OCEANOLOGICA ACTA, 1981, N° SP

Shikoku Basin
Daito Ridge- and Basin
Philippine Sea
Back-arc basins
Magnetic anomalies

Bassin de Shikoku
Bassin et ride du Daito
Mer des Philippines
Bassins arrière-arc
Anomalies magnétiques

Geological summary of the Shikoku Basin and northwestern Philippine Sea, Leg 58, DSDP/IPOD drilling results

G. deV. Klein[a], K. Kobayashi[b]
[a]Department of Geology, University of Illinois at Urbana-Champaign, 245 Natural History Building, 1301 W. Green St. Urbana, Illinois 61801, USA
[b] Ocean Research Institute, University of Tokyo, 15-1, 1-chome, Minamidai, Nakano-ku, Tokyo 164, Japan

ABSTRACT

Leg 58 drilled three sites (442, 443, 444) in the Shikoku Basin and two (445, 446) in the Daito Ridge and Basin province (BRBP). At the Shikoku Basin sites, drilling penetrated hemipelagic clays and underlying tholeitic pillow basalts and sills. Basalt sills intruded both sediments and pillow lavas. The oldest sediment at Site 442 was 18-21 MY and at Sites 443 and 444 was 14-15 MY. A K-Ar age of 17.2 ± 3.2 MY was determined on the youngest pillow basalt at 443. The oldest sediment age at 442 coincides with the magnetic anomaly 6 age for the site, but the oldest sediment ages at 443 and 444 are at variance with a proposed anomaly 6A age for those sites. The K-Ar age on pillow basalt is at variance with one magnetic anomaly interpretation, but in agreement with another. Rifting of the Shikoku Basin was either symmetrical or asymmetrical ; off-ridge volcanism in the basin has made basement age resolution ambiguous. Rocks at the DRBP sites (445, 446) consist of an upper pelagic interval and a lower section of volcaniclastic turbidites and debris flow sandstones and conglomerates (intruded by 26 sills at 446). Magnetic inclination data suggest that the DRBP drifted north 2,000 km from an equatorial latitude over the past 53 MY. The age of the oldest sediment recovered, 52-53 MY, indicates that this area formed in the earliest stages of rifting of the west Philippine Basin.

Oceanol. Acta, 1981. Proceedings 26th International Geological Congress, Geology of continental margins symposium, Paris, July 7-17, 1980, 181-192.

RÉSUMÉ

Résultats géologiques sommaires du Leg 58 DSDP/IPOD dans le bassin de Shikoku et la mer des Philippines.

Durant le Leg 58, trois sites (442, 443, 444) ont été forés dans le bassin de Shikoku et deux (445, 446) sur la ride et le bassin du Daito. Les forages dans le bassin de Shikoku ont rencontré des argiles hémipélagiques surmontant des basaltes tholéitiques en pillows ou sills. Les sills de basaltes recoupent les sédiments comme les pillow-lavas. Le sédiment le plus ancien au site 442 a un âge de 18 à 21 mA, qui coïncide avec celui de l'anomalie magnétique 6, sur laquelle est placé le forage. Néanmoins l'âge du sédiment le plus ancien aux sites 443 et 444 est de 14-15 mA, ce qui est différent de celui de l'anomalie magnétique 6 A proposée pour ces sites. L'âge K-Ar : 17.2 ± 3.2 mA du pillow le plus récent au site 443 est compatible avec une première interprétation d'anomalie magnétique, mais s'accorde mal avec une seconde.

L'ouverture du bassin de Shikoku a pu être symétrique ou non ; le volcanisme à l'extérieur de la ride dans le bassin rend délicate la résolution du problème de l'âge des basaltes.
La série rencontrée dans la zone du Daito est constituée d'un ensemble supérieur pélagique et d'un ensemble inférieur de turbidites volcanoclastiques et de coulées gréseuses ou conglomératiques (intrudés de sills au site 446). Les données de l'inclinaison magnétique suggèrent un déplacement de 2000 km vers le Nord à partir d'une latitude équatoriale de la zone du Daito depuis 53 mA. L'âge du sédiment le plus ancien — 52-53 mA — indique que cette zone a été créée pendant le stade d'ouverture du bassin des Philippines occidental.

Oceanol. Acta, 1981. Actes 26[e] Congrès International de géologie, colloque Géologie des marges continentales, Paris, 7-17 juil. 1980, 181-192.

INTRODUCTION

The terrain underlying the North Philippine Sea is characterized by both topographic and tectonic complexities formed by the convergence of the Pacific and Eurasian plates. This region contains an active trench and island arc system (Bonin Trench, Bonin Islands), remnant arcs (Kyushu-Palau Ridge, Daito Ridge, Oki-Daito Ridge), and inactive back-arc and interarc basins (Shikoku Basin, Daito Basin northwestern Philippine Sea). The geologic history of the area is also complex because of changing patterns of subduction (Hilde *et al.*, 1977 ; Kobayashi, Isezaki, 1976 ; Kobayashi, Nakada, 1977, 1978 ; Watts, 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 (Fig. 1).

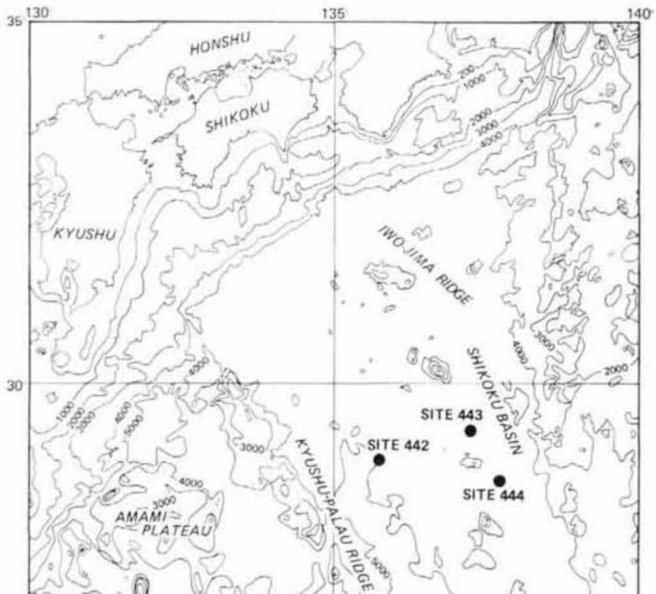

Figure 1
Bathymetric map, geographic features and Leg 58 sites, north Philippine Sea.

SHIKOKU BASIN

The Shikoku Basin is an inactive back-arc 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, Isezaki, 1976 ; Kobayashi, Nakada, 1977, 1978 ; Tomoda *et al.*, 1975 ; Watts, Weissel, 1975 ; Karig, 1975 ; Shih, 1980). The main evidence for the rifting by sea-floor spreading comes from analysis of lineated magnetic anomaly patterns. The rifting is considered to be either symmetrical (Tomoda *et al.*, 1975 ; Kobayashi, Isezaki, 1976 ; Kobayashi, Nakada, 1977, 1978 ; Watts, Weissel, (1975) asymmetrical (Shih, 1980), or single-limb (Watts, Weissel, 1975).

The objectives of the Leg 58 drilling program in the Shikoku Basin included : 1) drilling to acoustic basement to determine the age of the oldest sediment in order to calibrate magnetic anomaly ages and determine which of the three proposed spreading models characterized the basin ; 2) examination of the mineralogy and petrology of the basaltic basement in order to compare compositions of these back-arc basin basalts with those of mid-ocean ridges and island-arc basalts ; 3) determination of the sedimentary history of the basin in order to relate changes in sediment type to basin evolution ; and 4) determination of the paleocirculation of the basin. The results for objective 1 are discussed in this paper ; those for objective 2 were summarized by Marsh *et al.*, (1980), Dick *et al.* (1980), and Wood *et al.*, (1980) ; those for objectives 3 and 4 were reviewed by White *et al.* (1980), and Chamley (1980, *a*, *b*).

