Paleomagnetic Rotations and the Japan Sea Opening

Laurent Jolivet

Laboratoire de Géologie, Ecole Normale Supérieure, Paris, France

Hidetoshi Shibuya

Department of Earth Sciences, University of Osaka Prefecture, Japan

Marc Fournier

Laboratoire de Géologie, Ecole Normale Supérieure, Paris, France

The apparent incompatibility of the classical "bar door" opening model of the Japan Sea based on paleomagnetic studies and the pull-apart geometry based on the observation of shear zones in and around Japan is symptomatic of a lack of understanding of the tectonic history of the Japan Sea. After a critical review of paleomagnetic data and a discussion on the possible error bars we present information concerning the internal strain of the Japan arc during the opening. We show that it is possible to integrate both sets of data in a single model, provided that some of the paleomagnetic rotations are due to distributed deformation of SW and NE Japan and not to a rigid body rotation of 600 km long blocks. Rotations occur at all scales and the 50° of clockwise rotation of southwest Japan is the sum of 30° of rotation of southwest Japan as a whole and of 20° due to internal deformation. The amount of paleomagnetic rotation is then compatible with the kinematics based on the internal structure of the Japan Sea and the geometry of major dextral shear zones. The rigid body rotation of southwest Japan is accommodated by extension and left-lateral motion along the Median Tectonic Line which is a second order fault between the two major dextral shear zones that bound the Japan Sea to the east and to the west. The problem of the apparent instantaneous rotation of southwest Japan as opposed to the progressive opening of the Japan Sea probably results from the way paleomagnetic data and radiometric dates are averaged.

PROBLEM SETTING

The past ten years have seen the development of a debate on the opening mechanism of the Japan Sea (Figure 1). An important breakthrough was made by Otofuji et al. [*Otofuji and Matsuda*, 1983, 1984, 1987; *Otofuji et al.*, 1985, 1991, 1994] with their "bar door" opening model based on the observation that SW and NE Japan show consistent easterly and westerly deflected paleomagnetic declinations. The rotation interval was assigned to a very short period, less than 2 m.y. long, about 15 Ma. The model is that of a double rotation about two nearby poles and a double fan-shaped opening of the Japan Sea. The rigid behavior of the two continental blocks, each of them being more than 500 km long, implies that oceanic crust formation in the Japan Sea was contemporaneous with the rotation. A rapidly opening model was then postulated in concert with rapid rates of motion of the rotating blocks.

Based on different data, *Lallemand and Jolivet* [1985] postulated that major dextral strike slip faults guided the opening of the Japan Sea in a pull-apart manner, in opposition with the fan-shaped kinematics of *Otofuji et al.* Later *Jolivet et al.* [1989, 1991] and *Jolivet and Tamaki* [1992] introduced block rotations in the pull-apart model, describing the whole region as a wide dextral shear zone (Figure 2).

Active Margins and Marginal Basins of the Western Pacific
Geophysical Monograph 88

