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TECTONIC HISTORY OF THE SHIKOKU MARGINAL BASIN*

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Studies of marine magnetic anomaly data from the Shikoku basin reveal magnetic lineations which strike northwest almost parallel to the trend of the Palau–Kyushu ridge. The lineation pattern is best developed in the western part of the basin and we can confidently identify a sequence of anomalies 7 through 5E between the base of the Palau–Kyushu ridge and the center of the basin. In the eastern part of the basin the basement morphology is rough and complex and magnetic anomalies can not be identified unequivocally. We infer that the Palau–Kyushu ridge and the Izu–Bonin island arc began separating about 27 m.y. B.P. An interval of rapid separation (4.2 cm/yr) occurred between 26 and 22.5 m.y. B.P. which approximately coincides with a period of intense volcanic activity in Japan. The observed magnetic lineation pattern and basement morphology can be best explained if the Shikoku basin formed at a two-limb spreading system during the Late Oligocene to Middle Miocene. Subsequently the eastern half of the basin was disrupted by fractures as the Iwo–Jima ridge collided with the Japanese islands. The accretionary process which formed the crust of the Shikoku marginal basin appears similar to that operating at mid-ocean ridges of the world.

1. Introduction

Marginal basins of the western Pacific Ocean comprise the small semi-enclosed seas which occur behind most island-arc–trench systems. The Phillippine Sea and the region south of Fiji contain a series of these basins which show progressively deeper crust and a general decrease in mean heat flow with distance from the island arc [1–7]. Seismic refraction measurements and petrology of dredged samples indicate that the crust of marginal basins is oceanic in type.

Because most scientists now reject the concept that marginal basins are submerged continental crust, alternative hypotheses for the generation of these features have been proposed. Karig [1–3] and Packham and Falvey [4] proposed that marginal basins are formed during episodes of extension behind island arcs. Sequential intervals of extension during the Cenozoic have caused the series of marginal basins and aseismic ridges (remnant portions of the island arc) to the west of the Izu–Bonin–Mariana and the Tonga–Kermadec island-arc–trench systems. Age differences between successive basins grading away from the island arc have been inferred from heat flow data, crustal depths, sediment distribution and cores as well as from island geology. JOIDES drilling has supported a general age gradient across the Philippine Sea [9,10].

Karig [1,2] and Sclater et al. [5] have proposed that the Mariana Trough and the Lau-Havre basin are presently active extensional features. Additional evidence for this proposal for the Lau-Havre basin comes from the extremely high attenuation of S-waves in the upper mantle behind the Tonga–Kermadec arc [11]. Crustal extension behind island arcs may not, however, explain the formation of all marginal basins. Magnetic lineations which trend at high angles to active or remnant island arcs in the West Philippine basin and the Aleutian basin [12–14] cannot be easily explained by this hypothesis. These observations have led to the suggestion that some marginal basins form by entrapment of oceanic crust when an island-arc–trench system develops in situ [12,14,15].

As in the world's major oceanic basins, the manner of crustal generation behind island arcs may be re-

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flected in magnetic lineation patterns. Although magnetic lineations have been documented in some marginal basins of the western Pacific (Japan Sea – Isezaki and Uyeda [16]; Aleutian basin – Scholl et al. [14]; West Philippine basin – Louden [12]), they have not been convincingly correlated with the geomagnetic reversal time scale. Even though the general ages of the basins have been inferred from geological evidence there has been no detailed determination of the age pattern from magnetic lineations as there has been for the deep ocean floor.

In view of the alternative hypotheses for the origin of marginal basins, we will examine in detail the magnetic lineation pattern in the Shikoku basin, an "inactive" marginal basin behind the Izu–Bonin island arc [2]. We describe a pattern of lineations (Fig. 1) which can partially be correlated confidently with the geomagnetic reversal time scale. It is unlikely that a symmetric spreading pattern is preserved in the basin as proposed recently by Tomoda et al. [17,18]. We discuss the lineation pattern in relation to the history of plate motions in the region of Japan and to the mode of generation of oceanic crust in the basin.