Topography

The Shikoku Basin is an elongate, fan-shaped back-arc basin oriented approximately north-northwest to south-south-east. The topography (Fig. 2) of the basin is highly irregular, consisting of small-scale linear ridges and troughs and a series of seamounts, primarily on the east half. Seismic study of the basin reveals that the acoustic basement topography is also rough (Karig, Ingle *et al.*, 1975 ; Murauchi, Asanuma, 1974 ; 1977 ; Kobayashi, 1980). Some of this rough topography was filled with sediment, suggesting an early history of filling of topographic lows and subsequent basin-wide deposition of regional clastic wedges (White *et al.*, 1980). Basement topographic changes are masked by three clastic wedges, two of which merge in the west side of the basin, giving it a smooth appearance (White *et al.*, 1980). The eastern part of the basin is characterized by an extremely rough horst-and-graben topography, cut by a series of fracture zones.

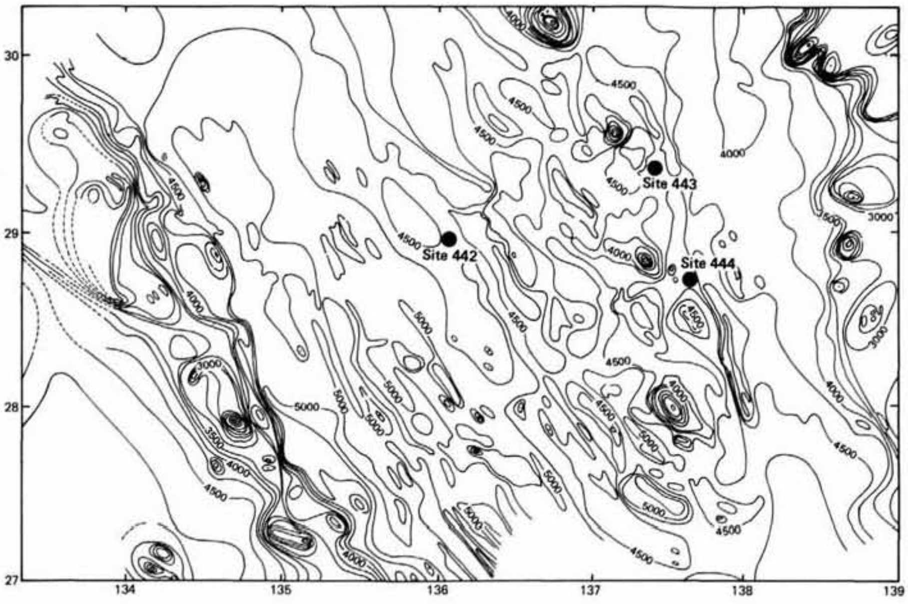

Figure 2
Bathymetry of Shikoku Basin (after Kobayashi, Nakada, 1978).

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, Asanuma, 1974 ; 1977 ; Karig, 1975 ; Karig, Ingle *et al.*, 1975 ; Kobayashi, 1980) indicate that the ridge-and-basin topography is offset and bounded by normal faults.

The irregular topography is independent of mapped magnetic anomaly alignments (Tomoda *et al.*, 1975 ; Watts, Weissel, 1975 ; Kobayashi, Isezaki, 1976 ; Kobayashi, Nakada, 1977 ; 1978 ; Shih, 1980), and its roughness has made correlation and identification of magnetic anomalies difficult (cf. Lawver, Hawkins, 1978). The presence of widespread intrusive sills in the basin indicates that offridge volcanism characterized both the late stages of basin spreading and the post-spreading phase of basin development (Dick *et al.*, 1980 ; Klein *et al.*, 1978). This volcanism also contributed to the irregular topography of the basin, particularly on its east side, and accounts in part for the difficulty identifying magnetic anomalies.

Petrology and stratigraphy of volcanic and intrusive igneous rocks

That igneous rocks recovered by drilling in Shikoku Basin are basalts that occur both as extrusive pillow lava flows (assumed to be emplaced during formation of the basin floor by sea-floor spreading) and intrusive sills (emplaced during offridge volcanism during the latest stages of basin formation and after spreading processes ceased). Of the basalts, 64 % are aphyric, 20 % are plagioclase phyric, and 15 % are plagioclase and olivine phyric. Olivene occurs as phenocrysts, microphenocrysts, or groundmass, and some of it 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 types are present (Wood *et al.* 1980).

The basalts from site 442 are all phyric and extremely vesicular (Dick, 1980). Calcite has replaced olivine. Spinel, enclosed by pyroxene, is a common accessory mineral. The high vesicularity is caused by the abnormally hydrous nature of the basaltic magma source (Dick, 1980).

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 the chill zone in the sequence, 38 cooling units can be identified at the three drill sites. The units range from 24 to less than lm in thickness, averaging 5.8 mo. At site 442, 69 m of massive basalt (16 subunits) is underlain by 102 m of pillow basalt with two interbeds of massive basalt. These units are typical mid-ocean pillow basalts.

The pillow basalts are interpreted as being extruded during active basin spreading, whereas the massive units are interpreted as either *subsediment flows* or intrusive sills emplaced by offridge volcanism (Dick *et al.*, 1980 ; Klein *et al.*, 1978).

Evidence for the timing and duration of volcanism in the Shikoku Basin is provided by the stratigraphy at the various sites, 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, Klock, 1980). At site 442 sediment overlying massive basalt is approximately 15 to 17 MY old, whereas that below the massive basalt and above the youngest pillow lava is 18 to 21 MY old. At site 443, the youngest pillow lava is 17.2 + 3.2 MY old (Tables 1 and 2), and at site 444, the sill intruding sediment is dated at 14.7 + 2.1 MY (McKee, Klock, 1980). Thus, the off-ridge volcanism occurred during the latest stage of ocean floor spreading and post-spreading igneous activity.

Stratigraphy and age relations of oldest sediment

Sediments recovered from the Shikoku Basin consist of a succession of tubidites and hemipelagic clays at site 297 (Karig, Ingle *et al.*, 1975) and hemipelagic clays from the distal parts of clastic wedges (442, 443, and 444). The hemipelagic clays appear to have been derived from the Japanese Islands, the Kyushu-Palau Ridge, the Iwo Jima Ridge and the Asian mainland (Chamley, 1980 *a*).

Table 1

Magnetic anomaly, paleontological, and K-Ar ages for oldest sediment and basaltic basement, Shikoku Basin[1].

Site	Magnetic anomaly	Magnetic Anomaly age (MY)[1]	Paleontological age, Oldest sediment (MY)	K-Ar Age (MY)	Remarks
442	6[2,3]	19-20.5	19-21		
443 uppermost	6A[2]	20.5-21.0	14-15	17.2 + 3.2	K-Ar age on
	5D-5C[3]	16.0-17.0		pillow basalt.[4]	
444 intruding	6A[2]	20.5-21.0	14-15	14.7 + 2.1	K-Ar age on sill
	5D[3]	17.0-17.5		sediment[5].	

1. Magnetic time scale after LaBreque *et al.* (1977).
2. Magnetic anomaly identification from Tomoda *et al.* (1975) Kobayashi and Isezaki (1976), Kobayashi and Nakada (1977, 1978) and Watts and Weissel (1975).
3. Magnetic anomaly identification from Shih (1980).
4. K-Ar age from sample 443-57-2, uppermost pillow basalt, see Table 2.
5. K-Ar age on sill intruding sediment at site 444 from McKee and Klock (1980).

Table 2

K-Ar age of sample site, site 443.

Procedure :	Whole-rock basalt, crushed, seived (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.
Analyst :	E. H. McKee, US Geological Survey, Menlo Park, Calif. (pers. comm., 1979).
Decay constants :	
	Atomic abundance of ^{40}K 1.167×10^4 mole/mole
Results :	$K_2O = 0.254$ %. $^{40}Ar = 6.3{,}072 \times 10^{-12}$ mole/g. Percent radiogenic $^{40}Ar = 6.5$.
Age :	17.2 ± 3.2 MY.

