 4.96 \times 10^{-10}\ \mathrm{yr}^{-1}$

Atomic Abundance of ^{40}K: 1.167×10^{-4} mole/mole.

Results: $K_2O = 0.254\%$.
$^{40}Ar = 6.3072 \times 10^{-12}$ mole/g.
Radiogenic $^{40}Ar = 6.5\%$.
Age = 17.2±3.2 m.y.

[a]Edwin H. McKee, pers. comm.

The stratigraphy of the sediments and associated basalts is summarized in Figure 3. The thick Pliocene sequence at Site 297 reflects deposition in the medial portion of the northern clastic wedge, identified from seismic profiles (Karig, 1975; Karig, Ingle, et al., 1975; White et al., this volume), whereas the thinner sections at Sites 442, 443, and 444 reflect distal deposition. During deposition, the sea floor at all these sites was near the calcite-compensation depth (White et al., this volume).

The ages of the oldest sediments drilled at each of the three sites during Leg 58 are shown in Table 1 and are compared to magnetic-anomaly ages, and the ages of the youngest extrusive basalt at Site 443 and the sill at Site 444. At Site 442, the sediment immediately overlying the massive upper basalt layer is 15 to 17 m.y. old (*Helicosphaera ampliaperta* Zone of nannofossils), but a sedimentary interbed between this massive basalt and the youngest pillow basalt is 18 to 21 m.y. old (*Discoaster drugii* Subzone of nannofossils). The age of the oldest sediment overlying massive basalts at Sites 443 and 444 is 14 to 15 m.y. (*Sphenolithus heteromorphus* Zone of nannofossils).

The oldest sediment age is in agreement with the magnetic-anomaly age at Site 442 (Table 1). At Sites 443 and 444, the oldest sediment age is clearly at variance with the magnetic-anomaly ages of Watts and Weissel (1975) and Kobayashi and Nakada (1977, 1978), but falls within the margin of error of the 17.2 ± 3.2 m.y. K–Ar age determination (E. H. McKee, pers. comm.; Table 2) for the youngest pillow basalt at Site 443. That K–Ar age determination is in agreement also with an independent magnetic-anomaly identification (5D; 17.0-17.5 m.y.) by Shih (this volume). The age of the intrusive sill at Site 444 is 14.7 ± 2.1 m.y., a finding consistent with organic-geochemistry measurements and age estimates of Waples and Sloan (this volume). Clearly, the discrepancies among the oldest sediment ages, K–Ar ages, and magnetic-anomaly ages at Site 443 and 444 need further analysis.

The cause for the discrepancy between the oldest sediment ages and the magnetic-anomaly ages at Sites