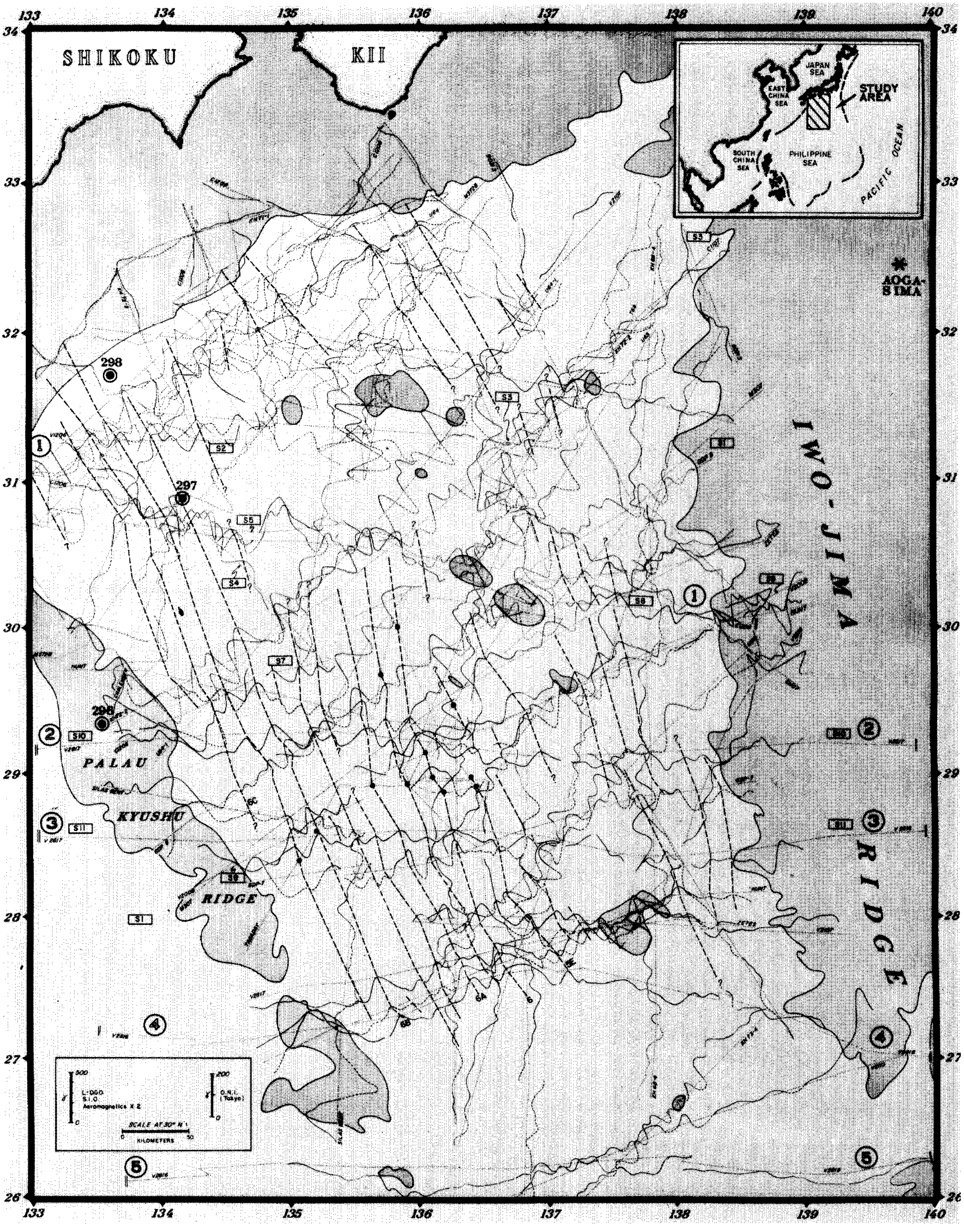
2. Shikoku basin

The Shikoku basin forms a broad depression about 4700 m deep at the northern end of the Philippine Sea between the Izu–Bonin island-arc–trench system and the northern Palau–Kyushu ridge. It is bounded on the north by the Nankai Trough, the site of active underthrusting of the Philippine Sea plate beneath Japan [20–22]. JOIDES drilling results indicate that the Shikoku basin and the eastern Parece Vela basin are both Late Oligocene or younger in age [9,10]. The trend of the Palau–Kyushu ridge changes from north-northeast to north-northwest between 23° and 26°N where the bathymetric map of Chase et al. [19] indicates physiographic trends discordant to the general trend of the Palau–Kyushu ridge. No JOIDES holes have been drilled in the western Parece Vela basin, and thus no conclusive tectonic relationship can be established between this basin and the Shikoku basin to the north.

Seismic refraction measurements [8,22] show that the crust of the Shikoku basin is similar in thickness and velocity structure to oceanic crust in the adjacent Pacific basin. The crust thickens from about 6.9 km beneath the center of the basin to about 14 km beneath the Iwo–Jima ridge and to about 9 km beneath Palau–Kyushu ridge. The sediment layer is relatively thick and stratified in the northern part of the basin (locally exceeding 1.5 km) but decreases markedly in thickness towards the south forming areas of thin and patchy cover (Fig. 2; [22–24]). Generally, the sediments thicken toward the western and eastern margins of the basin where they form a broad and thick sediment wedge behind the Iwo–Jima ridge and a thinner narrower wedge near the base of the Palau–Kyushu ridge (Fig. 2). The velocity in the sediment layer is about 2.0 km/sec at about 29°N in the center of the basin [8] and in the range of 2.0 to 3.1 km/sec at about 31.5°N in the northern part of the basin [22]. The increase in seismic velocity to the north may reflect the increasing proportion of turbidite to pelagic sediments towards Japan.

The morphology of the Shikoku basin increases in roughness and complexity from north to south [23] and in general from west to east (Fig. 2). Due to sediment blanketing the sea floor north of about 30°N is smooth (relief < 50 m) with average depths of about 4600 m. Apparent crustal flexure occurs seaward of the Japanese margin which may be associated with underthrusting of the Philippine Sea plate beneath southwest Japan. Isolated seamounts and groups of seamounts (the Kinan seamounts) occur in the northern and eastern parts of the basin. South of about 30°N the sea floor is more rugged (relief up to 1 km) and depths average about 4800 m. This region shows a contrast in the basement morphologic fabric between the western and eastern parts of the basin (Fig. 2). The eastern part shows a complex horst and graben morphology whereas the western part shows less rugged morphology which slopes uniformly toward the Palau–Kyushu ridge. Harian [23] presented

Fig. 1. Magnetic anomaly profiles along tracks in the Shikoku basin. The sources of data are discussed in the text. Profiles 1–5 are presented in Fig. 3 and profiles S1–S11 in Fig. 5. Heavy dots indicate where correlations have been made on ship's tracks along which magnetic anomaly profiles are not shown. Heavy asterisk indicates a historically active volcano. JOIDES leg 31 drill sites [10] are denoted by circles with solid centers.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IWO-JIMA RIDGE
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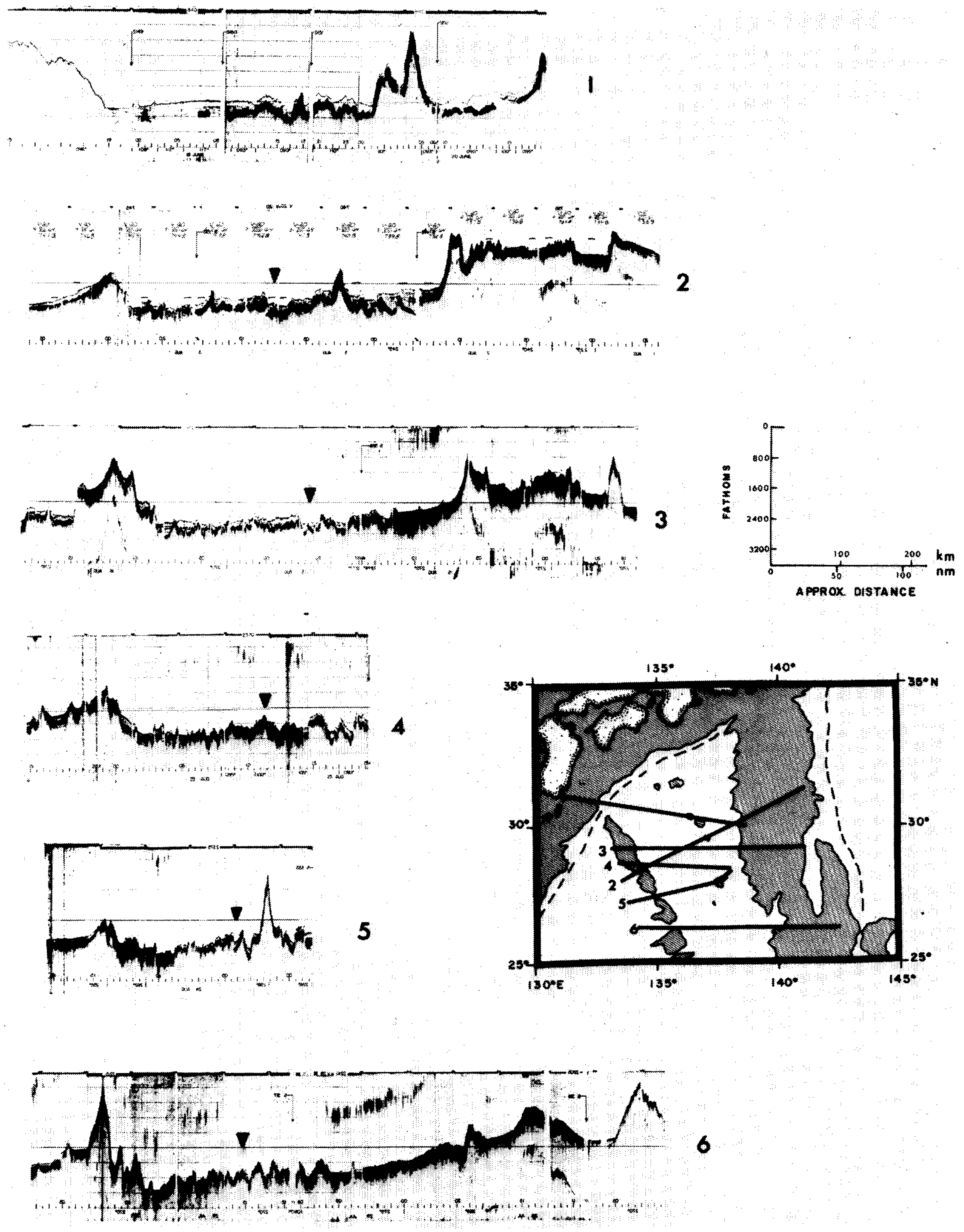

