Magnetic Anomalies in the Sea of Japan: A Speculation on the Tectonic History

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Geomagnetic anomaly profiles obtained by Isezaki and Uyeda are reanalysed to infer the mode and time of opening of the Sea of Japan, especially in the Japan Basin. The anomalies show a roughly ENE–WSW trend which is subparallel to the coastlines of Honshu island and Sikhote Alin. It is inferred from the analysis that Vine-Matthews type magnetic anomalies are present at least in the Japan Basin. Possible reasons why the anomalies could not be correlated in the previous analyses with the geomagnetic reversal time scale are also examined. One possibility is that the anomaly patterns in the Sea of Japan is not a product of simple sea-floor spreading but is obscured by the complexity in the mode of opening or in the tectonic evolution. However, the most plausible explanation is that the assumption of symmetric spreading about some spreading center was wrong. The shape analysis shows that a better fit is obtained for one-sided spreading with a spreading center near the coast of Sikhote Alin. A satisfactory fit is obtained for a magnetic profile with a model generated for the period of 10–15 Ma.

This timing for the opening of the Sea of Japan is broadly consistent with the paleomagnetic data from the northeastern part of Honshu island. It is suggested that the original Vine-Matthews anomaly pattern was “contaminated” by the off-ridge volcanism which is also responsible for the creation of the abundant seamounts in both the Japan Basin and Yamato Basin.

1. Introduction

The Sea of Japan separates the Japanese islands from the eastern edge of Asian continent. It has a typical oceanic structure (MURAUCHI, 1972; LUDWIG *et al.*, 1975) with an average depth of 3.5 km, a very thin lithosphere of about 30 km (ABE and KANAMORI, 1970), and a high heat flow (WATANABE *et al.*, 1977). It is usually thought that Honshu island was separated from the Asian continent and migrated southeastwards to the present position, opening the Sea of Japan behind the island arc. Although recent reappraisal of the geology of Japanese islands shows that many parts of the post-Jurassic geologic formations are accreted from the Pacific side as subduction complex or allochthonous bodies, the basic concept of the opening of the Sea of Japan does not need a drastic change.

From the analysis of the paleomagnetic data in Japan, KAWAI *et al.* (1961, 1969, 1971) concluded that the northeastern and southwestern parts of Honshu island rotated counterclockwisely and clockwisely, respectively, around a hinge in the central part of Honshu island at some time between Cretaceous and Upper Tertiary. This concept was further elaborated by additional paleomagnetic and age data from

both the southwestern (OTOFUJI and MATSUDA, 1983, 1984) and northeastern Japan (OTOFUJI *et al.*, 1985; TOSHA, 1984). As a consequence of these recent studies, it now seems plausible that the opening of the Sea of Japan took place in a relatively short period in Upper Tertiary in conjunction with the rotation of two parts of Honshu island.

The present paper deals with an analysis performed on the existing geomagnetic anomaly data of ISEZAKI and UYEDA (1973). The nature of the magnetic anomalies in the Sea of Japan are examined, and the anomaly profiles are compared with the theoretical wave forms constructed from the geomagnetic reversal time scale of the Cenozoic. It is concluded that, as far as the northeastern part of the Sea of Japan is concerned, a one-sided opening in the period of 15–10 Ma is the most plausible interpretation of the magnetic profiles.

2. Geomagnetic Anomaly Data and Block Models

A most extensive magnetic survey of the Sea of Japan was carried out by N. Isezaki and others in the autumn of 1970 using a chartered fishing boat. ISEZAKI and UYEDA (1973) summarized this and other results from earlier magnetic surveys and compiled the total intensity anomaly map of the Sea of Japan (Fig. 1). The dominant feature of the anomaly map is the ENE–WSW trend of the linear magnetic anomalies with an amplitude of 200–400 nT and a typical wavelength of 30 to 50 km. These anomalies are smaller in amplitude and have shorter wavelengths compared to the ones observed in the Pacific Ocean to the east of the Japan Trench (ISEZAKI, 1973).

The anomaly lineations do not seem to continue to the Yamato Bank, where anomalies show disturbed patterns in some parts and reduced amplitudes in others. This is perhaps because the Yamato Bank is not a normal ocean floor but a continental fragment originally attached to the eastern margin of the Asian continent. Seismic data show that the crust under the Yamato Bank is quite thick and is probably of continental origin (LUDWIG *et al.*, 1975). To the west of the Yamato Bank, the amplitudes of anomalies become smaller, so that magnetic lineation cannot be unambiguously determined from the chart. Our analysis will therefore be focused to the north and east of the Yamato Bank, especially to the Japan Basin where the linear trend is the most prominent.