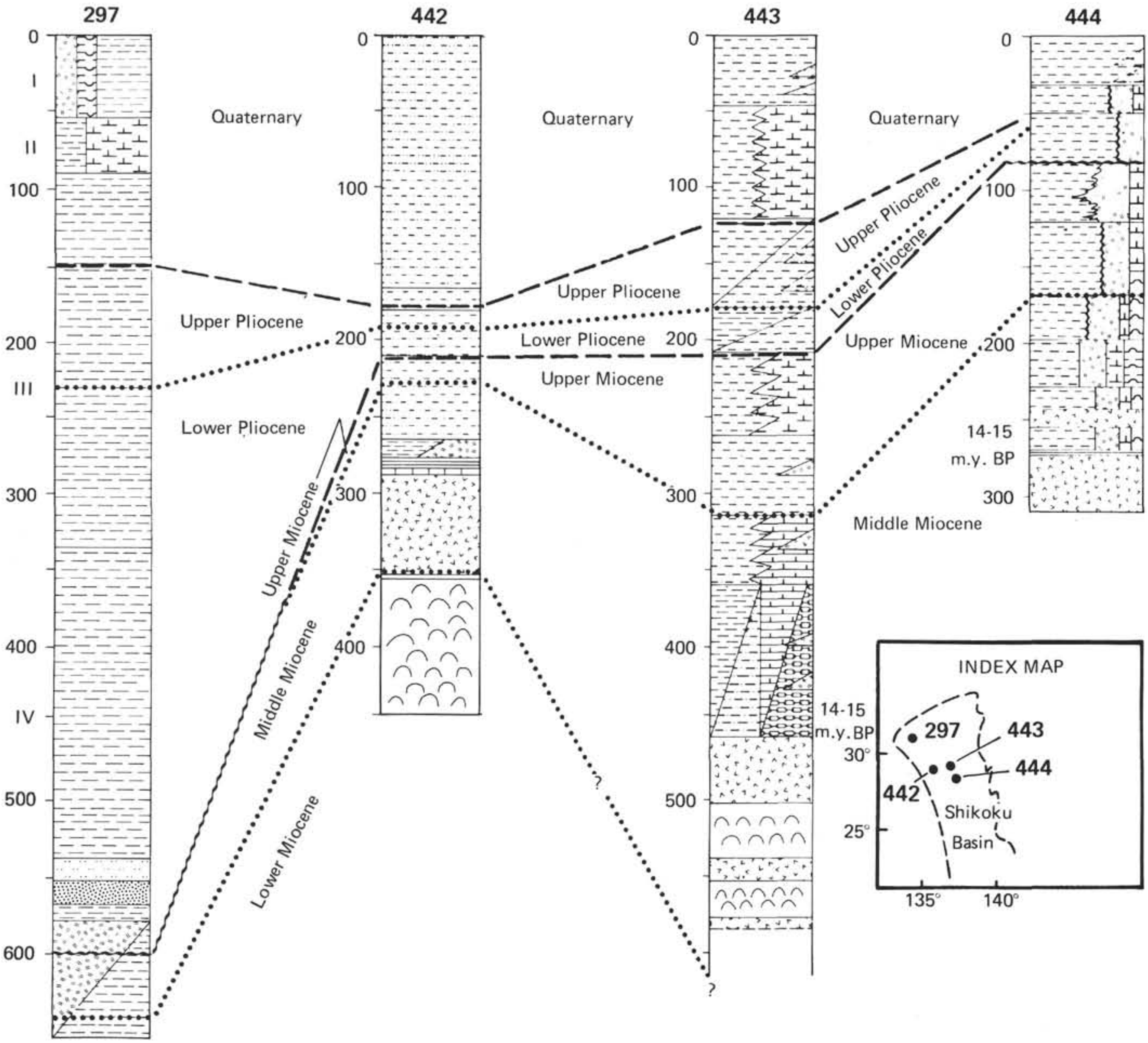

Figure 3. *Stratigraphic correlation of DSDP Sites 297, 442, 443, and 444. (Symbols explained in introduction to this volume.)*

443 and 444 appears to be the nature of the basaltic basement. At both sites, the uppermost basalt is an intrusive sill, whereas at Site 444 only intrusive sills were encountered. At Site 443, a fragment of highly recrystallized limestone is interbedded with the pillow lavas, suggesting that the intrusive sills obscured the true contact between oldest sediment and pillow basalt. Hence, a paleontological age determination of the acoustic basement rocks is not possible at Sites 443 and 444 by this method, leaving the calibration of the magnetic anomaly ages ambiguous. The K-Ar age for Site 443 (17.2 ±3.2 m.y.; Table 2) is the best basement age obtained.

The differences in the Shikoku Basin basalts are genetic: pillow basalts are true extrusives associated with the spreading phase of basin evolution, whereas the intrusive sills are the result of late-spreading or postspreading, off-ridge volcanism in the basin (Dick et al., this volume; Klein et al., 1978). This postspreading, off-ridge volcanism has obscured the paleontological age relations of Sites 443 and 444.

Magnetic-Anomaly Data

Several magnetic-anomaly surveys and maps of the Shikoku Basin have been published. Tomoda et al. (1975) recognized a linear anomaly pattern for the basin and proposed a symmetrical-spreading model to explain its origin, as did Karig (1975). Later, Watts and Weissel (1975) published data from a few survey lines showing a linear magnetic-anomaly pattern; they identified the ages of anomalies only on the western side of the basin. The anomalies on the eastern side of the Shikoku Basin were indeterminate, and they proposed that either a symmetrical or a single-limb model can explain their data. A single-limb model is now untenable because of the K-Ar age of 17.2 ±3.2 m.y. for the youngest pillow basalt at Site 443. Later work by Kobayashi and Isezaki (1976) and Kobayashi and Nakada (1977, 1978) confirmed the linear pattern and identified the anomalies on the eastern side of the basin. Their analysis led to recognition of a symmetrical-spreading model for the basin, starting slightly prior to anomaly-6C time (25 Ma) and ending with anomaly-5D time (17.2 Ma). Kobayashi and Nakada (1978) also recognized a set of localized transform faults in the northern and southern part of the basin, giving rise to local anomaly offsets. The basin appears to have opened earlier and at a greater rate in the north at anomaly-6C time, and later in the southern part at anomaly-6B time, giving rise to the wider, fan-like basin shape. A reconstruction of the spreading of the Shikoku Basin, using their data, is shown in Figures 4 through 8.

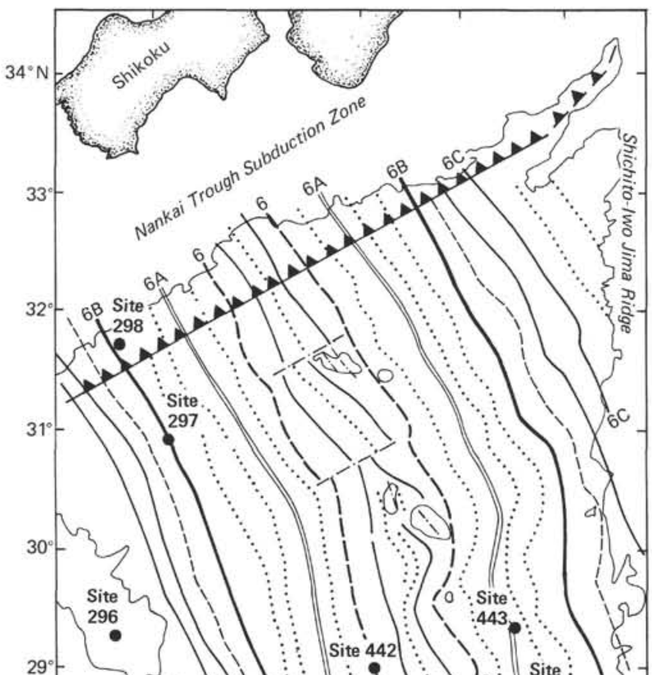

Figure 4. *Present magnetic-anomaly pattern in the Shikoku Basin, assuming that spreading ceased 17 Ma (from Kobayashi and Nakada, 1978).*