Fig. 2. Seismic reflection profiles across the Shikoku basin. The Palau–Kyushu ridge (Fig. 1) can be seen on the left-hand side of profiles 2–6 and the Iwo–Jima ridge (Fig. 1) on the right-hand side of profiles 2, 3 and 6. Profiles 2–6 clearly show a contrast in the basement morphology between the western and eastern part of the basin. The eastern part shows complex rugged morphology whereas the western part shows less rugged morphology. Solid triangles indicate the position of anomaly 5E, the most easterly well-identified anomaly in the basin. The significance of these observations is discussed in the text.

seismic profiler data from near the center of the basin which show considerable distortion of subbottem reflectors between apparent fault blocks. This may reflect renewed tectonic activity in the Shikoku basin after its formation. Harian notes that the regional morphology of the Shikoku basin in the south often shows a dome-shaped cross-section imposed on a general east to west deepening of the sea floor.

From studies of morphology and sediment distribution, Karig [2,3] suggested that both the Shikoku and Parece Vela basins are inactive marginal basins formed by the rifting apart of the Izu–Bonin–Mariana island arc during the Late Oligocene/Early Miocene. Geological evidence [25] suggests that the Izu–Bonin–Mariana island arc may have formed a continuous arc since the Eocene. Thus, the Palau–Kyushu ridge at the western margin of the basin is an aseismic remnant arc isolated by the rifting process. This is supported by JOIDES site 296 [10] on the Palau–Kyushu ridge which suggests volcanism had terminated on the ridge by the Late Oligocene. Other JOIDES sites in the Shikoku and Parece Vela basins [9,10] have confirmed in a general way the inferred age of the crust.

3. Magnetics data

3.1. Data sources and presentation

This study utilizes total magnetic field intensity data obtained mainly on cruises of Japanese and U.S. research vessels between 1964 and 1973. The principal sources of data are Lamont-Doherty Geological Observatory (L-DGO; Fig. 1), Scripps Institution of Oceanography (SIO; Fig. 1; [26]), and the Ocean Research Institute, University of Tokyo (ORI, Fig. 1; [18]). Included in these data are recent cruises of R/V "Washington" (Tasaday, leg 5; Karig, personal communication) and "Glomar Challenger", leg 31 (Karig, personal communication.). We have also used two aeromagnetic lines obtained by the U.S. Naval Oceanographic Office across the basin. These lines were flown at heights of about 2.0–2.5 km above sea level and are consequently more distant from the sources of magnetization.

We present the magnetics data as magnetic anomaly profiles plotted along track or flight line (Fig. 1) and as selected projected profiles (Figs. 3 and 5). In preparing Fig. 1, the SIO magnetics data from the basin were photographically enlarged and replotted with the L-DGO data at a common scale. The ORI data were photographically enlarged to the same map size but the gamma scale is consequently different from that of the SIO and L-DGO magnetics. We note that photographic enlargement preserves any errors inherent in the original maps and may add some due to distortion in the photographic process.

3.2. Magnetic lineation pattern

As others have noted previously [27,17,18], magnetic anomalies in the Shikoku basin are lineated almost parallel to the north-northwest trend of the Palau–Kyushu ridge. In the western half of the basin we can confidently correlate magnetic anomalies from track to track as shown in Fig. 1. In the eastern and northeastern parts of the basin where the local morphologic relief is greater and seamount groups occur [23]; Fig. 2) the magnetic lineations are more difficult to map. However, where tracks intersect in these uncertain areas, magnetic anomalies have greater "wavelengths" along tracks running mostly north–south than on tracks running mostly east–west. We believe, therefore, that although the correlations in the eastern and northeastern part of the basin are less certain, they are nonetheless real.

The inferred lineation pattern in Fig. 1 differs in detail from that proposed by Tomoda et al. [17,18]. and we feel that this is due to several factors. A greater quantity of data is available to us. Uncertainties in ships' positions vary according to whether satellite navigation was used or not. Some of the SIO and most of the L-DGO tracks were satellite navigated. As satellite navigation was not used, except on cruises of the "Hakuho Maru" (KH, Fig. 1), the locations of most ORI data may suffer from large uncertainties. Although Tomoda et al. [18] show a simple pattern of four fracture zones offsetting the magnetic lineations in the basin, seismic data of Harian [23] and Fig. 2 show large areas of rough acoustic basement, thus indicating the actual fracture zone pattern may be much more complex. Because of this complexity, we have not attempted to map a fracture zone pattern for the basin in Fig. 1.