The stratigraphy of the sediments and associated basalts is shown in Figure 3. The thick lower Pliocene sequence at site 297 reflects deposition in the medial part of a northern clastic wedge identified from seismic profiles (Karig, 1975 ; 442, 443, and 444 indicate distal deposition. During deposition, the sea floor at all sites was near the calcite compensation depth (White *et al.*, 1980).

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 anomally ages and the age of the youngest extrusive basalt at site 443 and the age of the sill at site 444. At site 442, the sediment immediately overlying the massive upper basalt layer is dated at 15 to 17 MY (*Helicosphaera ampliaptera* zone of nannofossils), and a sedimentary interbed between this massive basalt and the youngest pillow basalt is dated as 18 to 21 MY (*Discoaster drugii* subzone of nannofossils). The age of the oldest sediment overlying massive basalts at sites 443 and 444 is 14 to 15 MY (*Spheonolithus 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 (Table 1) with the magnetic anomaly age of Watts and Weissel (1975) and Kobayashi and Nakada (1977 ; 1978) but falls within the 3.2 MY margin of error of K-Ar age determination (Tables 1 and 2) for the youngest pillow basalt at site 443. That K-Ar age determination is in agreement also with an independent magnetic anomaly identification (5 D ; 17.0-17.5 MY) ; Table 1 by Shih (1980). The age of the intrusive sill at site 444 is 14.7 + 2.1 MY, a finding consistent with organic geochemical measurements and age estimates by Waples and Sloan (1980). Clearly, the discrepancies between the oldest sediment ages, K-Ar ages, and magnetic anomaly ages at sites 443 and 444, which range from 2 to 6 MY need further analysis.

The cause for the discrepancy between the oldest sediment ages and the magnetic anomaly ages at sites 443 and 444 appears to be the nature of the basaltic basement. At both sites, the uppermost basalt is an *intrusive sill*, overlying pillow lavas whereas at site 444, only *intrusive sills* were encountered. At site 443, a fragment of highly crystallized limestone interbedded between the pillow lavas suggests that, most likely, the intrusive sills obscured the true contact between sediments and the youngest pillow basalts. Hence a paleontological age determination of the acoustic basement rocks is not possible at sites 443 and 444 by this method, and the calibration of the magnetic anomaly ages is ambiguous. The K-Ar age for site 443 (17.2 + 3.2 MY Table 2) is the best basement age we obtained there.

The basaltic basement in the Shikoku Basin was characterized by two modes of genesis : Pillow basalts are true extrusive rocks associated with the spreading phase of basin evolution, whereas the intrusive sills are the result of late-spreading or post-spreading offridge volcanism in the basin (Dick *et al.*, 1980 ; Klein *et al.*, 1978). This post-spreading off-ridge volcanism has obscured the paleontological age relations of sites 443 and 444, with respect to extrusive pillow lavas comprising basement.

Magnetic anomaly data

Several magnetic anomaly surveys and maps have been published from the Shikoku Basin. Tomoda *et al.* (1975) recognized a linear anomaly pattern for the basin and proposed a symmetrical spreading model to explain its

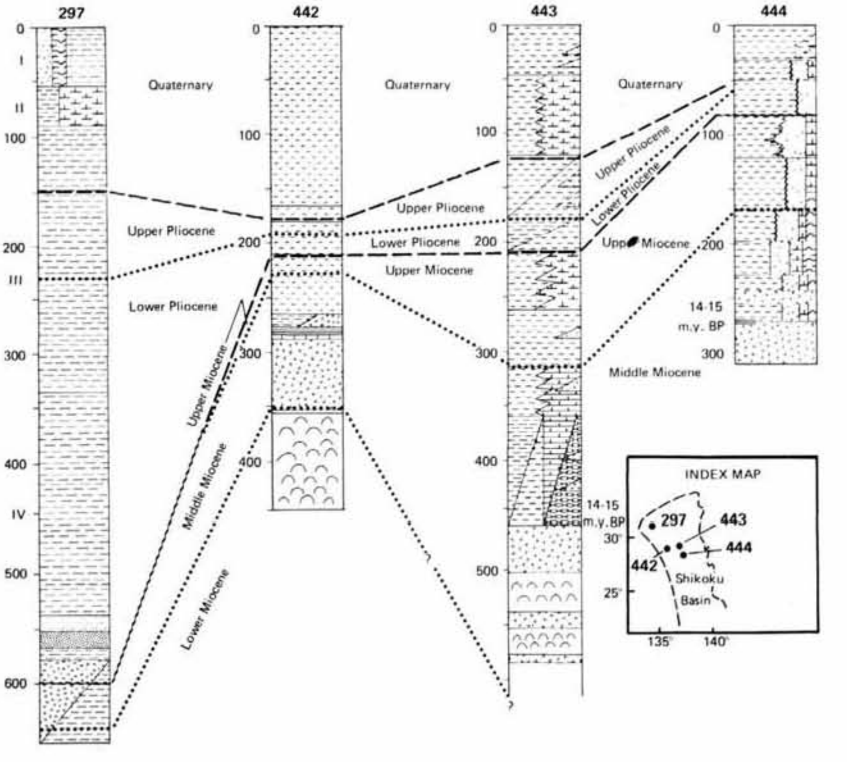

Figure 3
Stratigraphic correlation of sites 297, 442, 443 and 444.

origin, as did Karig (1975). Later Watts and Weissel (1975) published data from a few survey lines of anomalies only on the west side of the basin. The anomalies on the east side of the Shikoku Basin were indeterminate, and Watts and Weissel (1975) proposed that either a symmetrical or a single-limb model could explain their data. The single-limb model is now untenable because the K-Ar age of 17.2 + 3.2 MY for the youngest pillow basalt at site 443 is far younger than the 23.0 MY (anomaly 6A time) age suggested by such a model. Later work by Kobayashi and Isezaki (1976) and Kobayashi and Nakada (1977 ; 1978) confirmed the linear pattern and identified the anomalies on the east side of the basin. Their analysis lead to a symmetrical spreading model for the basin, starting slightly prior to anomaly 6C''' time (25 MY) and ending with anomaly 5D time (17.2 MY). Kobayashi and Nakada (1978) also recognized a set of localized transform faults in the northern and southern part of the basin that could cause anomaly offsets. The basin appears to have opened earlier and at a faster rate in the north at anomaly 6C time and later in the south at anomaly 6B time, producing the fan-like basin shape. A reconstruction of the spreading history of the Shikoku Basin, using their data, is shown in Figures 4 through 8.

A third magnetic anomaly model that may explain the complexities of the Shikoku Basin is presented by Shih (1980). His data suggest continuity of linear magnetic anomalies in the west side of the basin (in agreement with other workers) but less continuous trends in the east side of the basin because of the presence of several fracture zones there (Fig. 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 MY) in the southern part of the basin, whereas in the central part, it is identified as 5B (14.5 MY). His half-spreading rates also differ during the opening of the basin, ranging from 4.8 to 5.3 cm/yr for anomaly 7 to 6B time (25.2 to 22.5 MY), to 2.4 cm/yr from anomaly 6B to 6 time (22.5 to 19.5 MY), and 1.7 cm/yr from anomaly 6 to 5B time (19.5 to 14.5 MY). Thus the basin is

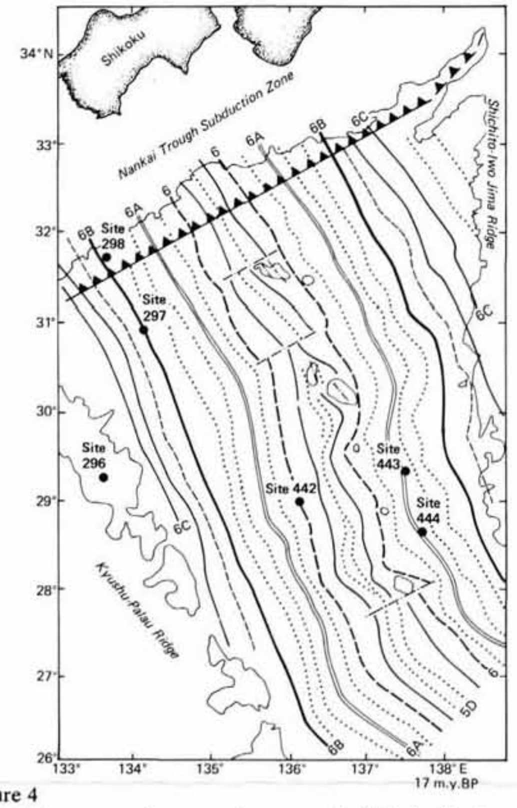

Figure 4
Present-day magnetic anomaly pattern in Shikoku Basin assuming that spreading ceased 17 MY ago (after Kobayashi, Nakada, 1978).