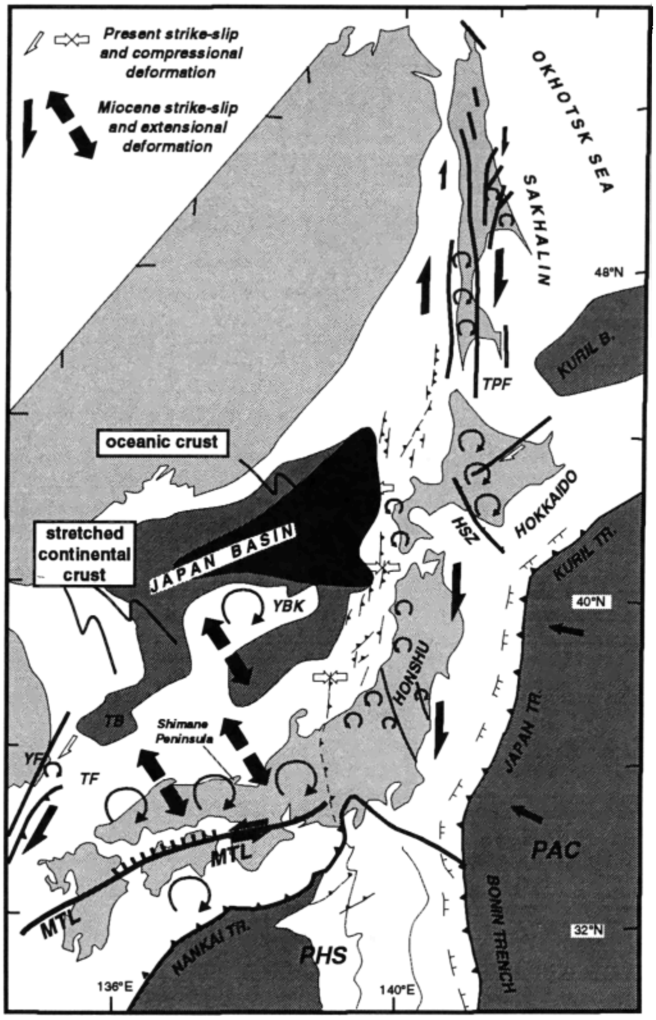

Fig. 1. Tectonic map of the Japan Sea area after *Jolivet and Tamaki* [1992]. Two successive stress fields are shown (Miocene and Present). Paleomagnetic rotations are indicated. YBK: Yamato Bank, TPF: Tym Poronaisk fault, TB: Tsushima basin, TF: Tsushima fault, YF: Yangsan fault, MTL: Median Tectonic Line, HSZ: Hidaka shear zone, PAC: Pacific Plate, PHS: Philippine Sea Plate. Oblique Mercator projection.

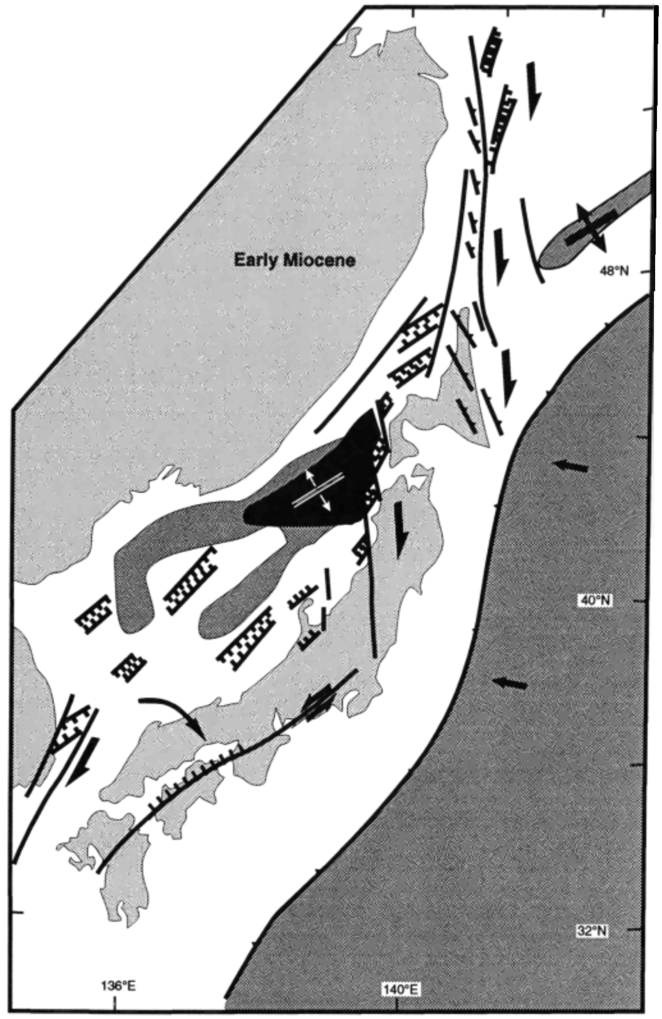

Fig. 2. Possible reconstruction of the Japan Sea in the early Miocene during the opening after *Jolivet et al.* [1992].