The major point of departure from previous work concerns the identification of the magnetic anomalies

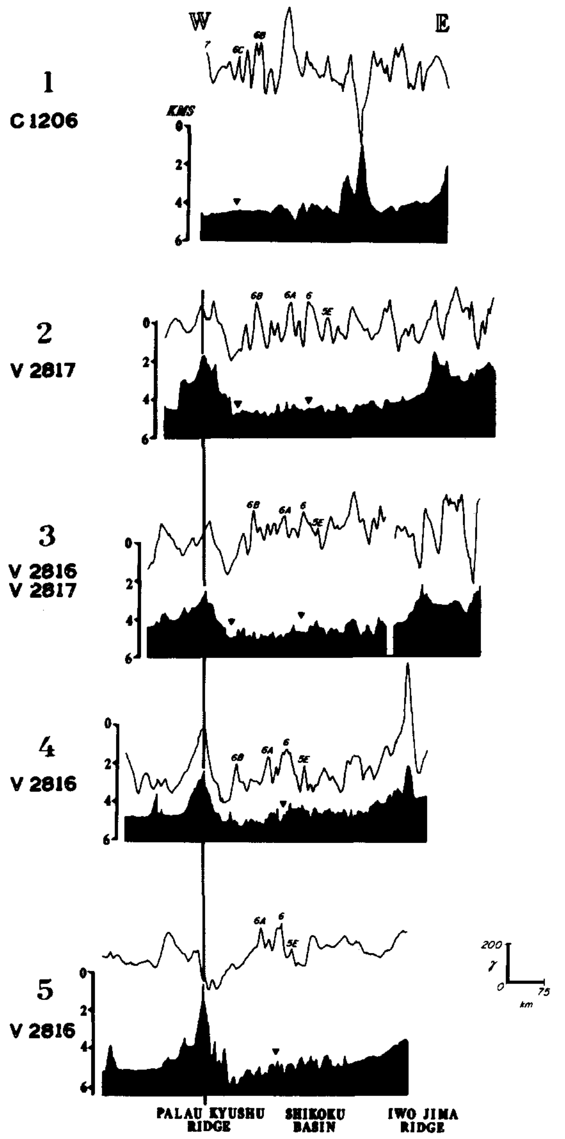

Fig. 3. Magnetic anomaly and topographic profiles across the Shikoku basin (profiles 1–5, Fig. 1). The identification of magnetic anomalies in the western part of the basin is based on the geomagnetic time scale [28–30] and is discussed in the text. The triangles indicate empirical depths based on the global empirical depth against age curve of Hays and Pitman [43]. Note that the western part of the Shikoku basin is generally at least 200–300 m deeper than the empirical depth.

in the Shikoku basin. Tomoda et al. [18] proposed that the magnetic lineations were generated symmetrically between 22.8 and 9.3 m.y. B.P. (corresponding to anomalies 6A through 5 in the Heirtzler et al. [28] and Chase et al. [29] geomagnetic reversal time scale). However, we can confidently identify anomalies 7 through 5E [28–30] in the western part of the basin. Figs. 1, 2 and 3 show that although the east flank of the Palau–Kyushu ridge appears to be step-faulted in a similar manner to some rifted continental margins, anomalies 7 to 6C pinch out in succession from north to south at the base of the ridge. We infer that initial separation of the Palau–Kyushu ridge and the Iwo–Jima ridge proceeded from north to south during the interval from about 27.5 to 25 m.y. B.P.

We note that JOIDES site 297 is situated in the northwestern part of the basin on a lineation that we identify as 6B (Fig. 1). Although basement was not reached at this site, Karig (written communication) predicts an age of earliest Miocene for the sediments at the bottom of the hole. From our interpretation the age of the crust at site 297 is about 24 m.y. B.P. (Late Oligocene according to the time scale of Berggren [32]) which agrees well with Karig's estimate.

Assuming that the sequence of anomalies in the western part of the basin is correctly identified, we can interpret the eastern anomalies as a sequence symmetric about anomaly 5E (~ 19 m.y. B.P.) which is located roughly in the center of the basin or as a continuous sequence getting younger to the east. It is also possible that spreading occurred about a ridge axis which was located in the eastern part of the basin but which cannot now be recognized in morphologic or magnetic profiles.

The choice between these possibilities cannot be made on the basis of magnetic anomaly data alone. Normally in the deep ocean basins magnetic lineation patterns are associated with distinctive morphologic patterns. A basement "axial high" may represent an extinct spreading center, as for example, the extinct ridge axis in the Tasman basin [31]. An axial high in the center of the Shikoku basin is observed ([23]; profile 6, Fig. 2; profiles 4 and 5, Fig. 3), but only in the southern part of the basin. Magnetic anomaly profiles 4 and 5 (Fig. 3), however, do not show a sequence of anomalies which are repeated either side of the axial high. Northward, the axial high diminishes as a topographic feature although its projected extension marks the contrast in morphologic fabric between the east and west parts of the basin seen in profiles 1–6 (Fig. 2). Magnetic anomaly profiles show that the well-lineated and easily identifiable magnetic anomalies 7 through 5E in the western part of the basin (west of the axial high in the south) occur over the smoother basement morphology whereas the uncertain anomaly sequence in the east occurs over rough and complex basement morphology. Therefore, available morphologic and magnetic data apparently exclude the possibility that a simple extinct ridge axis is preserved in the center of the Shikoku basin. Instead the eastern anomalies could represent part of a continuous sequence of anomalies across the basin. Alternatively a two-limb spreading system may have generated crust in the basin but later tectonic activity severely modified the eastern limb disrupting the magnetic lineation pattern and producing the observed rough morphology. Due to this uncertainty we have not identified the eastern anomalies in Figs. 1 and 3 even though we show that a limited pattern of lineations does in fact exist in the eastern part of the basin.

We projected magnetic anomaly profiles along directions perpendicular to the local trends of the lineation pattern. We assumed that the magnetic anomalies across the Shikoku basin are part of a continuous sequence and, while recognizing that this is only one explanation for the data, we computed "half spreading rates" for the basin. All profiles were aligned along the positive anomaly between 6B and 6C and distances to other anomalies were measured from this point. The resulting spreading rate curve shows at least two breaks in slope, and the rates are shown in Fig. 4. To further emphasize our uncertainty in the eastern part of the basin, this portion of the spreading rate curve is broken in Fig. 4. Apparently, in the latest Oligocene