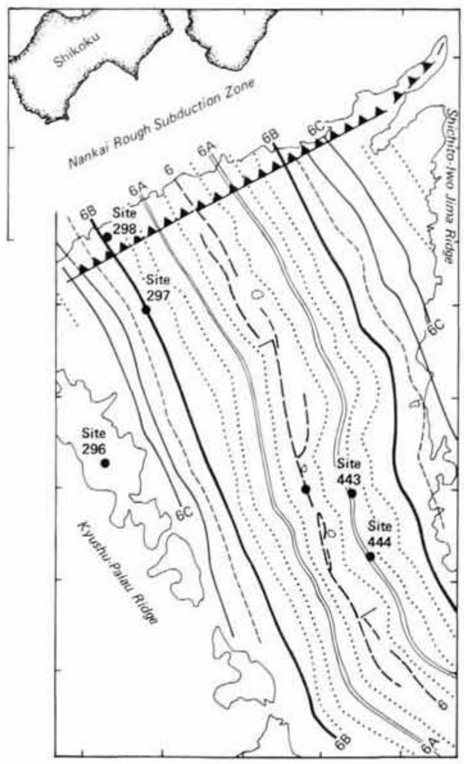

Figure 5

Configuration of Shikoku Basin, 20 MY (anomaly 6 time), using anomaly data of Kobayashi and Nakada (1978).

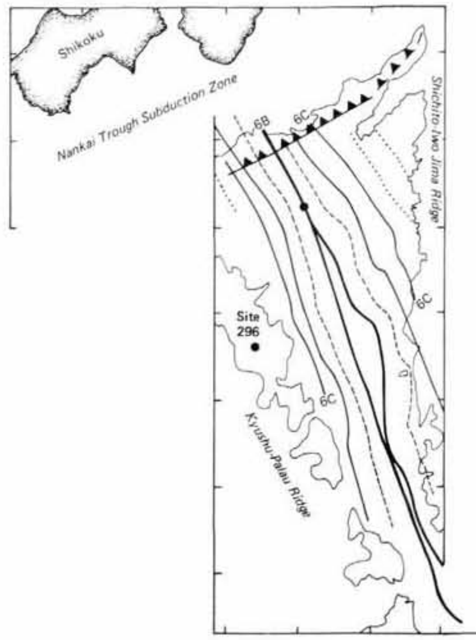

Figure 7

Configuration of Shikoku Basin, 22.5 MY (anomaly 6B time), using anomaly data Kobayashi and Nakada (1978).

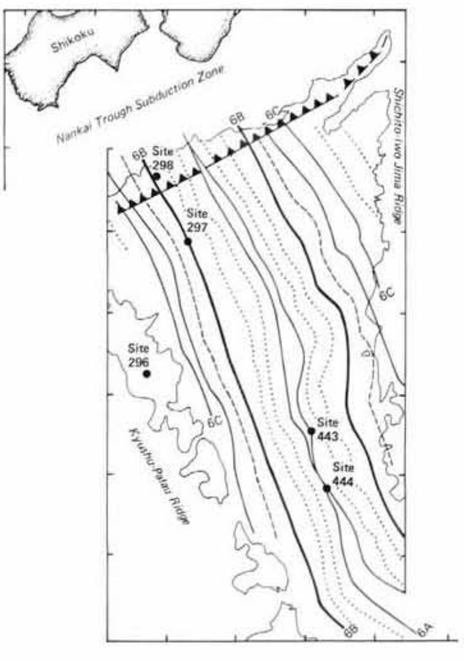

Figure 6

Configuration of Shikoku Basin, 21 MY (anomaly 6A time), using anomaly data of Kobayashi and Nakada (1978).

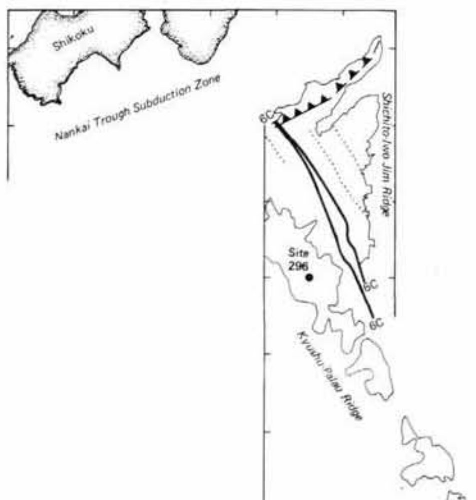

Figure 8

Configuration of Shikoku Basin, 25 MY (anomaly 6C time), using anomaly data of Kobayashi and Nakada (1978).

wider at its northern end because of an earlier, faster half-spreading rate and also because spreading ceased earlier in the southern part (5C time) than the northern part of the basin (5B time). The anomaly on the west side is 6B (22.5 MY) to 6C (24 MY), whereas the oldest anomaly identified on the east side of the basin is 6A (21 MY), and resembles asymetries of spreading reported from the East Pacific Rise by Rea (1976 *a*, *b*, 1977, 1978) where changing spreading rates are known. The proposed sequence of events is shown in Figure 10.

Critical factors in Shih's (1980) argument are the ages of the oldest sediment and the youngest pillow basalt. At site 442,

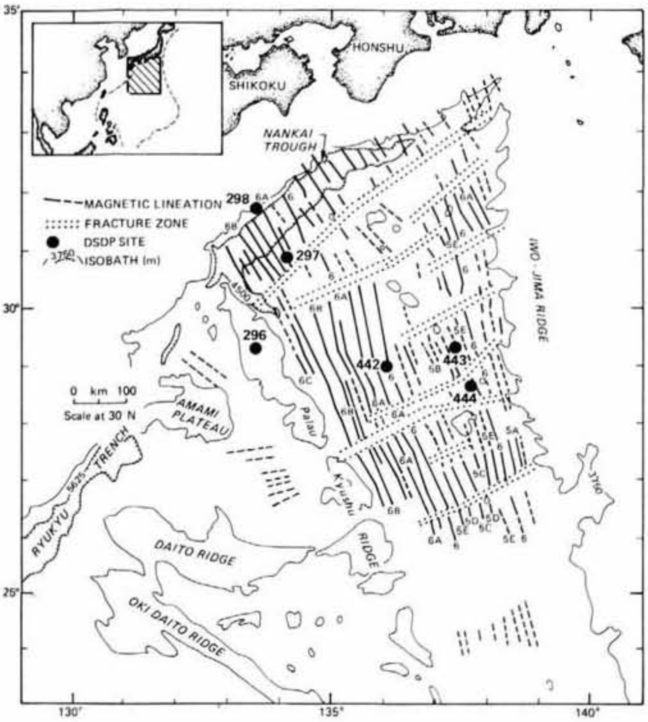

Figure 9

Magnetic anomaly pattern for the Shikoku Basin according to Shih (1980).