Even with these recent adaptations the strike-slip model remains apparently incompatible with paleomagnetic data because it suggests a progressive opening between 25 and 12 Ma (Figure 3), with progressive block rotations instead of the instantaneous ones in the fan-shaped model. Most geological and geophysical data, acquired on land as well as offshore, show that the Japan Sea did not open instantaneously and that it was already widely opened by 15 Ma [*Tamaki*, 1988; *Tamaki et al.*, 1992]. Recent deep sea drilling at several sites in the Japanese waters of the Japan Sea reached the volcanic basement, which is everywhere older than 15 Ma, and subsidence curves show a maximum during the early Miocene [*Ingle* 1992]. Previous geophysical investigations had also shown that heat flow and depth distribution in the basin are compatible with an early Miocene opening [*Tamaki*, 1986, 1988].

We start this paper with the assumption that both paleomagnetic data and other geological data are relevant and that the apparent inconsistency is symptomatic of a lack of understanding of the geometry and timing of opening, and we try to reconcile both sets of data in a single model. We first present a critical review of published paleomagnetic data putting the emphasis on the length of error bars. We then present observations on the way the Japan arc deformed during the opening of the Japan Sea and on the geometrical relationships between this

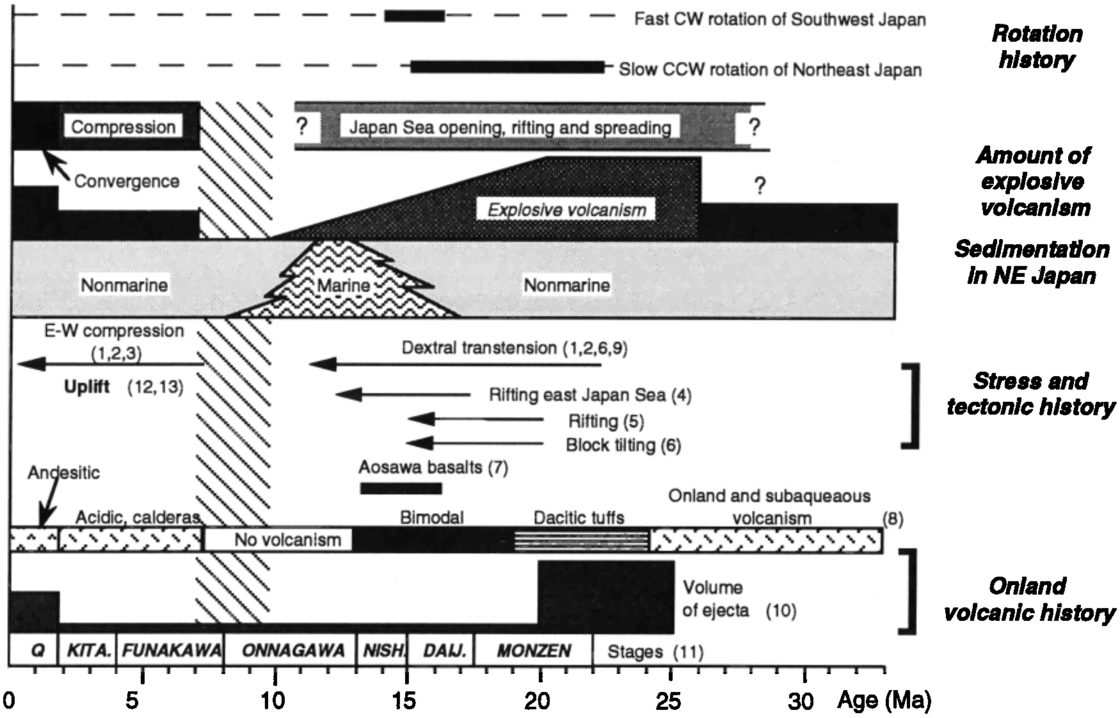

Fig. 3. Synthesis of the tectonic and volcanic events in northeast Honshu after *Jolivet and Tamaki* [1992] compared to the timing of large scale paleomagnetic rotations of NE and SW Japan discussed in text: (1) *Jolivet and Huchon* [1989], (2) *Jolivet et al.* [1991], (3) *Nakamura and Uyeda* [1980], (4) *Suzuki* [1989], (5) *Yamaji* [1989, 1990], (6) *Amano and Sato* [1989], (7) *Tsuchiya* [1989, 1990], (8) *Usuta* [1989], (9) *Otsuki* [1989], (10) *Sugimura et al.* [1963], (11) *Fujioka* [1986], (12) *Sugi et al.* [1983], and (13) *Iijima and Tada* [1990].