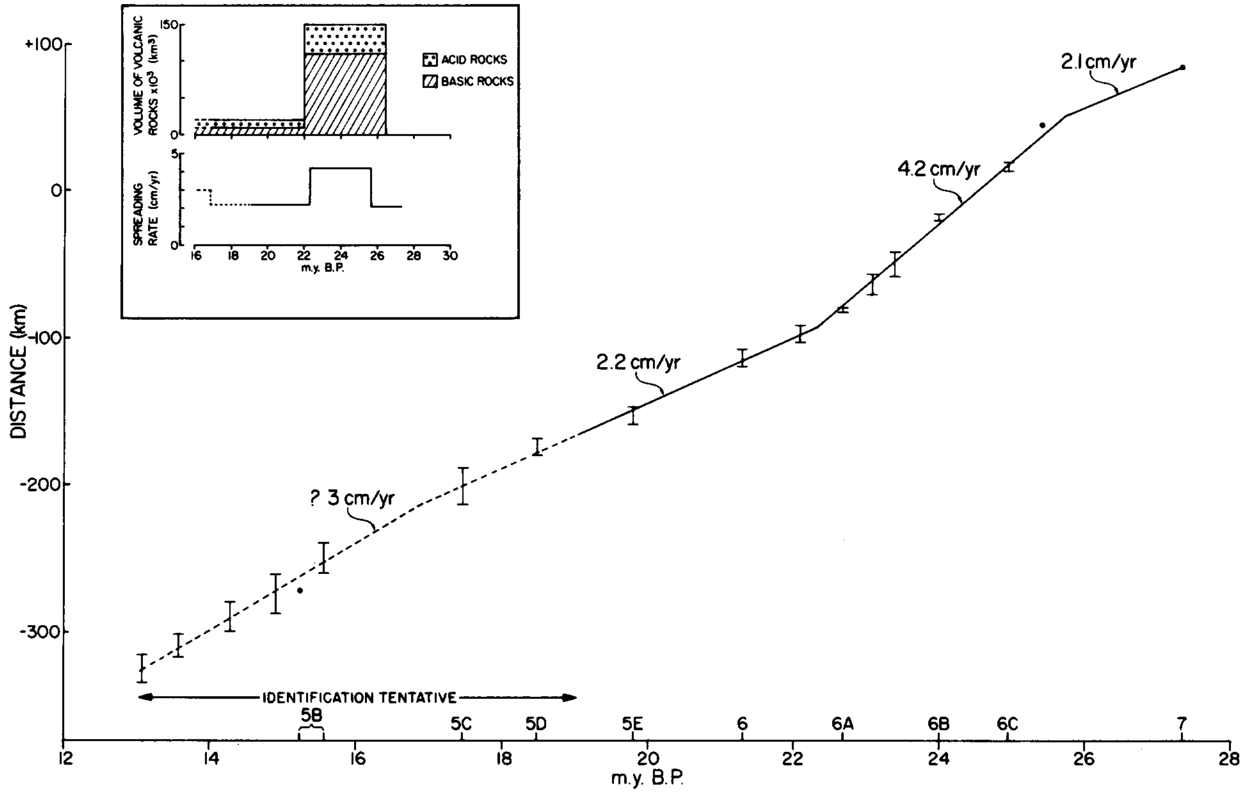

Fig. 4. Spreading rate diagram for the Shikoku basin. The spreading rates have been computed assuming magnetic anomalies in the basin are part of a continuous (one-limb) sequence. The rates shown are analogous to the normal concept of half spreading rates. The inset shows the correlation between spreading rate and volume of volcanic rock production in Japan. The volume estimates of the rocks are from Sugimura et al. [44] and their absolute ages from Chinzei [45]. Note the striking correlation between an increase by a factor of 2 of the spreading rate and a rapid increase in volume of volcanic rocks produced in Japan.

26–22.5 m.y. B.P., the Shikoku basin was opening at a relatively fast rate (4.2 cm/yr) but near the Oligocene/Miocene boundary the spreading rate decreased to almost half (2.2 cm/yr).

3.3. Model studies

To test the validity of our anomaly identifications and calculated spreading rates, we computed theoretical magnetic anomaly profiles for comparison with observed profiles. The model used for the magnetic layer consists of a horizontal lamina divided into vertical-sided blocks which are assumed to be infinitely long parallel to the trend of the magnetic lineations. This is a good assumption if the depth to the blocks is much less than their length. The sequence of blocks in the lamina is determined by spreading rates calculated above and the geomagnetic reversal time scale [28,30].

The parameters required in the computations are the depth to the upper surface of the lamina, the strike of the blocks, the thickness of the lamina, the intensity and direction of the magnetization of the blocks and the ambient geomagnetic field parameters. We assumed a depth to the upper surface of 4.7 km, layer thickness of 0.5 km and a uniform magnetization contrast of 0.0085 emu/cm^3. The layer thickness is similar to that deduced by Talwani et al. [33] and Atwater and Mudie [34] from studies of sea-surface magnetic anomalies across the Reykjanes Ridge and near-bottom magnetic anomalies across the Gorda Rise respectively. Also, the blocks are assumed uniformly magnetized in situ. We invoke this simplifying assumption because of conflicting paleomagnetic results from the Philippine Sea plate [35,36].

We computed the synthetic profiles in Fig. 5 assuming that the observed magnetic anomalies across the basin constitute a continuous one-limb sequences getting younger to the east. The model profiles satisfy the observed data in a general way. However, the "goodness of fit" varies dramatically across the basin. We believe that the model profiles show that anomalies 7 through 5E in the west are correctly identified. These anomalies constitute the first unequivocal identifications of sea-floor spreading-type magnetic anomalies in a marginal basin in the western Pacific. The synthetic profiles fit the eastern anomalies poorly, indicating that a one-limb model may not be correct.

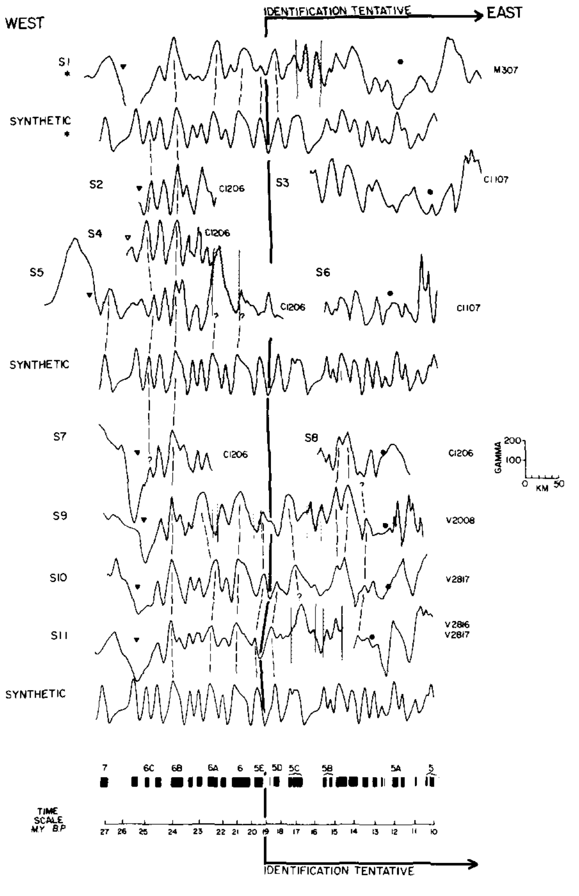

Fig. 5. Selected observed magnetic anomaly profiles across the Shikoku basin compared to computed profiles. The profiles have been projected at azimuths of 68° to 72°. The computed profiles assume magnetic anomalies in the basin are part of a continuous (one-limb) sequence, the geomagnetic time scale [28–30] and model parameters are discussed in the text. The asterisks at the top of the figure denote aeromagnetic profiles. The solid triangles mark the base of the Palau–Kyushu ridge, the solid circles mark the base of the Iwo–Jima ridge.