In spite of extensive studies, ISEZAKI and UYEDA (1973) could not correlate anomalies with the existing geomagnetic reversal time scales. ISEZAKI (1975) examined the symmetry of deskewed anomalies in an effort to locate possible spreading centers in the Sea of Japan and pointed out that correlation coefficient is good at several places in the Japan Basin and Yamato Basin. However, he could not assign ages to these possible spreading centers. Thus the age of the Sea of Japan has remained essentially unknown, though some values were reported on dredged materials by radiometric method (KANEOKA, this issue) or on sediments recovered by Deep Sea Drilling Project (DSDP) by dating fossils.

It may be that the opening of the Sea of Japan was a complex event which cannot be satisfactorily represented by a simple model of sea floor spreading from a linear ridge. If the opening was due to randomly distributed sources, for instance, there is no way to reveal the history of formation simply by the analysis of magnetic anomalies. Worse still, the age of dredged or drilled rocks may not directly correspond to the age

Fig. 1. Total intensity magnetic anomalies in the Sea of Japan. Solid and broken contours indicate positive and negative anomalies at 50 nT intervals. After ISEZAKI and UYEDA (1973).

of the oceanic crust in such cases. A vast amount of age determination may be needed for the understanding of the tectonic history, just as the geology of the island arcs such as Japan itself is so.

Rather than pursuing the outcome of this unencouraging situation, we may look into the existing data to know if there really is not some clue of a simple tectonic process which can be deciphered from the magnetic anomalies. First, we should point out that though lineations are not extensively developed in the Sea of Japan, the ENE-WSW trend is very prominent in the anomaly map (Fig. 1). This is particularly true in the Japan Basin as pointed out by ISEZAKI and UYEDA (1973) and ISEZAKI

(1975). Magnetic anomaly profiles in the Japan Basin are reproduced in Fig. 2. Second, ISEZAKI (1975) searched for centers of symmetry in deskewed magnetic anomaly profiles to locate the possible spreading centers. He suggested several places for possible extinct spreading centers in Japan Basin and Yamato Basin. However, these results are not very convincing because the correlation coefficients were not very high (0.4 to 0.7).

In a model with uniformly magnetized blocks of rectangular shape, the observed total intensity anomaly can be expressed as a sum of the contributions from individual blocks:

$$A_i = \sum_j K_{ij} J_j \quad (1)$$

where A_i is the observed anomaly at point i , J_j is the intensity of magnetization of block j , and K_{ij} is the system response function, which can be conveniently expressed as

$$K_{ij} = 2F [\sin B \log (r_B r_D / r_A r_C) + \cos B (\phi_A - \phi_B + \phi_C - \phi_D)] \quad (2)$$

where A, B, C, D are four corners of the rectangular cross section of the block j named in a clockwise order, r_A, r_B, r_C, r_D and $\phi_A, \phi_B, \phi_C, \phi_D$ are lengths of lines connecting the point i to each of the four corners and angles these lines form with the positive horizontal direction (BOTT and HUTTON, 1970). F and B represent magnitude and skewness of the anomaly, respectively, and are calculated as

$$\begin{aligned} F &= (M_x^2 + M_z^2)^{1/2} + (H_x^2 + H_z^2)^{1/2}, \\ B &= \tan^{-1} (\hat{M}_z / \hat{M}_x) + \tan^{-1} (\hat{H}_z / \hat{H}_x), \end{aligned} \quad (3)$$

where $(\hat{M}_x, \hat{M}_z)$ and $(\hat{H}_x, \hat{H}_z)$ are the direction cosines of the magnetization and regional field, respectively, in the direction of spreading (or, orthogonal to the strike of lineation) and in vertically downward direction.

To obtain anomaly profiles corresponding to block models based on the geomagnetic reversals, it is necessary to assume the spreading velocity and the skewness parameter B . In the present case, the skewness parameter can be estimated with small ambiguity in the following way. The declination anomaly or the rotation of the pre-Miocene paleomagnetic directions are estimated to be about 45–50° eastward for the southwest Japan (OTOFUJI and MATSUDA, 1983) and 45–50° westward for the northeast Japan (OTOFUJI *et al.*, 1985; TOSHA, 1984; TOSHA and KONO, 1985). The value of $\pm 40^\circ$ can be taken as the possible extremes for the declination of magnetization in the sea floor, because it can be as small as 0° if only Honshu island rotated (and not the sea floor) while forming the Sea of Japan by moving away from Asia. As for the inclination, there is no reason to assume an angle greatly different from the axial dipole direction. The remanence inclination and declination can therefore be taken as $59^\circ \pm 3^\circ$ and $0^\circ \pm 40^\circ$, respectively.