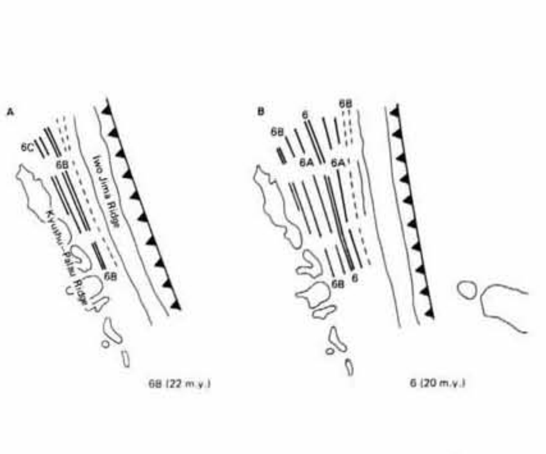

Figure 10

Evolution of Shikoku Basin (after Shih, 1980 at anomaly 6B time (a), *anomaly 6 time* (b), *anomaly 5D time* (c), *and anomaly 5C time* (d), *which is same as present configuration.*

the oldest sediment age (19-21 MY) and the magnetic anomaly 6A age (20.5 to 21 MY) agree (Table 1). Shih (1980) proposed, from his magnetic correlation, that site 444 was located on anomaly 5D (17 MY). Allowing for an age gap of one or two million years between basement ages and oldest sediment ages, (Table 1) a gap within the margin of error of dating basements (Van Andel, Bukry, 1973 ; Shih, 1980) correlation appears to be in agreement with oldest sediment ages.

A K-Ar age determination on the youngest pillow basalt at site 443 (Table 2) gave a K-Ar age of 17.2 ± 3.2 MY, which is in agreement with Shih's (1980) magnetic anomaly determination for that site. The error in the age determination is large enough, however, that this correlation must be accepted with caution.

Summary

Identification of the age of the sea floor of the Shikoku Basin hinges on interpretation of the ages of the oldest sediment and interpretation of magnetic anomalies. Shikoku Basin, like many back-arc basins of the western Pacific, shows complex magnetic anomaly patterns, topography, and geology. Although all workers now agree that the magnetic anomaly pattern is lineated, disagreement remains concerning the interpreted magnetic anomaly ages in the east half of the basin. Results of drilling during Leg 58 eliminated the single-limb model of basin evolution but did not resolve whether the magnetic anomaly pattern is asymmetrical in age disposition (Kobayashi, Isezaki, 1976 ; Kobayashi, Nakada, 1977 ; 1978) or symmetrical (Shih, 1980).

Our paleontological age determinations of the oldest sediment are in agreement with magnetic anomaly age determinations on the west side of the basin (site 442) but ambiguous on the east side (sites 443 and 444). The apparent reason for this ambiguity is that off-ridge volcanism was more extensive on the eastern side. Intrusive igneous activity has obscured contact relations ; at both sites 443 and 444, the oldest sediment overlies sills, but at site 443 these sills in turn overlie pillow basalts. Calibration of magnetic anomaly determinations by paleontological dating of the oldest sediment in a borehole will prove successful only if the oldest sediment conformably overlies basalt emplaced during basin spreading.

Shih (1980) made a strong case for correlating the 14 to 15 MY age of the oldest sediment with magnetic anomaly 5D (16 to 17 MY) for sites 443 and 444 on the grounds that the approximate 2 MY age gap between paleontological and magnetic ages is reasonably close. That argument fits an evaluation of "so-called basement" ages for dating ocean crust by van Andel and Bukry (1973) who demonstrated that for nannofossil zones, a million-year margin of error is common. K-Ar dating of the youngest pillow basalt below the sill at site 443 yields a 17.2 ± 3.2 MY age and supports Shih's argument, although the error is perhaps too large to provide precise resolution of the problem. With the data at hand, neither dating method can resolve whether a symmetrical or an asymmetrical spreading model applies to the Shikoku Basin.

Dick *et al.* (1980), Wood *et al.* (1980), Marsh *et al.* (1980) and Nisterenko (1980 *a*) concluded that the basalts of the Shikoku Basin are mostly of mid-ocean ridge derivation and composition, although alkaline island arc basalts were both

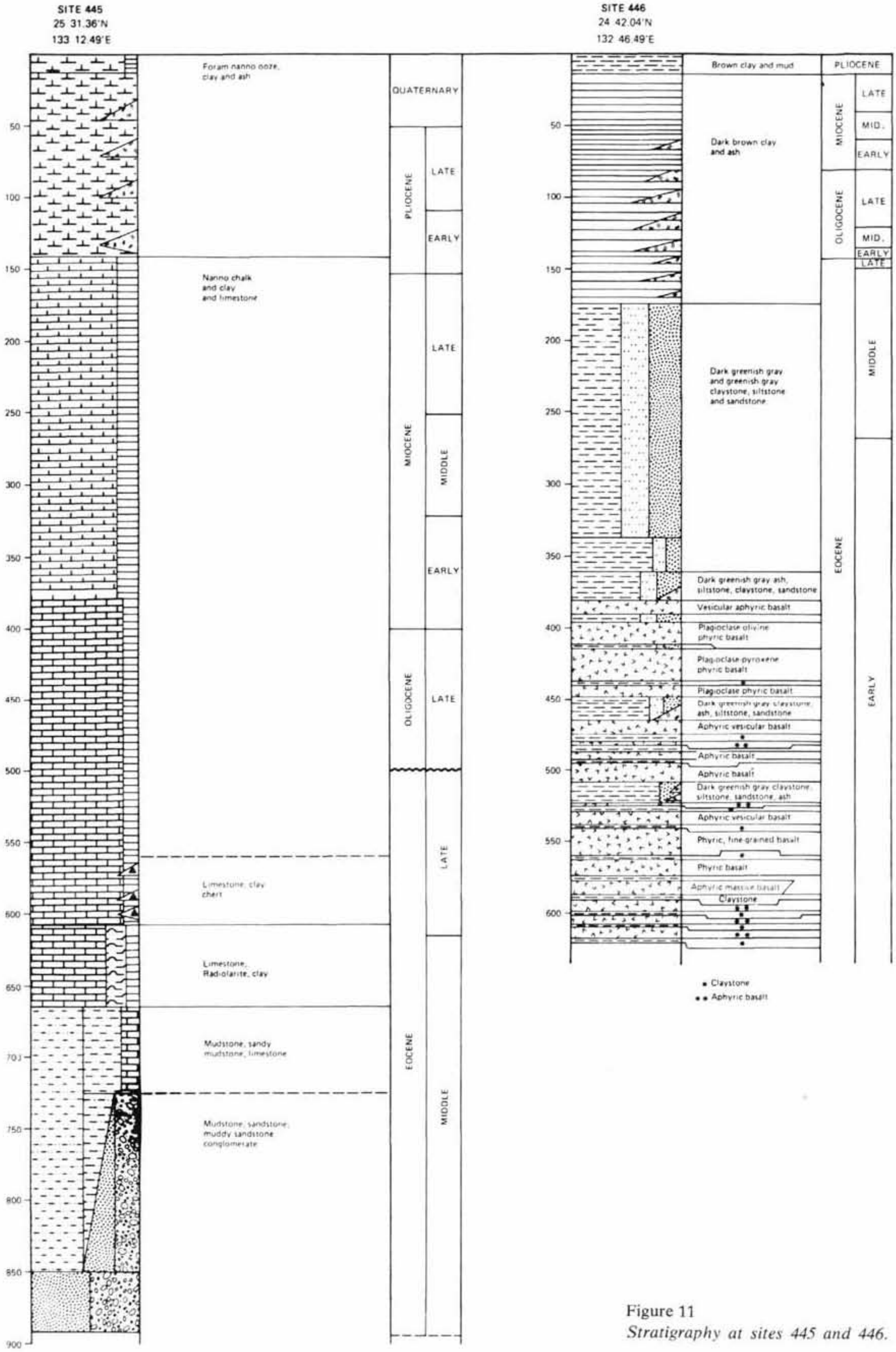

Figure 11
Stratigraphy at sites 445 and 446.

extruded and intruded during spreading-center and off-ridge volcanic events. During active spreading, pillow basalts were extruded onto the ocean floor, whereas intrusive off-ridge volcanism occurred during later stages of spreading and for about 1 to 5 MY after spreading ceased. Off-ridge volcanism occurred at the same time as regional tectonic uplift and igneous intrusive events in southern Japan (Oba, 1977) so all these events are most likely related to broader regional tectonic changes. The chemical variation observed in the Shikoku Basin basalts (Marsh *et al.*, 1980 ; Wood *et al.*, 1980) could be due to the sudden access to the surface of differing magmas along newly defined regional fracture systems during such post-spreading regional tectonic events.