Even though Fig. 5 shows that anomalies in the eastern part of the basin can not be identified unequivocally, anomalies can be correlated between profiles.

Studies of width and amplitude relations between observed and computed magnetic profiles show that a vertical-sided block model of constant magnetization is unrealistic. Compared to the computed profiles the "narrow" observed anomalies (particularly those between anomalies 6 and 6A and between 6A and 6B) are diminished in amplitude relative to adjacent "wide" anomalies. This probably arises because the boundary separating the model block is not a simple discontinuity but a complex zone of mixed polarities. If the blocks are "narrow" contamination may significantly reduce their bulk magnetization. Similar observations have been made elsewhere in the major ocean basins of the world. The well-developed positive anomaly between anomalies 6B and 6C (Fig. 5) is associated with a geomagnetic event 0.18 m.y. long, corresponding to a block of constant polarity 7.5 km wide for a spreading rate of 4.2 cm/yr (Fig. 4). If the process of accretion occurred over a wider interval than 7.5 km the anomaly would be broad and not easy to recognize in observed profiles. Therefore the processes of accretion (at least in the western part of the basin) occurred over a width less than 7.5 km, similar to widths inferred elsewhere in the major ocean basins [37].

We also examined the magnetic effects of rough basement morphology and seamounts which occur in the eastern half of the basin by modifying the upper surface of the lamina model. We calculated a maximum difference of about 25 γ between the simple lamina model and the model that includes the effect of basement morphology in areas of up to 1 km basement relief. The effects of basement morphology thus contribute in minor ways to the observed profiles and these regions are shaded in Fig. 5.

In Fig. 5 we present a model in which the sequence of magnetic anomalies increases in age from east to west across the basin. We also attempted to match the computed and observed anomalies using a model in which the age distribution is strictly symmetric about the center of the basin. We found that some of the general characteristics of the observed anomalies in the eastern part of the basin could be explained by a two-limb model. For example anomaly ?5C (Fig. 5) on the eastern side could be the counterpart of anomaly 6 on the western side. The two short-duration events between 6B and 6C on the western side could be matched with two short-duration events between ?5B and ?5A on the eastern side. An increase in spreading rate by a factor of about 2 is needed to explain the different distances of anomalies 6 to 6A either side of the assumed center of symmetry. Thus, the observed anomalies in the eastern part of the basin cannot be explained by a strictly symmetric model.

4. Discussion and implications

The inferred Late Oligocene to Early Miocene history of opening of the Shikoku basin correlates in time with tectonic events in the region of Japan. Fig. 4 shows that the inferred pulse of rapid spreading in the basin 26–22.5 m.y. B.P. occurred at about the same time as a period of increased volcanism in Japan. Geological evidence [38] suggests the Nankai Trough (Fig. 6) was a site of underthrusting of the Philippine Sea plate beneath southwest Japan from Early to Late Miocene. Intensely folded Early Miocene sediments now observed along the southern coasts of Kii peninsula, Shikoku, Kyushu and also in the Ryukyu islands [38] may be related to this interval of underthrusting. Thus we infer that part of the newly formed Shikoku basin crust was consumed beneath southwest Japan soon after its formation.

From geomorphological evidence Hoshino [39] suggested that Suruga Bay (Fig. 6) formed after the Late Miocene. Matsuda [40] from studies in the South Fossa Magna area (Fig. 6) suggests that during the Middle to Late Miocene sediments of Early Miocene age were broadly folded. This folding phase was followed during the Pliocene and Pleistocene by strong compression forming broken folds and thursts. We infer from these studies that beginning in the Middle to Late Miocene the Iwo–Jima ridge, which was part of the Philippine Sea plate, approached and collided with Honshu in response to the overal convergence of the Asian and Philippine Sea plates. Seismological evidence indicates [41] that at the present time north–south compression generally exists in the Izu Peninsula and the northern part of the Iwo–Jima ridge. The observed pattern of en echelon northeast–southwest ridges and troughs on the northern part of the Iwo–Jima ridge may have been produced by fracturing in response to this north–south compression [42]. If this fracture pattern extends into the Shikoku basin it may explain the disrupted magnetic lineation pattern and rough basement morphology observed in the eastern part of the basin. Thus, significant "intraplate" deformation may have occurred in the basin contrary to what is observed (or assumed) for ridge flanks in the major ocean basins of the world.

In Fig. 5 we have attempted to match the observed magnetic data with a magnetic block model. The best fitting model based on magnetic data alone is unusual