deformation and internal structures of the Japan Sea. We emphasize the fact that deformation occurred at various scales, and that distributed strain of the SW Japan and NE Japan blocks might partly explain the observed rotations. We finally propose a geometry of opening which partly reconciles both data sets, and we discuss points that do not fit in this scheme and possible explanations for these remaining discrepancies.

PALEOMAGNETIC CONSTRAINTS

The counterclockwise rotation of NE Japan and the clockwise rotation of SW Japan (Figure 4) were discovered in the early works on paleomagnetism in Japan [*Kawai et al.*, 1961, 1969]. Kawai and his colleagues measured remanent magnetization of granitic rocks in NE and SW Japan. Their material would be considered inappropriate by today's standards, but these were the only rocks systematically dated in those days with a strong enough magnetization for the magnetometer they used.

This work, which was summarized in *Kawai et al.* [1971], suggested that the Japanese islands had been bent between 120 and 80 Ma. No link was proposed with the opening of the Japan Sea. These results were not easily accepted because the material was not suitable for paleomagnetic tests. Because all samples were Cretaceous in age they all showed normal polarity. Their magnetization was not usually strong and stable enough for the demagnetization procedures in use in the sixties.

Yaskawa [1979] first proposed a possible correlation between the observed rotations and the opening of the Japan Sea, but the data he gathered did not unambiguously constrain the age of rotation.

Although Ito and his colleagues [*Ito and Tokieda*, 1980; *Ito et al.*, 1980] also considered a possible link between the observed rotations and the Japan Sea opening, it was not until the work of Otofuji and colleagues that the rotation of SW Japan and the opening of the Japan Sea were linked in the same mechanism and dated as middle Miocene. The first paper appeared in 1983 [*Otofuji and Matsuda*, 1983]. A thermal demagnetization technique was applied to acidic volcanic rocks which were not suitable for alternating field demagnetization because of a slight metasomatism. They also dated the samples and found that the clockwise