The ambiguity in estimation of the direction of the geomagnetic field in the survey area ($38\text{--}42^\circ\text{N}$, $132\text{--}138^\circ\text{E}$) is much less than that for the remanence. The present field direction can well be approximated by an inclination of $54^\circ \pm 2^\circ$ and a

declination of $-8^\circ \pm 1^\circ$. The azimuth of x direction (which is perpendicular to the magnetic lineation) can be taken as $149^\circ \pm 2^\circ$. Taking all these values as well as their uncertainties into consideration, the values of F and B in Eq. (2) can be calculated as

$$\begin{aligned} F &= 0.94 \pm 0.1, \\ B &= 119^\circ \begin{matrix} +20^\circ \\ -8^\circ \end{matrix}. \end{aligned} \quad (4)$$

The range in B is obtained by taking extreme values in the directions of the remanence and the field. It is, therefore, sufficient if we calculate magnetic anomalies with the skewness parameters between 110° and 140° . Incidentally, ISEZAKI (1975) assumed that inclinations and declinations of both the field and the remanence are 58° and 0° and the azimuth of x is 160° , which corresponds to $B=119^\circ$.

With the estimated skewness parameter, a search can be made to see if any period in Cenozoic will produce anomaly profiles which are similar to the observed ones (Fig. 2). For this purpose, anomaly patterns corresponding to the skewness parameters between 90° and 180° were generated at 10° intervals for the entire Cenozoic using the geomagnetic reversal time scale of HARLAND *et al.* (1982). Both symmetric and one-sided opening models were constructed for each 10 Ma period and the obtained anomaly profiles were compared with the observed ones. In this comparison, it is not necessary to assume the spreading velocity, since only the shape of the profile is important. Figure 3 shows model anomalies for the skewness parameter of 120° for the period of 0 and 60 Ma.

The most prominent feature of the observed profiles (Fig. 2) is that the anomalies have typical wavelengths of 40–50 km, superposed by fluctuations of smaller amplitude and shorter wavelengths. As the shape of the anomalies are fairly distinct, the places for polarity changes in the source layer can be estimated rather easily, provided that VINE and MATTHEWS (1963) scheme really applies to the Japan Basin. In such visual matching, relative spacing of the polarity intervals seems the deciding factor. The model profiles were expanded or reduced in size as was seemed appropriate to match with the observed anomaly forms (Fig. 2). Comparison of Fig. 2 with Fig. 3 (and many other such figures) suggests that considerable period in the Cenozoic can be excluded on the basis of magnetic anomaly characteristics if we expect a fast spreading. For instance, times older than about 43 Ma are not adequate because of the small number of recorded reversals.

Although extensive search was carried out, correspondence between the observed and predicted anomalies was not satisfactory in every case except one. Figure 4 shows comparison of the profile No. 5 in Fig. 2 with models calculated with skewness parameters estimated by (4) for the anomalies 5 through 5B corresponding to Middle Miocene. The models assume a spreading rate of 10 cm/year for the interval of 10 to 15 Ma. The difference in the shape of predicted anomalies due to change in the skewness parameter B is subtle, but the profile with $B=120^\circ$ seems to best fit the observed anomaly. We must note, however, even the adjacent profiles do not show a satisfactory fit with the model profiles. As seen from Fig. 2, linear trend exists in the magnetic anomalies in Japan Basin, but it is not well developed.

In spite of the failure to match profiles other than No. 5, we shall take a view that other profiles were somehow “contaminated” and that the match shown in Fig. 4 is

(a)

Fig. 2.

Fig. 2. The ship tracks (a) and observed anomaly profiles (b) in Japan Basin. From ISEZAKI (1975).

real. If this interpretation is correct, the Japan Basin off the northeast Honshu island with a width of about 500 km opened in about 5 Ma in Middle Miocene from a spreading center situated near Sikhote Alin with a moderately high speed of 10 cm/year.