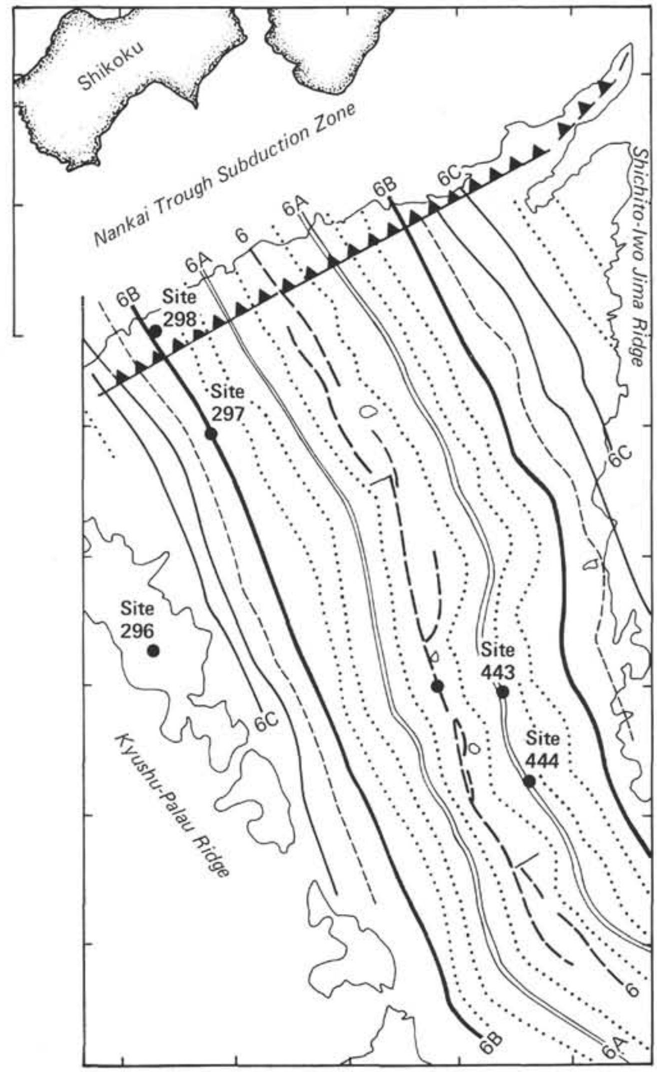

Figure 5. *Configuration of Shikoku Basin, 20 Ma (anomaly-6 time).*

A third magnetic-anomaly model that may explain the complexities of the Shikoku Basin is presented by Shih (this volume). His data suggest continuity of linear magnetic-anomaly trends in the western part of the basin (in agreement with other workers), but less-continuous trends in the eastern part of the basin because of several fracture zones there (Figure 9) which can be traced to fracture zones recognized by Karig and Moore (1976) in the Iwo Jima Ridge. Shih's anomaly identifications differ from those of previous workers in several respects. First, the central anomaly is identified as 5C (16 m.y.) in the southern part of the basin, whereas in the central portion it is identified as 5B (14.5 m.y.). His half-spreading rates are also different during the opening of the basin, ranging from 4.8 to 5.3 cm/yr from anomaly 7 to 6B time (25.2–22.5 m.y.) to 2.4 cm/yr from anomaly 6B to 6 time (22.5–19.5 m.y.), and 1.7 cm/yr from anomaly 6 to 5B time (19.5–14.5 m.y.). Thus, the basin is wider at its northern end because of greater half-spreading rates there and because spreading