DAITO RIDGE AND BASIN PROVINCE (DRBP)

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

The stratigraphy at sites 445 and 446 is nearly identical (Fig. 11). The basal part of the section consists of interbedded volcaniclastic mudstone, siltstone, turbidite sandstone, and debris-flow conglomerate. These are overlain by resedimented pelagic foraminifera nonoplankton ooze, chalk, and limestone at site 445, and pelagic clay at site 446. The volcaniclastic sediments at site 446 are intruded by at least 26 basalt sills.

Although no seismic refraction data are available from the Daito Ridge, it appears also to be a remnant arc, because dredge hauls there recovered igneous and metamorphic rocks similar to those from island arcs (Mizuno *et al.*, 1975 ; Shiki *et al.*, 1977). The dredge hauls contained andesite, basalt, hornblende, schist, and granodiorite. In addition, conglomerate recovered from a sub-bottom depth of 700 to 892 m at site 445 included clasts of basalt, andesite, rhyolite, and hornblende schist (Nisterenko, 1980 *b* ; Tokuyama *et al.*, 1980 ; Mills, 1980), 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 is distinct from those recovered in the Ryuku Islands west of the DRBP. Dissimilarity of species thus precludes their transport by turbidity currents and debris flow from the west and indicates that our samples of *Nummulites* were transported by gravity processes from local ridges such as the Daito and Oki-Daito Ridge.

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. Subsequently it subsided about 1,500 m to its present depth. Isotopic ages of igneous rocks obtained by drilling during Legs 31 and 58 of the Deep Sea Drilling Project and dredge hauls (McKee, Klock, 1980 ; Ozima *et al.*, 1977) indicate that this province (including the Amami Plateau) may be one of the oldest parts of the Philippine Sea (Fig. 12). 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 MY with a spreading center approximately near the present Central Basin fault. If these ages are correct, the

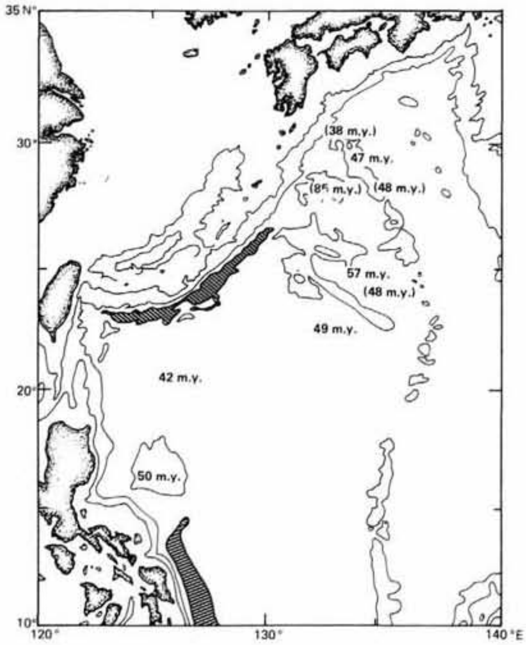

Figure 12
Ages of igneous rocks in Daito Ridge and Basin province. Numbers in parentheses show ages determined by K-Ar method ; numbers without parenthesis indicate ages obtained by ^{40}Ar-^{39}Ar method.

DRBP was formed before and during the opening of the west Philippine Basin.

Louden (1977) measured the paleomagnetic inclination of sediment cores from DSDP Leg 31 and demonstrated that site 292 on the Benham Rise migrated from the southern hemisphere since at least 42 MY. If his results are plotted together with Kinoshita's (1980 *a*, *b*) data from Leg 58, and assuming a southern hemisphere location of the DRBP in the early Eocene, both curves (Fig. 13) of paleolatitude migration are consistent, although the DRBP and the Benham Rise are at present approximately 1,000 km apart and the latter is located south of the Central Basin fault.

Louden's analysis of skewness in marine magnetic anomalies 12 to 21 (40 to 50 MY) in the southern part of the west Philippine Basin also indicate an origin at a low southern latitude for that part of the basin. The phase shifting of

Figure 13
Paleolatitude of sites 445 and 446 compared to site 292 since Eocene (after Louden, 1977).

anomalies also suggests a clockwise rotation of about 55° between the Philippine Basin and the magnetic pole after the anomalies formed (Louden, 1977).

All of this evidence indicates that the west Philippine Basin and the DRBP migrated northward 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 recovered from site 446 (Dick *et al.*, 1980) indicates that these rocks are similar to those in part of the igneous basement at site 444 in the Shikoku Basin. This finding suggests that the site 446 basalts were formed also by off-ridge volcanism in the Daito back-arc basin, although an island-arc origin, magmatic activity at site 446 was caused by subduction below the DRBP because magma both beneath the back-arc basin and under the island arc was supposedly derived from a subducted slab (Karig, 1971 ; Ida, 1978).

We propose a possible model to illustrate the evolutionary history of the DRBP since about 60 MY from prior work and Leg 58 drilling results. This explanation includes a solution for the direction of the paleosubduction zone. As shown in Figure 14 *a*, the DRBP migrated northward with the spreading of the west Philippine Basin starting about 60 MY ago. The northern oceanic plate was being subducted under the DRBP 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 formed the Daito Basin and occurred between the Daito and northern Kyushu-Palau Ridges (Watts *et al.*, 1977 ; Isezaki, Miki, 1978). The existence of linear magnetic anomalies seems to support a spreading origin for the basin. However, data are still insufficient to identify the anomalies in that basin, and no alignment was 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 paleo-trench, 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), whereas migration of the northwest Pacific plate (10 to 15 cm/yr before 40 MY from paleomagnetic evidence if a southern hemisphere origin of the DRBP is assumed) occurred later. 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 Hilde *et al.* (1977) discussed later.

About 40 mY, probably soon after the opening of the west Philippine Basin ceased, the whole region including the west Philippine Basin and the DRBP rotated clockwise ; this rotation may have been accompanied by the formation of the Philippine Trench and the creation of the Caroline plate. After rotation, both the northern and southern parts of the Kyushu-Palau Ridge were facing the west-northwest motion of the Pacific plate, which began about 42 MY ago. The Kyushu-Palau Ridge became part of a trench complex with westward subduction (Fig. 14 *b*). Most of the igneous rocks found at the crest of the Kyushu-Palau Ridge (except granodiorite older than 42 MY) 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 then changed into a remnant arc and subsided after 28 MY as indicated by the sedimentary section at site 296 on that ridge (Karig, Ingle *et al.*, 1975).

Acknowledgements

The Deep Sea Drilling Project is supported by the National Science Foundation through its grant NSF-C482. Klein was responsible for the section on the Shikoku Basin, and Kobayashi for the section on the DRBP. The interpretations were developed jointly. We thank our shipboard colleagues for their data as well as their discussion of this regional geologic summary on board ship and later. We thank E. H. McKee, US Geological Survey, Menlo Park, CA., for the K-Ar age determination of sample 443-57-2. The senior author completed this manuscript while at the University of Chicago as a Visiting Exchange Professor of Geophysical Sciences, sponsored by the Committee on Interinstitutional Cooperation, and thanks that institution for space and facilities. J. R. Kirkpatrick and D. K. Rea reviewed an earlier version of this paper.