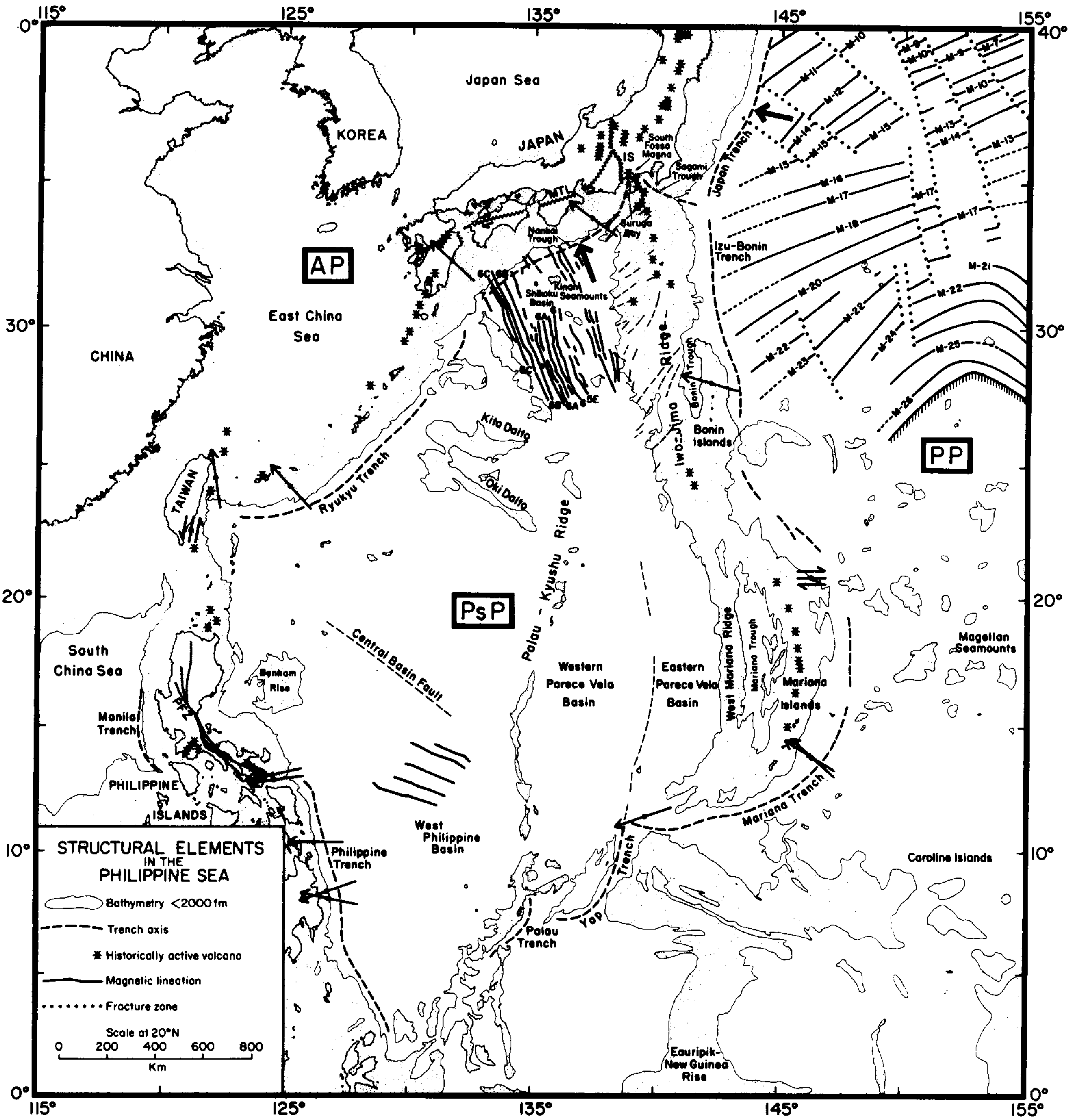

Fig. 6. Structural elements of the Philippine Sea. Solid circles denote shallow earthquakes with thrust-fault or strike-slip focal mechanisms which are interpreted as representing motion between two plates [20]. The inferred direction of relative motion between the Asian (AP) and Pacific (PP) plates [46] and between the Asian and Philippine Sea (PsP) plates [21] are indicated by solid arrows. Magnetic lineations are based on Hilde [47] in the Pacific east of the Izu–Bonin and Japan trenches, on Fig. 1 in the Shikoku basin and unpublished L-DGO and SIO magnetics data in the west Philippine basin. The inferred direction of motion on the Median Tectonic Line (MTL) is from Huzita et al. [48]. Faint broken lines on the northern Iwo–Jima ridge indicate trends of ridges identified by Karig and Moore [42]. IS = Itoigawa–Sizuoka Line [38] and PFZ = Philippine Fault Zone.

as it implies that the tectonic history of the Shikoku basin can be described by a one-limb system of crustal generation. We therefore caution that interpreting magnetic data from the Shikoku basin in terms of the normal concepts of sea-floor spreading and plate tectonics may be incorrect. If other data such as basement morphology (Fig. 2) and the known tectonic history of the surrounding region are taken into account, we conclude that probably a two-limb system generated the Shikoku basin but that significant deformation of the eastern part of the basin has occurred due to the collision and continuing state of compression existing between the Japanese islands and the Iwo–Jima ridge.

Although Packham and Falvey [4] suggest that crust is generated in an asymmetric (one-limb) manner behind island arcs, Karig [2] and Sclater [7] believe that crust accretes at a two-limb system in a similar manner to accretion at mid-ocean ridge systems. We suspect, however, that the thermal regime within a rifting frontal arc would be complex and may be different from thermal regimes associated with spreading ridges. Initially the manner of crustal generation in marginal basins may depend on the proximity of the locus of rifting to the volcanic chain on the island arc. At spreading rates calculated in this paper (Fig. 4) the local thermal regime at the locus of accretion is unlikely to be modified by heat that is conducted horizontally from the active volcanoes of the island arc. We would therefore expect that a two-limb system would be set up in marginal basins soon after initial rifting of the frontal arc. From the study of width and amplitude relations of observed magnetic anomalies we suggest that crust was accreted in the Shikoku basin in a manner similar to processes occurring at mid-ocean ridge systems of the world.

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References

1 D.E. Karig, Ridges and basins of the Tonga–Kermadec island-arc system, J. Geophys. Res. 75 (1970) 239.
2 D.E. Karig, Origin and development of marginal basins in the western Pacific, J. Geophys. Res. 76 (1971) 2542.
3 D.E. Karig, Structural history of the Mariana island-arc system, Geol. Soc. Am. Bull. 82 (1971) 323.
4 G.H. Packham and D.A. Falvey, An hypothesis for the formation of marginal seas in the western Pacific, Tectonophysics 11 (1971) 79.
5 J.G. Sclater, J.W. Hawkins, J. Mammerickx and C.G. Chase, Crustal extension between the Tonga and Lau ridges: petrologic and geophysical evidence, Geol. Soc. Am. Bull. 83 (1972) 505.
6 J.G. Sclater, U.G. Ritter and F.S. Dixon, Heat flow in the southwestern Pacific, J. Geophys. Res. 77 (1972) 5697.
7 J.G. Sclater, Heat flow and elevation of the marginal seas of the western Pacific, J. Geophys. Res. 77 (1972) 5705.
8 S. Murauchi, N. Den, S. Asano, H. Hotta, T. Yoshii, T. Asaruma, K. Hagiwara, K. Ichikawa, R. Sato, W.J. Ludwig, J.I. Ewing, N.T. Edgar and R.E. Houtz, Crustal structure of the Philippine Sea, J. Geophys. Res. 73 (1968) 3143.
9 Scientific Staff, Deep-Sea Drilling Project, Leg 6, Geotimes 14 (1969) 13.
10 Scientific Staff, Deep-Sea Drilling Project, Leg 31, Geotimes 18 (1973) 22.
11 M. Barazangi and B. Isacks, Lateral variations of seismic-wave attenuation in the upper mantle above the inclined earthquake zone of the Tonga island arc: deep anomaly in the upper mantle, J. Geophys. Res. 76 (1971) 8493.
12 K. Louden, Magnetic anomalies in the west Philippine basin (1974) in preparation.
13 Z. Ben-Avraham, C. Bowin and J. Segawa, An extinct spreading centre in the Philippine Sea, Nature Lond. 240 (1972) 453.
14 D.W. Scholl, A.K. Cooper and M.S. Marlow, Magnetic lineations in the Bering Sea marginal basin (abstract), EOS 55 (1974) 232.
15 S. Uyeda and A. Miyashiro, Plate tectonics and the Japanese Islands: a synthesis, Geol. Soc. Am. Bull. 85 (1974) 1159.
16 N. Isezaki and S. Uyeda, Geomagnetic anomaly pattern of the Japan Sea, J. Mar. Geophys. Res. 2 (1973) 51.
17 Y. Tomoda, K. Kobayashi, J. Segawa and N. Nomura, Magnetic anomalies in the Shikoku basin, northern Philippine Sea, IUGG Program and Abstracts for the Second General Scientific Assembly, Kyoto, Japan (1973).
18 Y. Tomoda, K. Kobayashi, J. Segawa, M. Nomura, K. Kimura and K. Saki, Linear magnetic anomalies in the Shikoku basin, northeastern Philippine Sea (1974) in preparation.
19 T.E. Chase, H.W. Menard and J. Mammerickx, Bathymetry of the North Pacific, Scripps Institution of Oceanography and Institute of Marine Resources, Chart Nos. 1–7 (1970).
20 M. Katsumata and L.R. Sykes, Seismicity and tectonics

