MAGNETIC ANOMALIES AND TECTONIC EVOLUTION OF THE SHIKOKU INTER-ARC BASIN

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Detailed analysis of magnetic anomalies has revealed a clear pattern of symmetric lineations in the Shikoku Inter-arc Basin, northern Philippine Sea. Amplitudes of anomalies are in general a few hundred nannotesla (gammas, peak to peak), which are moderate compared to those of the normal ocean basins accreted from the mid-oceanic ridges and are relatively larger than those of some other inter-arc basins such as the Parece Vela Basin, Mariana Trough and West Philippine Basin. Correlation of anomalies is usually so good that age identification can be convincingly performed except for the axial irregular zone. Mode of opening derived from the distribution of magnetic anomalies as well as the topographic features provides the evolutionary history of the Shikoku Basin in the following manner:

1) The Kyushu-Palau and Shichito-Iwojima Ridges began rifting at their northern end at about 30 mybp. The rifting propagated towards south at a speed of about 10 cm/year.

2) After the whole basin was rifted at about 25 mybp, it continued to open symmetrically from the central spreading axis at a half rate of nearly 4 cm/year until about 22 mybp.

3) In the latest stage of opening the spreading became slower and even irregular. The spreading axis jumped in some parts of the basin. A chain of seamounts was formed and widespread off-ridge intrusions occurred in the eastern portion of the basin.

1. Introduction

The Shikoku Basin south off the Island of Shikoku, southwestern Japan is one of the most typical inter-arc basins ever recognized in the world ocean. It is bordered by the N-S trending Shichito-Iwojima Ridge (active island arc) on the east and by the NWN-SES trending Kyushu-Palau Ridge (remnant arc) on the west. Its northern boundary is the Nankai Trough at which floor of the basin sinks under the Shikoku continental crust (Fig. 1).

The crust of the Shikoku Basin is oceanic in its seismological structure (Murauchi et al., 1968) and characterized by existence of linear magnetic anomalies trending nearly parallel to those of the marginal ridges, as first pointed out by Tomoda et al. (1968, 1975). Watts and Weiszel (1975) postulated a correlation of these magnetic anomalies and discussed a tectonic history of this basin. Kobayashi and Isezaki (1976) summarized geophysical and geological data available at that time and proposed a model of evolution of the inter-arc basins. However, some problems remained unsolved mostly because of lack of very detailed survey in this area of the sea.

Under the aegis of the Geodynamics Project of Japan the total magnetic forces and water depths in the Shikoku Basin have been extensively measured together with seismic reflection profiling along more than twenty parallel tracks crossing the basin roughly vertical to its axis with spacings of 5 to 10 nautical miles. Kobayashi and Nakada (1977)
published a map of magnetic anomaly profiles of this basin using these results along with available data previously collected by other cruises. All tracks surveyed after 1972 were controlled by the satellite navigation fixes and the accuracy of position is usually better than 1 nautical mile. Detailed bathymetric maps were also drawn with results of these cruises. The basin between 27°N and 33°N in latitude was particularly well surveyed.

In this article we will present an identification of magnetic anomalies based upon these newly obtained results. Magnetic structure of the eastern part of the basin, particularly around the Kinan Seamount Chain can be properly understood with our detailed magnetic and bathymetric maps. Some tectonic implications of the results to the evolutionary history of the Shikoku Basin are then postulated.

2. Topographic Features of the Shikoku Basin

Figure 2 represents a topographic map of the basin between 27°40'N and 30°40'N which was contoured by ourselves using bathymetric data along the ships’ tracks the same as used for magnetic analysis. Addition of other results would not substantially change the topography of the basin, as density of the data used for this mapping is sufficiently high. In contrast topography of the Kyushu-Palau and Shichito-Iwojima Ridges in this map is only provisional and should be greatly modified by more detailed survey and collection of additional reliable information.