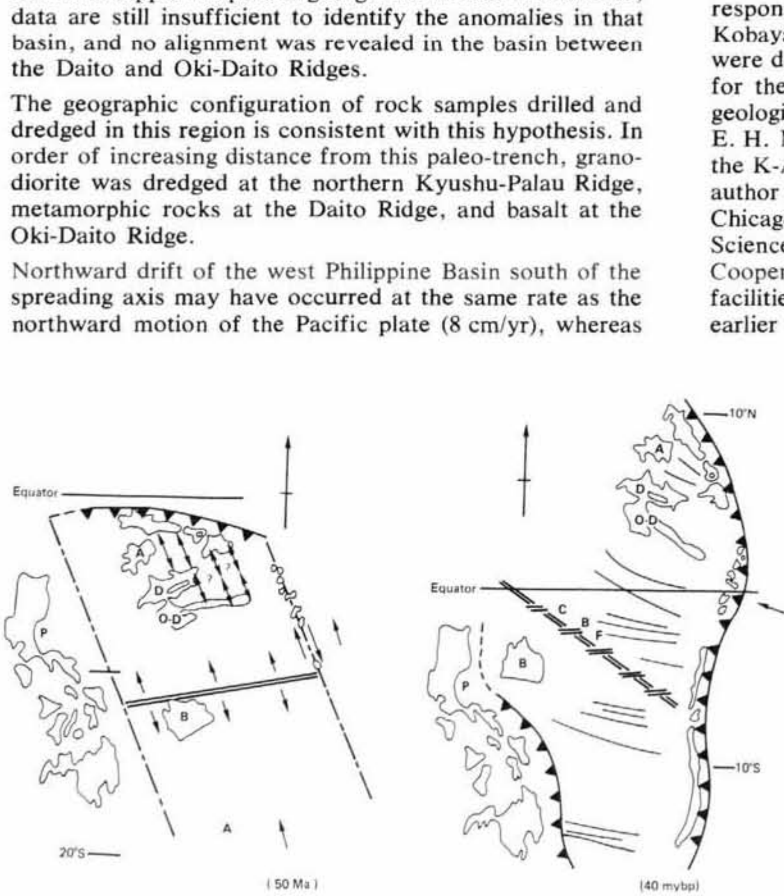

Figure 14
Interpretation of evolution of Daito Ridge and Basin province and northwestern Philippine Basins (a) *50 MY ;* (b) *40 MY, Abbreviations : A, Amami Plateau ; D, Daito Ridge ; O-D, Oki-Daito Ridge ; B, Benham Rise ; P, Philippines ; CBF, Central Basin fault.*

REFERENCES

Chamley H., 1980 *a*. Clay sedimentation and paleoenvironment in the Shikoku Basin since the Middle Miocene (Deep Sea Drilling Project Leg 58, North Philippine Sea), in : *Initial Reports of the Deep Sea Drilling Project*, edited by G. deV. Klein, K. Kobayashi *et al.*, Washington, US Gov. Print. Off., **58**, 669-682.

Chamley H., 1980 *b*. Clay sedimentation and paleoenvironment in the area of the Daito Ridge (Northwestern Philippine Sea) since the early Eocene, in : *Initial Reports of the Deep Sea Drilling Project*, edited by G. deV. Klein, K. Kobayashi *et al.*, Washington, US Gov. Print. Off., **58**, 683-692.

Dick H. J. B., 1980. Vesicularity of Shikoku Basin basalt : a possible correlation with the anomalous depth of back-arc basins, in : *Initial Reports of the Deep Sea Drilling Project*, edited by G. deV. Klein, K. Kobayashi *et al.*, Washington, US Gov. Print. Off. **58**, 845-904.

Dick H. J. B., Marsh N. G., Bullen T. D., 1980. Deep Sea Drilling Project Leg 58 abyssal basalts from the Shikoku Basin : their petrology and major-element geochemistry, in : *Initial Reports of the Deep Sea Drilling Project*, edited by G. deV. Klein, K. Kobayashi *et al.*, Washington, US Gov. Print. Off., **58**, 843-872.

Hilde T. W. C., Uyeda S., Kroenke L., 1977. Evolution of the western Pacific and its margins, *Tectonophysics*, **38**, 145-165.

Ida Y., 1978. Oceanic crust in the dynamics of plate motion and back-arc spreading, *J. Phys. Earth.*, **26**, S55-S67.

Isezaki N., Miki H., 1978. A compilation of magnetic data in the northwestern Pacific and in the north Philippine Sea, *J. Phys. Earth*, **26**, S403-S407.

Karig D. E., 1970. Ridges and basins of the Tonga-Kermadec Island Arc System, *J. Geophys. Res.*, **75**, 238-254.

Karig D. E., 1971. Origin and development of marginal basins in the western Pacific, *J. Geophys. Res.*, **76**, 2542-2561.

Karig D. E., 1975. Basin genesis in the Philippine Sea, in : *Initial Reports of the Deep Sea Drilling Project*, edited by D. E. Karig, J. C. Ingle *et al.*, Washington, US Gov. Print. Off., **31**, 857-880.

Karig D. E., Moore G. F., 1975. Tectonically controlled sedimentation in marginal basins, *Earth Planet. Sci. Newslett.*, **26**, 233-238.

Karig D. E., Ingle J. C. et al., 1975. *Initial reports of the Deep Sea Drilling Project*, Washington, US Gov. Print. Off., **31**, 927 p.

Kinoshita H., 1980 *a*. Paleomagnetism of sediment cores from Deep Sea Drilling Project Leg 58, Philippine Sea, in : *Initial Report of the Deep Sea Drilling Project*, edited by G. deV. Klein, K. Kobayashi *et al.*, Washington, US Gov. Print. Off., **58**, 765-768.

Kinoshita H., 1980 *b*. Details of magnetic-polarity transitions recorded in sediment cores from Deep Sea Drilling Project Site 445, Philippine Sea, in : *Initial Reports of the Deep Sea Drilling Project*, edited by G. deV. Klein, K. Kobayashi *et al.*, Washington, US Gov. Print. Off., **58**, 769-776.

Klein G. deV., Kobayashi K., Chamley H., Curtis D. M., Dick H. J. B., Echols D. J., Fountai D. M., Kinoshita H., Marsh N. G., Mizuno A., Nisterenko G. V., Okada H., Sloan J. R., Waples D. M., White S. M., 1978. Offridge volcanism and seafloor spreading in the Shikoku Basin, *Nature*, **273**, 746-748.

Kobayashi K., 1980. Underway geophysical data, Deep Sea Drilling Project Leg 58, from Yokohama, Japan, to Naha, Okinawa, in the north Philippine Sea, in : *Initial Reports of the Deep Sea Drilling Project*, edited by G. deV. Klein, K. Kobayashi *et al.*, Washington, US Gov. Print. Off., **58**, 943-948.

Kobayashi K., Isezaki N., 1976. Magnetic anomalies in the Sea of Japan and the Shikoku Basin : possible plate tectonic implications, in : *The geophysics of the Pacific Ocean Basin and its margin*, edited by G. H. Sutton, M. H. Manghnani and R. Moberly. *Am. Geophys. Union Monogr.*, **19**, 235-251.

Kobayashi K., Nakada M., 1977. Local magnetic anomaly profiles, Shikoku Basin, northwestern Pacific Ocean (map), *Contrib. Geodyn. Proj. Jpn.*, 77-2.

Kobayashi K., Nakada M., 1978. Magnetic anomalies and tectonic evolution of the Shikoku interarc basin, *J. Phys. Earth*, **26**, S391-S402.

LaBreque J. L., Kent D. V., Cande S. C., 1977. Revised magnetic polarity time scale for late Cretaceous and Cenozoic time, *Geology*, **5**, 330-335.

Lawver L. A., Hawkins J. W., 1978. Diffuse magnetic anomalies in marginal basins : their possible tectonic and petrologic significance, *Tectonophysics*, **45**, 323-339.

Louden K. E., 1976. Magnetic anomalies in the west Philippine Basin, in : *The geophysics of the Pacific Ocean Basin and its margins*, edited by G. H. Sutton, M. H. Manghani and R. Moberly, *Am. Geophys. Union Monogr.*, **19**, 253-267.