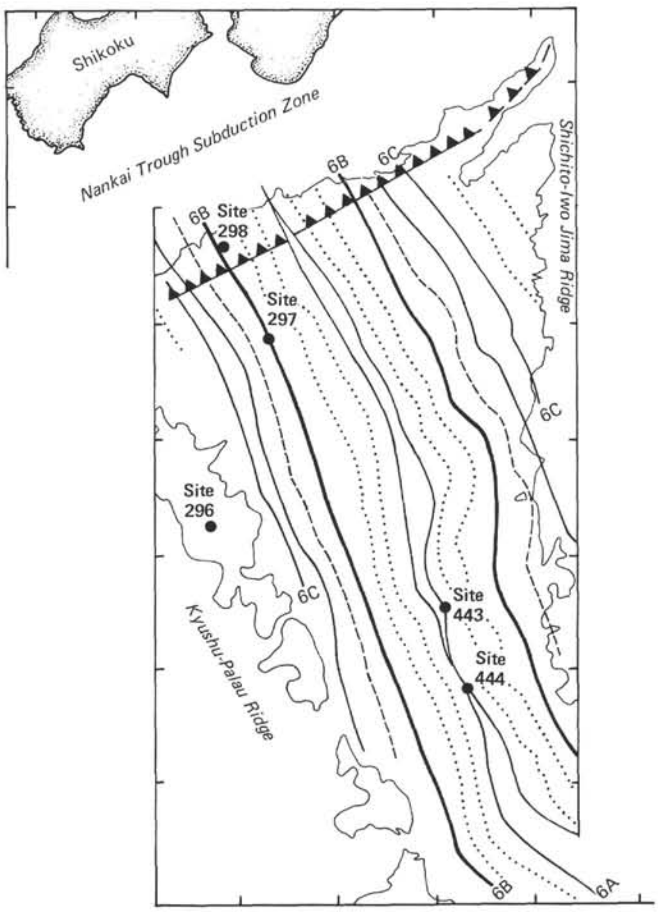

Figure 6. *Configuration of Shikoku Basin, 21 Ma (anomaly-6A time).*

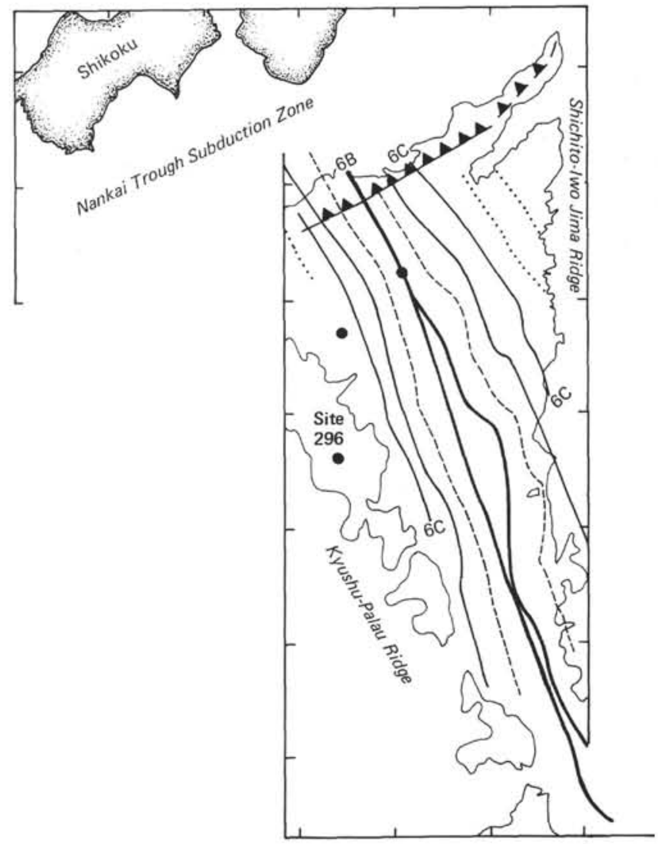

Figure 7. *Configuration of Shikoku Basin, 22.5 Ma (anomaly-6B time).*

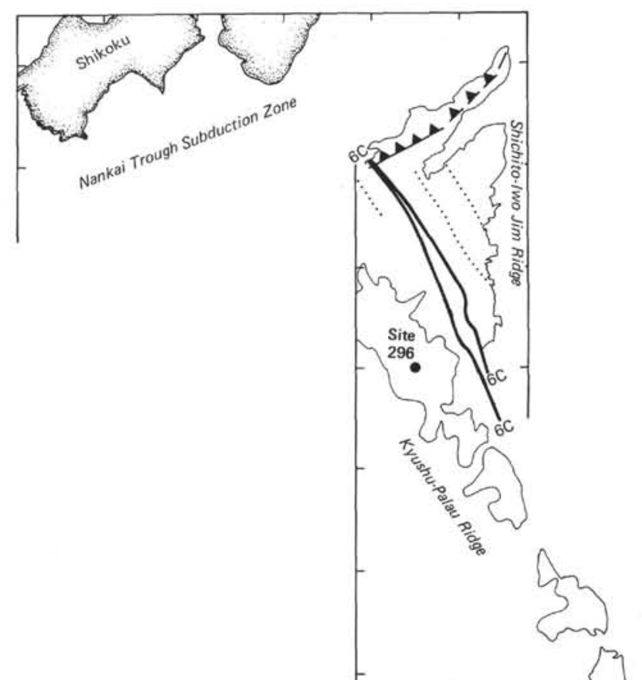

Figure 8. *Configuration of Shikoku Basin, 25 Ma (anomaly-6C ''' time).*

ceased earlier in the southern portion of the basin (anomaly-5C time) than in the northern part of the basin (5B time). The oldest anomaly on the western side is 5B (22.5 m.y.) to 6C (24 m.y.), whereas the oldest anomaly identified on the eastern side of the basin is 6A (21 m.y.), indicating asymmetric spreading (Shih, this volume). This asymmetric spreading was similar to asymmetries of spreading reported from the East Pacific Rise by Rea (1976a,b, 1977, 1978), where changing spreading rates are known. The proposed sequence of events is shown in Figure 10.