General topography of this basin clearly indicates a lineated feature trending nearly parallel to the trend of the Kyushu-Palau Ridge. Parallel ridge and trough sequences are distinctly recognized in the basin having an average water depth of about 4,500 m. Maximum water depth of troughs exceeds 5,500 m, while the crests of ridges are shallower than 4,000 m. It is thus implied that this basin was formed under an extensional stress perpendicular to its linear trend, as postulated by KARIG (1971a, b) with the Parece Vela Basin and the Mariana Trough.

Distribution of sediments revealed by seismic reflection profiling along the same survey tracks has been published by MURAUCHI and ASANUMA (1977). Thickness of sediment cover decreases towards the south and generally amounts to 300 to 500 m in the central zone of the basin except for small sediment ponds. There exist thick sediment wedges on both margins of the basin. A multichannel seismic profile between 29°29'N,
Fig. 2. A detailed topography of the Shikoku Basin between 27°40'N and 30°40'N. Contour interval: 2,500 m.

Fig. 3. Seismic reflection profile of the Shikoku Basin nearly perpendicular to the basin axis. Survey by Kaiyo-Maru of the Japan Petroleum Exploration Co., Ltd. (IPOD-JAPAN, 1977). Unprocessed record.

137°49'E and 28°52'N, 135°40'E (IPOD-JAPAN, 1977) shows that the sediment structure in the central zone of the basin is generally concordant with the morphology of acoustic basement so that study of bottom topography alone would reveal tectonic patterns of the basin formation. No evidence of the present tectonic activity of the basin is seen in the profile (Fig. 3), although apparently deformed sediment reflectors in the lower levels of layer one above the acoustic basement may possibly indicate some tectonic movement after the formation of the basin.

A chain of seamounts called the Kinan Seamount Chain occurs in the eastern part of the central zone in the basin, as seen in Fig. 2 and other topographic maps. Some of the
Source of DATA

shown in INDEX MAP
as below

--- JAPANESE VESSELS
HAGYO-MARU
UKITA-MARU
ROSEI-MARU
TANSEI-MARU

--- U.S. VESSELS
VEMA
CORMOR
GLOMAR CHALLENGER (Leg 37)

Fig. 4. Magnetic anomaly profiles in the Shikoku Basin used for the present analysis (KOBAYASHI and NAKADA, 1977).
seamounts, for example, one located at 30°15'N, 136°40'E: Daini-Kinan Seamount and one at 28°00'N, 137°40'E: Hakuho Seamount (tentative name) are as large as those occurring in the Mid-Pacific seamount region. Apparently the seamounts in the Shikoku Basin compose a chain roughly parallel to the trend of the basin but the topographic highs are not so continuous as those in the mid-oceanic ridges. Each seamount is separated from the adjacent ones by deep moats to form segmented alignment of topographic highs. Their crests are not located on the geometric axis of symmetry of the basin but are appreciably off-centered towards the eastern margin.

A large boulder of pillow basalt was collected by dredge haul from the crestal area of the Hakuho Seamount. Chemical and mineralogical composition of the rock indicates that it is quite similar to that of the abyssal tholeiites (Tokuyama and Fujioka, 1976) and different from rocks derived from hot spots and island-arc volcanoes. The origin of the Kinan Seamount Chain should therefore be explained as a specific stage of seafloor spreading in the Shikoku Basin. Fossils of nannoplankton contained in the ferromanganese coating and vesicles of the rock sample have been identified to be of late Middle Miocene (12–14 mybp), which provides the minimum age limit of eruptions at the Hakuho Seamount (Uchio, private communication).

3. Magnetic Lineations

Our magnetic analysis wholly relies upon a recently published 1/1,000,000 map of magnetic anomaly profiles of the Shikoku Basin (Kobayashi and Nakada, 1977, Fig. 4). As the spacing of two adjacent profiles is generally less than 10 nautical miles which is much shorter than wavelengths of the local magnetic anomalies, profile to profile correlation of magnetic anomalies can convincingly be done.