of the western Pacific: Izu–Mariana–Caroline and Ryukyu–Taiwan regions, J. Geophys. Res. 74 (1969) 5923.

21 T.J. Fitch and C.H. Scholz, Mechanism of underthrusting in southwest Japan: a model of convergent plate interactions, J. Geophys. Res. 76 (1971) 7260.

22 T. Yoshii, W.J. Ludwig, N. Den, S. Murauchi, M. Ewing, H. Hotta, P. Buhl, T. Asanuma and N. Sakajiri, Structure of southwest Japan margin off Shikoku, J. Geophys. Res. 78 (1973) 2517.

23 A.M. Harian, Area XVII, Vol. 3, Bathymetry and Subbottom Profiling, Prepared by Alpine Geophysical Associates, Inc., U.S. Naval Oceanographic Office, N62306-1688 (1968).

24 W.J. Ludwig, N. Den and S. Murauchi, Seismic reflection measurements of southwest Japan margin, J. Geophys. Res. 78 (1973) 2508.

25 H. Tsuya, On the volcanism of the Huzi volcanic zone, with special reference to the geology and petrology of Idu and the southern islands, Bull. Earthquake Res. Inst. Tokyo 15 (1937) 215.

26 T.W. Chase, S.M. Smith, D.A. Newhouse, W.L. Crocker, M. Schoenbechler, L. Hydock and U. Ritter, Track charts of SIO Bathymetric Data and track charts of SIO Magnetic Data in the Pacific Ocean, IMR TR-25 Sea Grant Publ. No. 7, Scripps Institution of Oceanography (1972).

27 R. Vajk, Area XVII, Vol. 4, Magnetics, Prepared by Alpine Geophysical Associates, Inc., U.S. Naval Oceanographic Office, SP-96-XVII-4 (1968).

28 J.R. Heirtzler, G.O. Dickson, E.M. Herron, W.C. Pitman and X. Le Pichon, Marine magnetic anomalies, geomagnetic anomalies, geomagnetic field reversals and motions of the ocean floor and continents, J. Geophys. Res. 73 (1968) 2119.

29 C.G. Chase, H.W. Menard, R.L. Larson, F.G. Sharman and S.M. Smith, History of sea-floor spreading west of Baja California, Geol. Soc. Am. Bull. 81 (1970) 491.

30 R.J. Blakely, Geomagnetic reversals and crustal spreading rates during the Miocene, J. Geophys. Res. 79 (1974) 2979.

31 D.E. Hayes and J. Ringis, Sea-floor spreading in the Tasman Sea, Nature Lond. 243 (1973) 454.

32 W.H. Berggren, Cenozoic time scale: some implications for regional geology and paleobiogeography, Lethaia 5 (1972) 195.

33 M. Talwani, C.C. Windish and M.G. Langseth, Reykjanes Ridge crest: a detailed geophysical study, J. Geophys. Res. 76 (1971) 473.

34 T.M. Atwater and J.D. Mudie, Detailed near-bottom geophysical survey of the Gorda Rise, J. Geophys. Res. 78 (1973) 8665.

35 W. Lowrie, R. Løvlie and N.D. Opdyke, Magnetic properties of Deep-Sea Drilling Project basalts from the north Pacific Ocean, J. Geophys. Res. 78 (1973) 7647.

36 V. Vacquier and S. Uyeda, Paleomagnetism of nine seamounts in the western Pacific and of three volcanoes in Japan; Bull. Earthquake Res. Inst. Tokyo 45 (1967) 815.

37 C.G.A. Harrison, Formation of magnetic anomaly patterns by dyke injection, J. Geophys. Res. 73 (1968) 2137.

38 A. Sugimura and S. Uyeda, Island Arcs: Japan and its Environs (Elsevier, Amsterdam, 1973) 247.

39 M. Hoshino, Relationship between geologic development of the Suruga Bay and the Median Tectonic Line (in Japanese), in: Median Tectonic Line (Tokyo University Press, 1973) 277.

40 T. Matsuda, Crustal deformation and igneous activity in the South Fossa Magna, Japan, Am. Geophys. Union, Monograph 6 (1962) 140.

41 M. Ichikawa, Re-analyses of mechanisms of earthquakes which occurred in and near Japan, and statistical studies on the Nodal plane solutions obtained 1926–1968, Geophys. Mag. 35 (1971) 207.

42 D.E. Karig and G.F. Moore, Tectonic complexities in the Bonin Arc system (1974) in preparation.

43 J.D. Hays and W.C. Pitman III, Lithospheric plate motion, sea-level changes and climatic and ecological consequences, Nature 246 (1973) 18.

44 A. Sugimura, T. Matsuda, K. Chinzei and K. Nakamura, Quantitative distribution of late Cenozoic volcanic materials in Japan, Bull. Volcanol. 26 (1963) 125.

45 K. Chinzei, An attempt for absolute chronology of Neogene in Japan by biostratigraphic correlation, J. Geol. Soc. Japan 73 (1967) 220.

46 X. Le Pichon, Sea-floor spreading and continental drift, J. Geophys. Res. 73 (1968) 3661.

47 T.W.C. Hilde, Mesozoic sea-floor spreading in the North Pacific, Ph. D. Thesis, University of Tokyo (1973).

48 K. Huzita, Y. Kishimoto and K. Shiono, Neotectonics and seismicity in the Kinki Area, southwest Japan, J. Geosci., Osaka City Univ. 16 (1973) 93.