Critical factors in Shih's argument are the ages of the oldest sediment and of the youngest pillow basalt. Agreement between the oldest sediment age (19–21 m.y.) and the age of magnetic anomaly 6 (20.5–21 m.y.) at Site 442 was documented earlier. (See Table 1.) Shih (this volume) proposed from his magnetic correlation that Site 443 is between anomaly 5D and 5C (16–17 m.y.) and that Site 444 is on anomaly 5D (17 m.y.). Allowing for an age gap of 1 to 2 m.y. between basement ages (Table 1) and oldest-sediment ages, an age gap within the margin of error for dating basements (van Andel and Bukry, 1973), Shih's correlation appears to be in agreement.

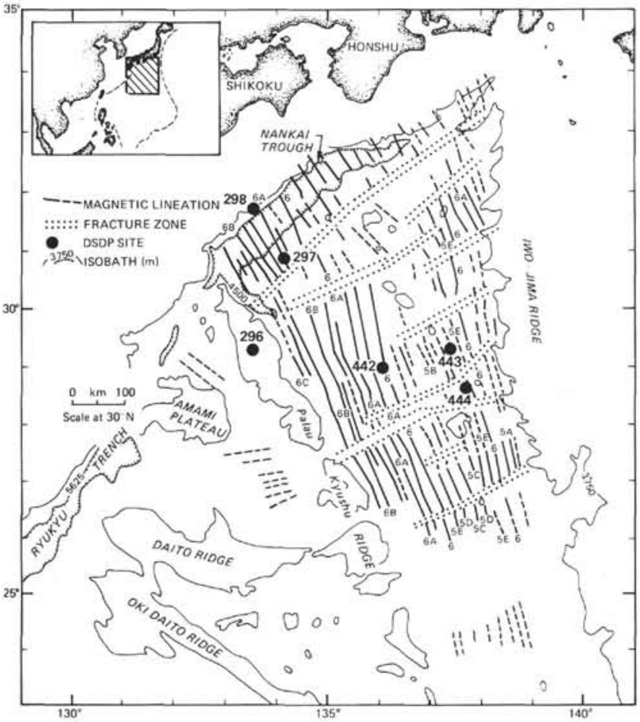

Figure 9. *Magnetic-anomaly pattern for the Shikoku Basin, according to Shih (this volume).*

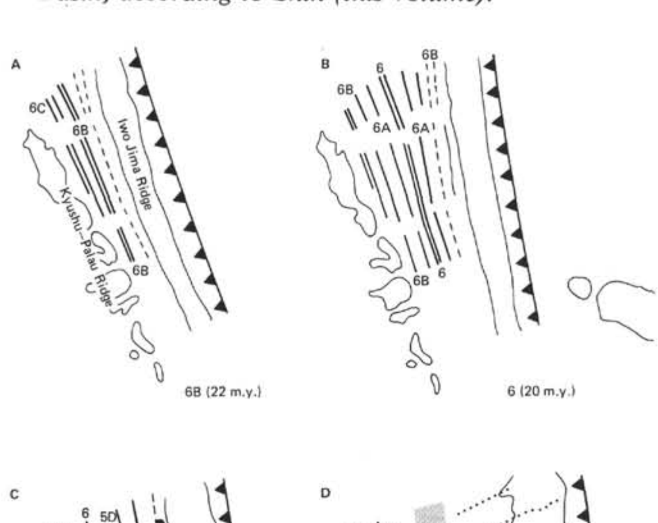

Figure 10. *Evolution of Shikoku Basin (after Shih, 1978).* A. *Anomaly-6B time.* B. *Anomaly-6 time.* C. *Anomaly-5D time.* D. *Anomaly-5C time, the present configuration.*

To test the model, arrangements were made to obtain a K-Ar age determination of the youngest pillow basalt at Site 443 from E. H. McKee (Table 2). That sample gave a K-Ar date of 17.2 ± 3.2 m.y., which is in agreement with Shih's magnetic-anomaly determination for that site. The error in the age determination is large enough, however, that acceptance of this correlation must be done with caution.

Summary and Conclusions — Shikoku Basin

The main results that emerged from our drilling in the Shikoku Basin deal with the age of acoustic basement and the mineralogy and petrology of the oceanic crust there.

Determination of the age of the ocean floor of the Shikoku Basin hinges on interpretation of the ages of the oldest sediment and interpretation of magnetic anomalies. The evolution of this interpretation of magnetic-anomaly data is reviewed above; data demonstrate clearly that the Shikoku Basin, like many back-arc basins of the western Pacific, shows complex magnetic-anomaly patterns, topography, and geology. Although there is agreement now among all workers in the Shikoku Basin that the magnetic-anomaly pattern is lineated, there is disagreement still concerning the interpreted magnetic-anomaly ages on the eastern half of the basin. Our drilling during Leg 58 permitted the elimination of one of the models of basin evolution (single-limb model), but did not permit resolution of the proposals that the magnetic-anomaly pattern is either symmetrical in age disposition (Kobayashi and Isezaki, 1976; Kobayashi and Nakada, 1977, 1978) or that it is asymmetrical (Shih, this volume).