Figure 5 shows six selected profiles of anomalies projected on a line perpendicular to the trend of the basin. Their correlation with a model profile simulated using standard polarity time scale (Blakely, 1974; Labrecque et al., 1977) between 18.5 and 27 mybp is also shown on an assumption of two-limb symmetric spreading. Correlation is generally satisfactory. Characteristic shapes of anomaly 6, 6A and 6B can be identified on both sides of the basin.

In the southwestern portion of the surveyed area the lineation pattern and age identification proposed by Watts and Weissel (1975) seem to be the most acceptable. In
this article we further extended it towards north with additional data. No fracture zones offsetting these lineations can be recognized. Magnetic anomalies in the eastern portion of the basin are somewhat irregular but still correlatable in the areas where magnetic observations on sufficiently close survey tracks are available. Correlation of anomalies without offsets seems to be also possible in this zone.

The most complex is the east-central zone surrounding a chain of seamounts and associated moats. In addition to localized magnetic anomalies caused by topography of seamounts, magnetic lineations seem to be disrupted in some places in this zone. A detailed survey was carried out in a 1° × 1° rectangular area surrounding the Hakuho Seamount. A couple of positive and negative circular anomalies is superimposed on the linear magnetic anomalies around the crest of the seamount. If this couple of positive and negative anomaly circles is due to magnetization of the seamount, overall direction of magnetization of this seamount is reversed with moderate inclination. The reversed polarity of rock is quite likely to occur because the crest of seamount is situated in a linear strip of negative magnetic anomaly.

Correlation of adjacent linear anomalies appears to be still possible, if the survey is so much in detail. Magnetic lineations in an area surrounding the seamount are segmented by right-lateral faults trending NE-SW. Amount of offset is about 20 to 30 km. The same size of offset can be found in the basement topography near the seamount. It must be noted that neither magnetic nor topographic offset is extended to the marginal zones of the basin. The faults are truncated at the boundaries between the central zone and both margins defined by linear anomalies.

Figure 6 represents aerial distribution of magnetic isochrons in the Shikoku Basin thus postulated. This pattern differs from the previously proposed ones in a point that
the fractures are existent only in the central zone. Anomalies on both margins can be smoothly correlated and seem to be symmetric in respect to the geographic axis of symmetry of this basin, as far as the proposed identification of anomaly is valid. T.-C. Shih postulated similar patterns of fracture zones (private communication, 1977), although his identification of anomalies is different from that proposed here.

According to the present identification of anomalies anomaly 6' (approximately 22 mybp) is the boundary between undisrupted margins and fractured center. In the fractured center anomalies are hardly identifiable and appear to be asymmetric. Assuming that there existed no hiatus in opening of the basin, the youngest isochron may be anomaly 5D (17 mybp) or 5C (16 mybp). Presumed axis of symmetry for these anomalies is, in some parts, off-centered from the geometrical axis of the basin. Tectonic significance of this catastrophic jump of spreading axis in the inter-arc basin will be discussed in a later section of this paper.

In both margins of the Shikoku Basin anomalies 7 to 6C pinch out in succession from north to south, as Watts and Weisell (1975) pointed out with the western margin only. We confirmed that the same configuration of anomalies occur in the eastern margin as well. Such a pattern of anomalies indicates that the basin began opening at its northern end and the rifting propagated longitudinally from north to south with a rate of approximately 10 cm/year.

Except for these margins and fractured center, rate of spreading are quite uniform on both sides of the axis. Distances of identifiable anomalies from the geometrical axis of the basin versus magnetic ages of anomalies are shown in Fig. 7. Half spreading rates are 4 to 6 cm/year between 26 and 22 mybp and decrease to about a half (2-3 cm/year)
in the later stage. Rates after 18 mybp (anomaly 5E) seem to be variable with time and space.

Spreading rates in the southern portion (around 27°N) are nearly equal to those in the northern part of the basin within a statistical fluctuation. This result indicates that separation of two ridges is essentially a parallel movement relative to each other. On a sphere such a motion is equivalent to a rotation around a pole 90 degree far from the sites.