3. Nature of Anomaly Sources

A reasonable fit is observed between the profile No. 5 in Fig. 2 and a model of spreading of the Sea of Japan in the interval of 15–10 Ma (Fig. 4). However, this fit is still not very convincing because other profiles cannot be correlated with any certainty. To conclude that the fit in Fig. 4 is real, we must show that the magnetic profiles in the Sea of Japan were created by the VINE and MATTHEWS (1963) scheme, but that most were contaminated later. The difficulty in identifying magnetic profiles may be attributed to one or more of the possible causes listed below.

(1) The sea floor was formed in a period when no reversals occurred or when the intensity of the geomagnetic field was very weak. Alternatively, the spreading occurred so quickly that the entire sea floor was formed while the geomagnetic field did not change its polarity.

(2) The sea surface magnetic anomalies are obscured because the suboceanic crust has very weak remanent magnetization due to its particular mineralogy or because the source layer is too thin or too deep.

(3) The mode of opening is quite different from what the original sea floor spreading theory assumes; i.e., nearly symmetrical spreading at linear ridges. Spreading from multiple ridges or frequent ridge jumps may obscure the magnetic signature and make the identification very difficult.

Fig. 3. Example of synthetic magnetic profiles for 0 to 60 Ma based on the reversal time scale of HARLAND *et al.* (1982). Spreading velocity of 5 cm/year and a source layer between 5 and 7 km is assumed. Intensities of remanence and magnetic anomaly are arbitrary.

(4) The anomaly pattern is distorted by skew, by later thermal events or by block motions in the crust.

We shall briefly examine each of the above possibilities to see if some of them are relevant to the case of the Sea of Japan.

3.1 Lack of reversals

If the formation of the Sea of Japan was a very old event, such as in Cretaceous long normal period, or if the spreading was very fast, the magnetic anomalies may be due to secular variation in the geomagnetic intensity and not due to reversals. However, if such is the case, the anomaly pattern will be distinctly different from the one observed. This is because of a fundamental characteristics of the geomagnetic field.

Statistical analyses of the geomagnetic paleointensity data for the last 10 Ma (KONO, 1971) or 5 Ma (MCFADDEN and MCELHINNY, 1982) show that the frequency distribution of geomagnetic dipole moment for one polarity (normal or reversed) closely resembles a normal distribution, with a standard deviation of about 34% of the

Fig. 4. (Top) Comparison of profile No. 5 with predicted anomalies for a model of spreading between 10 and 15 Ma at a speed of 10 cm/year. The source layer is between 5.4 and 7 km. Anomaly amplitudes are arbitrary. (Bottom) Fit of anomaly peaks with that predicted from the time scale of HARLAND *et al.* (1982).

mean (KONO, 1971). Since the dipole term dominates in the paleomagnetic field, this result shows that, for a time period long enough to include several reversals, the geomagnetic field may be modeled, to a good first approximation, by a square wave taking only values of +1 or -1 (PHILLIPS and COX, 1976). Although data are not enough for the older periods, stationarity of other geomagnetic field parameters (such as reversals frequencies) suggests that such characteristics may have lasted in the entire Cenozoic. The fact that the magnetic anomalies of the Cenozoic sea floor could successfully be simulated by the simple block models strongly supports this conclusion (e.g., HEIRTZLER *et al.*, 1968).

The square wave alternating between $+1$ and -1 has a standard deviation of 1, which is about three times as large as that for the intensity fluctuation in one polarity state (KONO, 1971). It may appear that the amplitude of magnetic anomalies for a single polarity may be about a third of the ones recording the reversals of the field. However, this is not true. The geomagnetic reversals occur abruptly in every 0.2 to 0.4 Ma on average, and the reversal process itself lasts only a few thousand years, compatible with the square wave modeling. On the other hand, fluctuation in the dipole moment occurs more gradually and continuously, typically with a period between 10^3 and 10^4 years (MCELHINNY and SENANAYAKE, 1982). If the spreading rate is 10 cm/year, one cycle of intensity fluctuation will be recorded in a sea floor strip of 100 to 1000 m wide. From the surface of the sea at 3 to 5 km above, such changes may be difficult to observe by magnetic surveys.

As the magnetic anomalies in the Sea of Japan can be simulated by simple block models, it is less likely that they record only intensity fluctuations of the geomagnetic field.

3.2 *Weak magnetization, thin or deep source layer*

The amplitude of observed anomalies in the Sea of Japan is 200–400 nT as previously mentioned. It is somewhat smaller than that of the anomalies in the Pacific Ocean to the east of Japan Trench which reaches 1000 nT level (ISEZAKI, 1973). However, it is still within the range to be expected from the volcanic rocks which form the source layer in the oceanic crust. The mean remanence intensities of basaltic rocks at 51 DSDP sites are distributed between 0.2 and 10 A/m, well over an order of magnitude (LOWRIE, 1977).