Our paleontological age determinations for the oldest sediments are in agreement with magnetic-anomaly age determinations on the western side of the basin (Site 442), but ambiguous on the eastern side (Sites 443, 444; Tables 1, 2). The apparent major reason for this ambiguity is that off-ridge volcanism was more prevalent on the eastern side. Consequently, intrusive igneous activity has obscured these contact relationships there. At both Sites 443 and 444, the oldest sediment overlies sills; at Site 443, these sills in turn overly pillow basalts. The lesson to be learned again from our experience is that calibration of magnetic-anomaly age determinations by paleontological dating of the oldest sediment in a borehole will prove successful only if the oldest sediment is in direct contact with lava which was emplaced during basin spreading. When the contact between oldest sediment and acoustic basement is intruded by sills, paleontological dating of magnetic anomalies will prove to be ambiguous at best.

Shih (this volume) has made a strong case for correlating the 14 to 15 m.y. age of the oldest sediment at Sites 443 and 444 with his identification of magnetic anomaly 5D (16–17 m.y.) for those sites, on the grounds that the approximately 2-m.y. age gap between paleontological and magnetic ages is reasonably close. That argument fits an evaluation of so-called basement ages for dating oceanic crust by van Andel and Bukry (1973), who demonstrated that for nannofossil zones, a millionyear margin of error is common. K-Ar dating of the youngest pillow basalt below the sill by McKee (Table 2) at Site 443 gives 17.2 ± 3.2 m.y. and supports Shih's argument, although the error in the age is perhaps too large to provide precise resolution of the problem. Therefore, although Shih's anomaly identification for Sites 443 and 444 seems to coincide more closely with various age determinations, it is our view that lack of precision in both dating methods allows us to say no more than that his identification looks promising. It is therefore our conclusion that *both* a symmetrical-spreading model and an asymmetrical-spreading model for the Shikoku Basin agree with the data in hand.

Our major findings regarding the composition of the ocean crust in the Shikoku Basin are summarized in accompanying chapters by Dick et al., Wood et al., and Nisterenko (all this volume). Their major findings and conclusions are that the basalts of the Shikoku Basin are mostly of mid-ocean-ridge derivation and composition, although alkaline island-arc basalts were both extruded and intruded during spreading-center and off-ridge volcanic events. During active spreading, pillow basalts were extruded onto the ocean floor, whereas during later stages of spreading and for about 3 to 5 m.y. after spreading ceased, intrusive off-ridge volcanism was dominant. This off-ridge volcanism occurred at the same time as regional tectonic uplift and intrusive igneous events in southern Japan (Oba, 1977), so it is likely that all these events are related to broader, regional tectonic changes. The chemical variation observed in the Shikoku Basin basalts (Marsh et al., this volume; Wood et al., this volume) could be due to sudden access to the surface of differing magmas along newly defined regional fracture zones during such post-spreading, regional tectonic events.

DAITO RIDGE AND BASIN PROVINCE

The Daito Ridge and Basin province (DRBP) is subdivided into deeper-water basins and relatively shallower ridges, including the Daito Ridge, the Oki-Daito Ridge, and their smaller extensions. The crustal structure of the Oki-Daito Ridge, as revealed by seismic refraction (Murauchi et al., 1968), shows similarities to island-arc crustal structure, including a layer 2 zone with $V_p = 6.0$ km/s as thick as 5 km, and a depth to the Moho in excess of 16 km.

Although no seismic-refraction data are available from the Daito Ridge, it appears also to be a remnant arc, because dredge hauls from there recovered igneous and metamorphic rocks similar to those from island arcs (Mizuno et al., 1975; Shiki et al., 1977). The dredge hauls contained andesites, basalts, hornblende schists, and granodiorites. In addition, conglomerates recovered from a sub-bottom depth of 700 to 892 meters at Site 445 include clasts of basalt, andesite, rhyolite, and hornblende schist (Nisterenko; Tokuyama et al.; Mills; all this volume), indicating an island-arc source. Both the dredge samples and the drill cores from Sites 445 and 446 contain the larger foraminifer *Nummulites boninensis*; the species we obtained is distinct from those recovered in the Ryukyu Islands west of the DRBP. Dissimilarity of species thus precludes the transport of these shells by turbidity currents and debris flow from the west and indicates that our *Nummulites* were transported by gravity processes from local ridges such as the Daito and Oki-Daito Ridges.

The recovery of resedimented tests of *Nummulites* indicates that the crest of the Daito Ridge was at or near sea level in middle- to late-Eocene time and has subsided subsequently about 1500 meters to its present depth. Isotopic ages of igneous rocks obtained by drilling during DSDP Legs 31 and 58 and dredge hauls (McKee and Klock, this volume; Ozima et al., 1977) indicate that this province (including the Amami Plateau) may be one of the oldest portions of the Philippine Sea (Figure 11). Analysis of magnetic-anomaly data by Louden (1976), Watts et al. (1977), and Shih (1978) indicates that the west Philippine Basin opened approximately 60 to 40 MYBP, with a spreading axis roughly near the present central basin fault. If these ages are correct, the DRBP was formed before and during the opening of the west Philippine Basin.