4. Alternative Models for Opening of the Shikoku Basin

WATTS and WEISSEL (1975) once postulated a one-limb spreading model to explain the magnetic lineations in the Shikoku Basin. Simulated anomalies based upon the one-limb model are reproduced and compared with those calculated from the present model in Fig. 8. Apparently correlation of simulated anomalies with observed ones appears to be also good in one-limb model, since the pattern of magnetic reversals between 18 and 11 mybp is, just by chance, similar to the mirror image of the reversal pattern occurring between 26 and 18 mybp. It is hard to judge which model is better fitted to the observed pattern by anomalies alone.

Paleontological age of the lowest recovered sediments obtained at the DSDP site 442, leg 58 (21 my) is quite consistent with the present models, regardless whether the spreading is symmetric or one-limbed, since the site is located in the western part of the basin (DSDP SCIENTIFIC STAFF, LEG 58, 1978; KLEIN et al., 1978). On the contrary age of sediments above the acoustic basement at DSDP sites 443 and 444 are 14 to 17 mybp which is apparently discrepant with magnetic ages of the symmetric model. It appears to be agreeable with the one-limb model age. However, the recovered sediments are only those above intrusive sills at the latter two sites and cannot provide the spreading ages.

Major difficulties of the one-limb model are: (1) Axial zone with irregular anomalies and rugged topography cannot be reasonably explained; (2) A rectangular area in the northeastern corner cannot be regarded as a rifting wedge, which could be interpreted in the symmetric model as described above. The basement ages of DSDP sites 449 and 450 drilled on the western and eastern parts of the Parece Vela Basin indicated validity of the symmetric spreading model (DSDP SCIENTIFIC STAFF, LEG 59, 1978). Ages of sites 53 and 54 located on the eastern part of the basin are also consistent with the spreading of the Parece Vela Basin in harmony with the opening of the Shikoku Basin. It is therefore the most reasonable to assume that the opening of the Shikoku Basin was symmetric and synchronous with the Parece Vela Basin situated in its southern extension.

Some other models of spreading may be possible if we assume asymmetric opening but they will be disregarded hereafter because of this reasoning.

5. Evolutionary History of the Basin and Its Tectonic Implications

Age identification of magnetic anomalies as shown in Fig. 6 indicates that the Shikoku Basin opened through three different stages; (1) rifting between the Kyushu-Palau and Shichito-Iwojima Ridges, (2) parallel spreading of the Shikoku Basin, (3) more irregular opening, formation of seamounts and post-spreading intrusion.
Rifting began at approximately 30 mybp from the northern boundary of the ridges at which the present Nankai Trough subduction zone intersects with the ridges and the basin. The rifting propagated towards south in a shape like a wedge front (Fig. 9). Such a shape of the rigid matters is unstable, as an infinite stress may be concentrated at the acute-angle wedge to cause propagation of rifting. The anomaly ages show the speed of southward propagation was approximately 10 cm/year. Similar growth of rifting in the initial stage of break-up of plate has been postulated with the South Atlantic (Wright, 1968; Burke, 1976), the Gulf of Aden (McKenzie et al., 1970) and the African Rift Valley (Maasha and Molnar, 1972).

At about 25 mybp the rifting reached a latitude of 25°N. The Parece Vela Basin was very likely to start rifting from its south end, although no distinct magnetic evidence is available there due to low latitude of the basin. The rifting of both basins got together probably around 25°N.

It must be noted here that the rifting of the Shikoku Basin (and possibly the Parece Vela Basin as well) began about 10 my after the Pacific plate changed its direction of motion. Prior to 42 mybp the Pacific plate moved northwards in a direction nearly parallel to the trend of the Kyushu-Palau, Shichito-Iwojima Ridges so that no subduction occurred along the ridges. Great amount of subduction possibly proceeded along the southwestern Japan and caused opening of the Japan back-arc basin in this stage of plate motion.