According to the seismic surveys, the crust under the Sea of Japan is of normal oceanic type except that the water depth of 3.5 km is less than the normal value of 5 km (MURAUCHI, 1972; LUDWIG *et al.*, 1975). Layer 2, with a velocity of 3.5 to 5.8 km/s begins at a depth of about 5 km and layer 3 with 6.7 km/s begins at about 7 km depth. The Moho in both the Japan Basin and Yamato Basin is estimated at about 12 km below sea level.

Figure 5 shows the effect of the depth of the source layer on the distinctness of magnetic anomalies. Even for a moderately slow spreading of 6 cm/year, they are clear enough if the source lies in either layer 2 or 3. This possibility is not relevant in the case of the Sea of Japan.

3.3 *Complex spreading mode*

This is the possibility advocated by many authors. If the spreading is not a two-dimensional, continuous process, as is postulated by the theory of VINE and MATTHEWS (1963), identification of magnetic anomalies will become very difficult. KOBAYASHI and ISEZAKI (1976), for example, suggest that the opening was not from a single central ridge but that there were multiple spreading centers when the Sea of Japan opened. If the opening was a very complex phenomenon with many spreading centers active at the same time, the identification of anomalies is not straight forward due to duplications and omissions. This possibility needs careful examination.

3.4 *Distortion by skew or by later events*

Magnetic anomalies change their shapes depending on the value of a single

Fig. 5. Loss of details in magnetic anomaly profiles due to deepening of the source layer. Anomaly profiles are computed for a sea floor created between 14 and 20 Ma with a source layer of 1 km thickness spreading at a velocity of 6 cm/year. Depth of top of the source layer is indicated in the figure. Amplitudes are arbitrary.

parameter skew defined by Eq. (3) (BOTT and HUTTON, 1970; SCHOUTEN, 1971). However, there is no problem in identification of magnetic anomalies even if these angles are not known precisely. A possible range can be estimated and anomaly shape is not so strongly dependent on B . This was well demonstrated in the calculation of B for the present case (see Fig. 4).

If magnetic profiles were "contaminated" by reheating of the crust after it was formed at spreading centers, the result can be chaotic and the anomalies may be difficult to delineate. In large oceans, reheating of the lithosphere by hot spots is seen to modify the depth-age relationship (e.g., HEESTAND and CROUGH, 1981), but this thermal event does not directly affect the magnetization in the oceanic crust, as the crust itself is not severely heated. What we think here is an event smaller but which directly affects the magnetic source layer. Consider, for example, off-ridge volcanism with eruption of lava flows or injection of dikes or sills. Even if the sea floor was originally created at a spreading center as the Vine-Matthews theory predicts, later reheating or addition of new crustal material would obscure magnetic lineations. The result is in a way similar to the opening from multiple spreading centers.

4. Discussion

The model fit to the profile No. 5 suggests a one-sided opening in Middle Miocene in the Japan Basin. If this interpretation is correct, the reason becomes obvious why ISEZAKI and UYEDA (1973) and ISEZAKI (1975) failed to correlate the magnetic anomalies to reversal time scale; they were expecting a spreading to both sides and therefore looking for anomaly patterns symmetric about possible spreading centers.

One-sided spreading seems less plausible as the mode of opening in normal oceans, but may not be so strange in back-arc basins. Figure 6 compares the situations of opening of the normal oceans and marginal seas. A normal ocean is formed when a continent breaks up at some weak line and both sides drift apart (Fig. 6(a)). Apparently, the situation is symmetric about the spreading center. The newly formed sea floor therefore tends to be also symmetric about the mid-ocean ridge. On the other hand, the situation at marginal seas is usually strongly asymmetric (Fig. 6(b)). On the one side there is a continent with a thick and bouyant crust and a thick and strong lithosphere, and on the other a lighter island arc under which oceanic lithosphere subducts into the deeper mantle. The flow lines under island arcs and marginal seas are asymmetric because of this boudary condition (MCKENZIE, 1969). There will be strong down flow below the island arc because of the drag of the subducting slab.