Paleomagnetism of sediment cores recovered from Sites 445 and 446 (site chapters, this volume; Kinoshita, this volume) indicates that the DRBP migrated north from an equatorial latitude over the past 52 m.y. Analysis of microfossils (Okada, this volume), clay minerals (Chamley, this volume) and pollen (Tokunaga, this volume) supports this paleomagnetism interpretation.

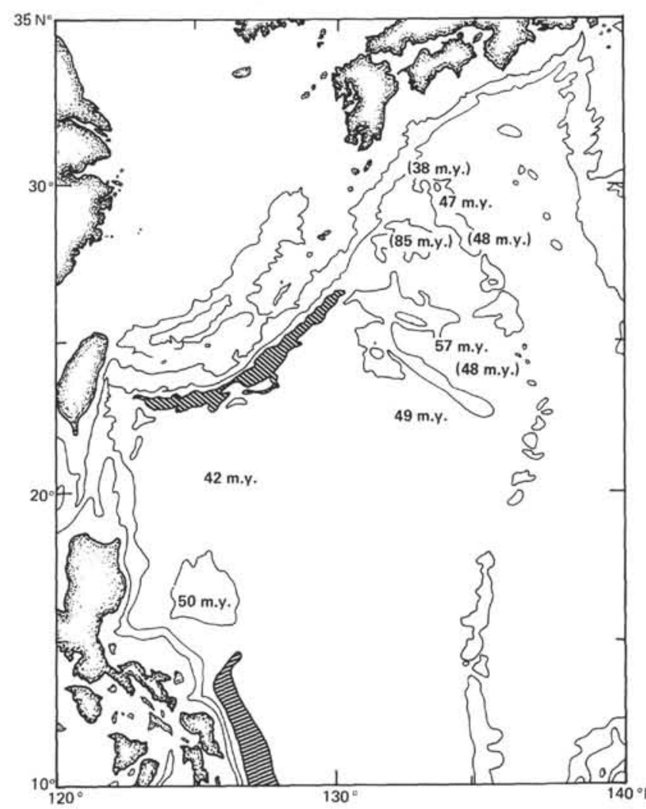

Figure 11. *Ages of igneous rocks in the Daito Ridge and Basin province. Numbers in parentheses shows ages determined by the K-Ar method; other numbers indicate ages obtained by the ^{40}Ar–^{39}Ar method.*

Louden (1977) measured the paleomagnetic inclination of Leg 31 sediment cores and demonstrated that Site 292 on the Benham Rise migrated from the southern hemisphere since at least 42 MYBP. If his results are plotted together with Kinoshita's data (Kinoshita, this volume), assuming a southern-hemisphere location of the DRBP in the early Eocene, both curves (Figure 12) of paleolatitude migration are consistent, although the DRBP and the Benham Rise are at present approximately 1000 km apart, and the latter is south of the central basin fault.

Louden's analysis of skewness in marine magnetic anomalies 17 to 21 (40–50 m.y.) in the southern portion of the west Philippine Basin also indicates a low-southern-latitude origin for that part of the basin. The phase shifting of anomalies also suggests a clockwise rotation of about 55 degrees between the Philippine Basin and the magnetic pole after the anomalies formed (Louden, 1977).

All this evidence indicates that the west Philippine Basin and the DRBP migrated north as a rigid plate after the west Philippine Basin formed. Contrary to an earlier interpretation by Mizuno et al. (1975), no convergent plate boundary existed between the northern margin of the west Philippine Basin and the DRBP.

Petrologic study of intrusive sills cored at Site 446 (Dick et al., this volume) indicates that these rocks are similar to igneous basement at Site 444 in the Shikoku Basin. This finding suggests that the Site 446 basalts also were formed by off-ridge volcanism in the Daito back-arc basin, although an island-arc origin for these basalts cannot be excluded entirely. Whatever the origin of these rocks, magmatic activity at Site 446 was caused by subduction below the DRBP, because magmas beneath the back-arc basin *and* under the island arc are supposedly derived from a subducted slab (Karig, 1971; Ida, 1978).

Recognition of this paleosubduction zone requires a determination of the direction of that subduction. We propose a model to illustrate the evolutionary history of

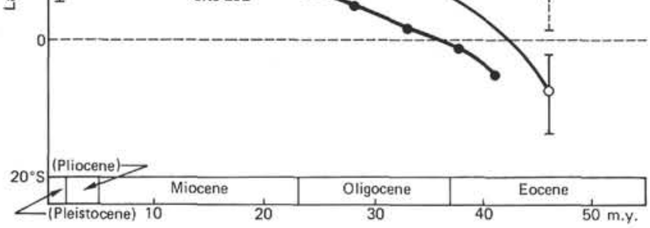

Figure 12. *Paleolatitude of DSDP Sites 445, 446, (this volume) and 292 since the Eocene (after Louden, 1977).*

the DRBP since about 60 MYBP, from Leg 58 drilling results and prior work. As shown in Figure 13, the DRBP migrated northward together with the spreading of the west Philippine Basin, starting around 60 MYBP. The northern oceanic plate was being subducted under the Daito province during this period. Most of the island-arc structures in the Daito Ridge and Oki-Daito Ridge were formed by this subduction. Back-arc spreading may have occurred between the Daito and Oki-Daito Ridges and between the Daito and northern Kyushu-Palau Ridges. Magnetic lineations trending approximately east-west have been postulated in the basin between the Daito and northern Kyushu-Palau Ridges (Watts et al., 1977; Isezaki and Miki, 1978). Linear magnetic anomalies seem to support a spreading origin for the basin. However, data are still insufficient to identify the anomalies in that basin, and no alignment has been revealed in the basin between the Daito and Oki-Daito Ridges.