Louden K. E., 1977. Paleomagnetism of DSDP sediments, phase shifting of magnetic anomalies, and rotation of the west Philippine Basin, *J. Geophys. Res.*, **82**, 2989-3002.

Marsh N. G., Saunders A. D., Tarney J., Dick H. J. B., 1980. Geochemistry of basalts from the Shikoku and Daito Basins, Deep Sea Drilling Project Leg 58, in : *Initial Reports of the Deep Sea Drilling Project*, edited by G. deV. Klein, K. Kobayashi *et al.*, Washington, US Gov. Print. Off., **58**, 805-842.

McKee E. H., Klock P. R., 1980. K-Ar ages of basalt sills from Deep Sea Drilling Project Sites 444 and 446, Shikoku Basin and Daito Basin, Philippine Sea, in : *Initial Reports of the Deep Sea Drilling Project*, edited by G. deV. Klein, K. Kobayashi *et al.*, Washington, US Gov. Print. Off., **58**, 921-922.

Mills W., 1980. Analysis of conglomerates and associated sedimentary rocks of the Daito Ridge, Deep Sea Drilling Project Site 445, in : *Initial Reports of the Deep Sea Drilling Project*, edited by G. deV. Klein, K. Kobayashi *et al.*, Washington, US Gov. Print. Off., **58**, 643-658.

Mizuno A., Okuda Y., Nagumo S., Kagami H., Nasu N., 1979. Subsidence of the Daito Ridge and associated basins, North Philippine Sea, in : *Geological and geophysical investigations of continental margins*, edited by J. S. Watkins, L. Montadert and P. W. Dickerson, *Am. Assoc. Pet. Geol. Mem.*, **29**, 239-243.

Mizuno A., Okuda Y., Tamaki K., Kinoshita Y., Nohara M., Yuasa M., Nakajima M., Murakami F., Terashima S., Ishibashi K., 1975. Marine geology and geological history of the Daito Ridge area, northwestern Philippine Sea, *Mar. Sci.*, **7**, 484-491, 543-548.

Murauchi S., Asanuma T., 1974. Seismic reflection profiles and sonobuoy refraction measurements during GDP-6 to 8 cruises, *Mar. Sci.*, **6**, 23-27.

Murauchi S., Asanuma T., 1977. Seismic reflection profiles in the western Pacific, 1965-1974, Tokyo, *Univ. Tokyo Press*, 232 p.

Murauchi S., Den N., Asano S., Hotta H., Yoshii T., Asanuma T., Hagiwara K., Ichikawa K., Sata K., Ludwig W. J., Ewing J., Edgar N. T., Houtz R. E., 1968. Crustal structure of the Philippine Sea, *J. Geophys. Res.*, **73**, 3143-3171.

Nisterenko G. V., 1980 *a*. Petrochemistry and geochemistry of basalts in the Shikoku basin and Daito Basin, in : *Initial Reports of the Deep Sea Drilling Project*, Philippine Sea, edited by G. deV. Klein, K. Kobayashi *et al.*, Washington, US Gov. Print. Off., **58**, 791-804.

Nisterenko G. V., 1980 *b*. Igneous rocks from the conglomerates of Deep Sea Drilling Project Hole 445, in : *Initial Reports of the Deep Sea Drilling Project*, edited by G. deV. Klein, K. Kobayashi *et al.*, Washington, US Gov. Print. Off., **58**, 659-660.

Ozima M., Kaneoka I., Ujiie H., 1977. 40 Ar-39 Ar age of rocks and development mode of the Philippine Sea, *Nature*, **267**, 816-818.

Rea D. K., 1976 *a*. Changes in the axial configuration of the East Pacific Rise near 6°S during the past 2 my, *J. Geophys. Res.*, **81**, 1495-1504.

Rea D. K., 1976 *b*. Analysis of a fast-spreading rise crest : the East Pacific Rise 9° to 12° South, *Mar. Geophys. Res.*, **2**, 291-313.

Rea D. K., 1977. Local axial migration and spreading rate variations, East Pacific Rise, 31°S, *Earth Planet. Sci. Lett.*, **34**, 78-84.

Rea D. K., 1978. Asymmetric sea-floor spreading and a nontransform axis offset : the East pacific Rise 20°S survey area, *Geol. Soc. Am. Bull.*, **89**, 836-844.

Shih T. C., 1978. Unpubl. Ph. D dissertation, Univ. Texas, Galveston.

Shih T. C., 1980. Magnetic lineations in the Shikoku Basin, in : *Initial Reports of the Deep Sea Drilling Project*, edited by G. deV. Klein, K. Kobayashi *et al.*, Washington, US Gov. Print. Off., **58**, 1017, 783-788.

Shiki T., Aoki H., Misawa Y., 1975. Geological results of recent studies of the Philippine Sea, *Mar. Sci.*, 454-460.

Shiki T., Misawa Y., Konda I., Nishimura A., 1977. Geology and geohistory of the northwestern Philippine Sea with special reference to the results of recent Japanese research cruises, *Mem. Fac. Sci., Kyoto Univ., Ser. Geol. Mineral.*, **44,** 67-78.

Tokuyama H., Yuasa M., Mizuno A., 1980. Conglomerate and sandstone petrography, Deep Sea Drilling Project Site 445, Philippine Sea, in : *Initial Reports of the Deep Sea Drilling Project*, edited by G. deV. Klein, K. Kobayashi *et al.*, Washington, US Gov. Print. Off., **58,** 629-642.

Tomoda Y., Kobayashi K., Segewa J., Nomura M., Kimura K., Saki T., 1975. Linear magnetic anomalies in the Shikoku Basin, northeastern Philippine Sea, *J. Geomag. Geoelectr.*, **28,** 47-56.

Uyeda S., Miyashiro A., 1974. Plate tectonics and the Japanese Islands, *Geol. Soc. Am. Bull.*, **85,** 1159-1170.

Van Andel Tj. H., Bukry D., 1973. Basement ages and basement depths in the eastern Equatorial Pacific from Deep Sea Drilling Project Legs 5, 8, 9, and 16, *Geol. Soc. Am. Bull.*, **84,** 2361-2370.

Watanabe T., Langseth M. G., Anderson R. N., 1977. Heat flow in back-arc basins of the western Pacific, in : Island arcs, deep sea trenches and back-arc basins, edited by M. Talwani and W. C. Pitman III, *Am. Geophys. Union, Maurice Ewing Ser.* 1., 137-161.

Waples D. W., Sloan J. R., 1980. Carbon and Nitrogen profiles in deep-sea sediments : new evidence for bacterial diagenesis at great depths of burial, in : *Initial Reports of the Deep Sea Drilling Project*, edited by G. deV. Klein, K. Kobayashi *et al.*, Washington, US Gov. Print. Off. **58,** 745-754.

Watts A. B., Weissel J. K., 1975. Tectonic history of the Shikoku marginal basin, *Earth Planet. Sci. Lett.*, **25,** 239-250.

Watts A. B., Weissel J. K., Larson R. L., 1977. Sea-floor spreading in marginal basins of the western Pacific, *Tectonophysics*, **37,** 167-181.

White S. M., Chamley H., Curtis D. M., deVries Klein G., Mizuno A., 1980. Sediment synthesis : Deep Sea Drilling Project Leg 58, Philippine Sea, in : *Initial Reports of the Deep Sea Drilling project*, edited by G. deV. Klein, K. Kobayashi *et al.*, Washington, US Gov. Print. Off., **58,** 963-1014.

Wood D. A., Joron J. L., Marsh N. G., Tarney J., Treuil M., 1980. Major and trace element variations in basalts from the north Philippine Sea drilled during deep sea drilling project Leg 58 : comparative study of back-arc basin basalts with lava series from Japan and mid-ocean ridges, in : *Initial Reports of the Deep Sea Drilling Project*, edited by G. deV. Klein, K. Kobayashi *et al.*, Washington, US Gov. Print. Off., **58,** 873-894.