After the Kyushu-Palau and Shichito-Iwojima Ridges were completely rifted, two ridges were separated further by parallel spreading of the Shikoku Basin. Rate of opening was nearly 4 cm/year (half rate) which is intermediate between that of the East Pacific Rise and that of the Mid-Atlantic and Mid-Indian Ridges. The spreading axis was not offset by transform faults but linear and continuous. Magnetic lineations formed in this stage are symmetric and most recognizable.

Spreading became more irregular at about 22 mybp (magnetic anomaly 6'). Spreading rate decreased to nearly a half of the previous value. Because magnetic anomalies are generally disrupted in this zone, it is rather difficult to identify their ages. Neverthe-
less, offsets of magnetic lineations are clearly recognized. If the spreading is still symmetric, equivalent amount of offsets of the accreting axis associated with transform faults should be assumed. Such a transition of axis configuration implies a jump of spreading axis at about 22 mybp. Similar discontinuous jumps of spreading center have been suggested with the northeastern Pacific (Harrison and Sclater, 1972; Shih and Molnar, 1975), the east-central Pacific (Anderson and Sclater, 1972; Herron, 1972; Handschumacher, 1976), Galapagos area (Hey and Vogt, 1977) and the Atlantic north of Iceland (Johnson and Heezen, 1967; Vogt et al., 1970). Local migration of spreading center has also been postulated (Blakely, 1975).

It seems reasonable to assume the second jump of the spreading axis in the Shikoku Basin to cause seamounts and moats in the central zone. Detailed examination of topography indicates that the seamounts and moats were formed under an extensional stress perpendicular to the trend of the basin in a similar manner to the formation of general microtopography of the basin. Origin of the seamount chain is, therefore, closely related to spreading of the basin rather than to hot spots or orogenic activity. A lack of the mirror images of the seamount topography in the western side of the basin indicates that the spreading axis producing the seamount chain should have existed on the seamounts themselves in the latest stage of spreading.

It is very likely that such jumps and the irregular behavior of spreading axis have caused complex stress in the older rigid oceanic lithosphere, particularly in the trenchward (eastern) side of the basin. At some spots where stress was extraordinarily concentrated, local cracks may have been generated to cause intrusions of magma forming sheets or sills. Sites 442, 443 and 444 of DSDP Leg 58 in the Shikoku Basin revealed occurrence of many post-spreading intrusions at periods (14 to 17 mybp) slightly after the spreading ceased (Klein et al., 1978). The result of drilling appears to be quite consistent with the present explanation of the evolutionary history of the basin.

Magnetization of the post-spreading intrusives takes a part as a noise in the observed magnetic anomalies. Thermal and chemical influence of the intrusive rocks on the previously seated materials may also disturb the original magnetic lineations recorded in the regularly accreted oceanic crust. Less remarkable linearity in the eastern portion of the Shikoku Basin can be explained by greater degree of off-ridge activity compared to the normal ocean and the western part of this basin.

Sudden decrease in spreading rate and abnormal behavior of the accreting axis in the late stage of opening in the Shikoku Basin may possibly be attributable to the distance of the axis too far from the down-going slab which supplies magma and heat to the spreading axis. At 22 mybp the geometrical axis of the basin was situated at a distance of about 500 km from the trench. If the subduction angle was 45° as observed with usual subduction zone such as the Japan and Kuril trenches, the upper surface of sinking lithosphere was 500 km deep beneath the spreading axis. Distances exceeding this amount may be too large to supply magma and heat unless a special channel of magma or heat conduit exists.

In the Mariana Trough the pattern of spreading appears to be more irregular than in the Shikoku Basin or other similar inter-arc basins throughout the whole basin of the "trough," although it is young and may be still opening (Karg et al., 1978). Difference between the Mariana Trough and the Shikoku Basin is that the subduction angle along the Mariana Trough is very steep and its accreting axis is already far from the source of magma and heat.
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REFERENCES