The geographic configuration of rock samples drilled and dredged in this region is consistent with this hypothesis. In order of increasing distance from this paleotrench, granodiorite was dredged at the northern Kyushu-Palau Ridge, metamorphic rocks at the Daito Ridge, and basalt at the Oki-Daito Ridge.

Northward drift of the west Philippine Basin south of the spreading axis may have occurred at the same rate as the northward motion of the Pacific plate (8 cm/yr), while migration of the northwest Philippine Basin together with the DRBP was faster than the motion of the Pacific plate (10–15 cm/yr before 40 Ma from paleomagnetic evidence, if a southern-hemisphere origin of the DRBP is assumed). The central part of the Kyushu-Palau Ridge was a transform fault between these two plates, as Uyeda and Miyashiro (1974) first postulated, and as discussed later by Hilde et al. (1977).

Around 40 MYBP, probably soon after the opening of the west Philippine Basin ceased, the whole region, including the west Philippine Basin and the DRBP, rotated clockwise, possibly accompanied by the formation of the Philippine Trench and the creation of the Carolina plate. After the rotation, both the northern and southern portions of the Kyushu-Palau Ridge were facing the west-northwest motion of the Pacific plate, which began about 42 MYBP. The Kyushu-Palau Ridge became part of a trench complex with westward subduction (Figure 13b). Most of the igneous rocks found at the crest of the Kyushu-Palau Ridge (except granodiorite with an age older than 42 m.y.) were formed by magmatic activity caused by this subduction. This period of island-arc formation at the Kyushu-Palau Ridge was succeeded by opening of the Shikoku and Parece Vela back-arc basins. The Kyushu-Palau Ridge was changed then into a remnant arc and subsided after 28 MYBP, as indicated by the sedimentary section at Site 296 on that ridge (Karig, Ingle, et al., 1975).

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Division of labor on this paper was as follows: Klein was responsible for the section on the Shikoku Basin, whereas Kobayashi was responsible for the section on the DRBP. Although

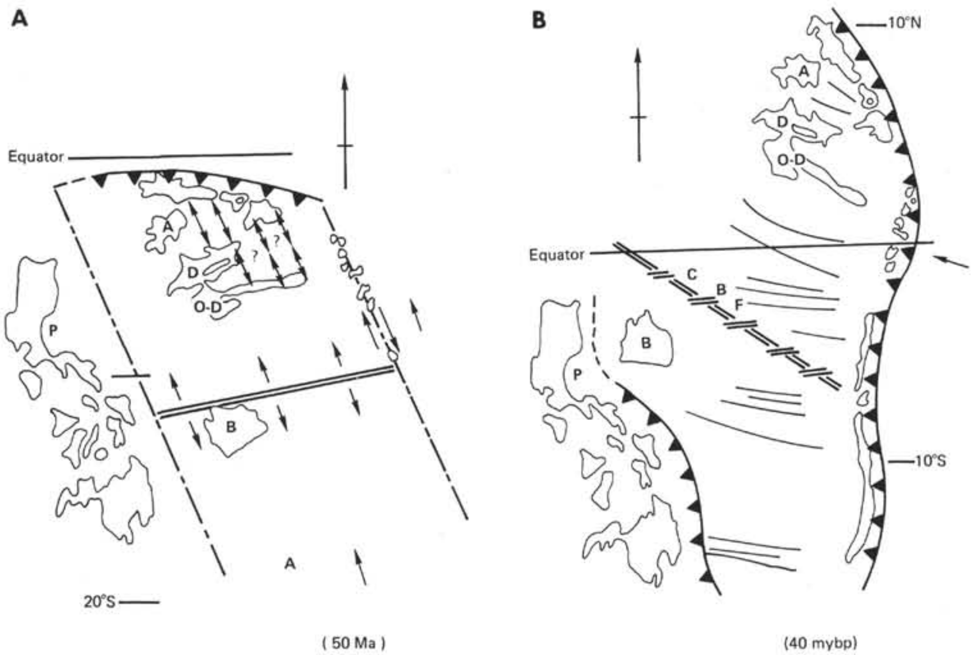

Figure 13. *Interpretation of the evolution of the Daito Ridge and Basin province and the west Philippine Basin.* A. *50 Ma.* B. *40 Ma. Abbreviations:* (A) *Amami Plateau;* (D) *Daito Ridge;* (O-D) *Oki-Daito Ridge;* (B) *Benham Rise;* (P) *Philippines;* (CBF) *central basin fault.*

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