For a back-arc basin to open, tensile regime should prevail above the subducting slab (UYEDA and KANAMORI, 1979). Such a situation can be realized if either the continental or oceanic lithosphere retreats relative to the wedge-shaped mantle. The trench axis on the Pacific side of the island arc may have retreated relative to the stationary Asian continent due to foundering of Pacific plate as proposed by the evolutionary model of KANAMORI (1977). If this was the case, material flow will come dominantly from the mantle under the continent to fill the gap. Then, the hottest material appears on the surface at the edge of the continental lithosphere (Fig. 6(b)). The newly formed sea floor retreats with the retreating slab (and the island arc), but

Fig. 6. Cartoons to show differences in the openings of normal oceans and back-arc basins. (a) A normal ocean is formed by the break up of a continent. Streamlines in the mantle are symmetric about the spreading center. (b) A back-arc basin is formed behind the retreating down-going slab. The situation is highly asymmetric and one-sided opening takes place.

the spreading center may be locked to this position for a considerable time. As the sea floor is still hot and weak, upwelling mantle flow as well as low melting fractions associated with island arc volcanism will erupt in many parts of the sea floor as off-ridge volcanism, of which the large scale ones may form prominent seamounts.

The scheme of opening presented here is somewhat different from the more popular hypothesis of opening from multiple sources (e.g., KOBAYASHI and ISEZAKI, 1976). We take the view that the opening of back-arc basin is more of a passive event controlled by the relative movements of surrounding continent and down-going slab. In a sense the new basin is more similar to a net than to a rigid plate; it moves in one body keeping its integrity but contains many patches where the crust is so thin or so weak that materials can be added later from below by off-ridge volcanism. Such a model is consistent with the observed high heat flow (WATANABE *et al.*, 1977) and thin lithosphere and shallow low Q zone (ABE and KANAMORI, 1970) in the Sea of Japan.

The magnetic anomalies in the Sea of Japan may thus be contaminated by remanent magnetizations acquired at later dates when the crust was subjected to off-ridge volcanism. The prevalence of later thermal events may be one reason why the amplitude of magnetic anomalies is smaller in the Sea of Japan compared to the Pacific Ocean east of Japan Trench.

Figure 7 is a rough sketch of the opening history of the Sea of Japan. The proposed time of Middle Miocene (10–15 Ma) coincides with the period when volcanic activity was the most active on the Japan arc, and is also consistent with the radiometric ages obtained from scattered places in the Sea of Japan mostly from seamounts (KANEOKA, this issue). The timing is not exactly coincident with the 15 Ma $\pm$ 1 Ma proposed for the clockwise rotation of the southwest Japan (OTOFUJI and MATSUDA, 1983, 1984), but is in good agreement with the paleomagnetic data from the northeast Japan where counterclockwise rotation is expected between about 10 and 20 Ma (OTOFUJI *et al.*, 1985; TOSHA, 1984; TOSHA and KONO, 1985).

5. Conclusions

Assessments were made on the possibilities why the magnetic anomalies in the Sea of Japan could not be correlated with the geomagnetic reversal time scale. It is very unlikely that the sea floor was created in a time of constant polarity, nor that magnetic anomalies cannot be distinguished because of chemical or geometrical properties of the source layer. The reasonable explanations are (1) spreading from multiple sources, and (2) contamination by off-ridge volcanism after it was formed at the spreading center. The present study suggests that the second of the above may be the case.

A reasonable agreement between one observed magnetic profile and a model based on one-sided spreading between 10 and 15 Ma is demonstrated. As the agreement does not extend even to adjacent magnetic profiles, this fit may be only coincidental. However, data for the Sea of Japan from other sources, e.g., seismology (ABE and KANAMORI, 1970), heat flow (WATANABE *et al.*, 1977), radiometric ages (KANEOKA, this issue), and paleomagnetic data from northeastern part of Honshu island (OTOFUJI *et al.*, 1985; TOSHA, 1984) are not inconsistent with this timing.

Possible causes of one-sided spreading is discussed. The most important reason seems to be the control of boundary conditions (continental lithosphere, down-going

Fig. 7. Sketch of opening of the Sea of Japan and bending of the northeastern part of Honshu island. Yamato Bank is delineated by the contour of 2500 m depth. (a) Anomaly 5B time (15 Ma). (b) Anomaly 5AA time (13 Ma). (c) Present.

slab, etc.) on the process of back-arc opening. In the case of the Sea of Japan, retreat of the oceanic lithosphere may be the cause of forming a net-like sea floor behind, with patches of weak portions which were susceptible to the later off-ridge volcanism. The difficulty in interpreting magnetic anomalies may be the result of the later thermal events which remagnetized a considerable portion of the sea floor.

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