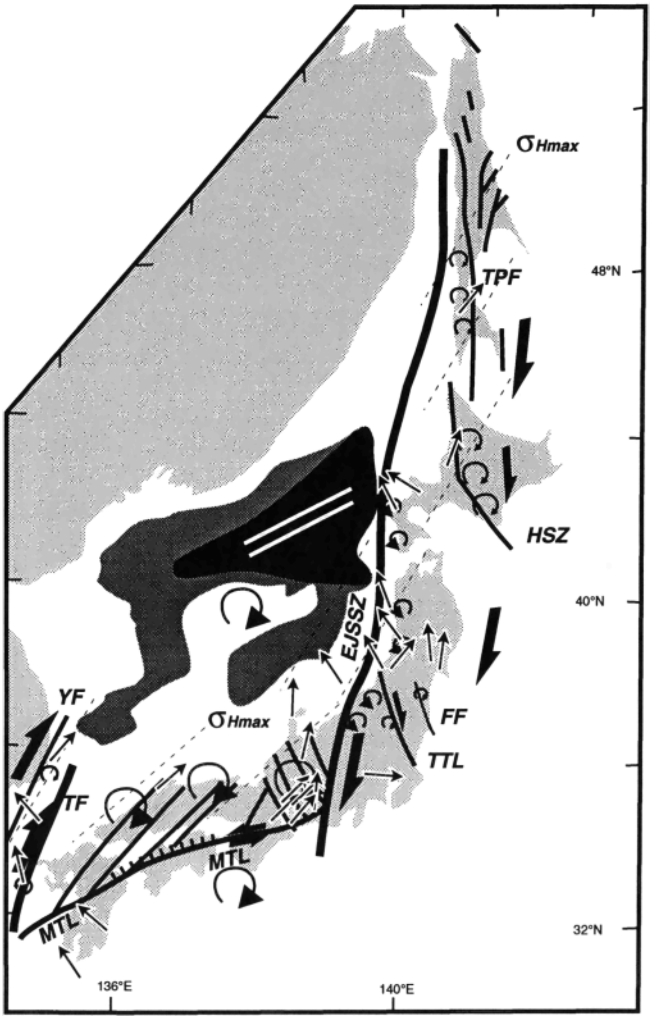

Fig. 4. Major faults and sense of block rotations around the Japan Sea. Most rotations are deduced from paleomagnetic studies (see text for references) except for those of NE Sakhalin which are suspected by *Fournier et al.* [1994] but not demonstrated and of the Yamato Bank which is deduced from *Jolivet et al.* [1991] kinematics. Also shown is the distribution of crustal blocks suspected by *Kanaori* [1990] in SW Japan and the direction of the maximum horizontal stress after *Jolivet et al.* [1991, 1992] and *Charvet et al.* [1992]. Paleomagnetic remanent directions were compiled from *Kodama et al.* [1991], *Kodama and Nakayama* [1993], *Ishikawa and Tagami* [1991], *Ishikawa et al.* [1989], *Kim et al.* [1986], *Otofuji et al.* [1985, 1991, 1994], *Hayashida and Ito* [1984], *Hayashida* [1986], *Hayashida et al.* [1991], *Itoh* [1988], *Hirooka et al.* [1986], *Hyodo and Niitsuma* [1986], *Yamazaki* [1989], *Tosha and Hamano* [1988], *Kodama et al.* [1993], *Takeuchi et al.* [1992]. Counterclockwise rotations in south Kyushu are post late Miocene.

rotation was as young as 20 Ma. Subsequent studies [*Otofuji and Matsuda*, 1984; *Hayashida et al.*, 1991] on sediments precisely dated by bio- and magnetostratigraphy suggested that the rotation occurred within a short period around 15 Ma. *Otofuji et al.* [1985] later found that the counterclockwise rotation of NE Japan was as young as that of SW Japan. Later works sought to constrain more precisely the timing and amount of rotation of NE and SW Japan.

Fast Rotation of SW Japan at 15 Ma

The study that most precisely constrains the timing of rotation was published by *Hayashida et al.* [1991] and *Hayashida and Ito* [1984]. They studied sediments of the Setouchi Miocene basins, distributed on the northern side of the Median Tectonic Line (MTL), which are dated with biostratigraphic and magnetostratigraphic techniques. Their data indicate that the rotation occurred after 16 Ma. Slightly younger sediments of the Morozaki area, in Blow's N9 foraminiferal zone (younger than 15 Ma) have smaller clockwise deflections, though the normal polarity leaves open the possibility that they were recently remagnetized. A similar chronology is found in the northern Chubu district (Yatsuo area) where *Itoh* [1988] also supports a smaller rotation within the *Denticulopsis Lauta* zone (younger than 15.7 Ma). Both studies found no significant rotation between 20 and 15 Ma. K-Ar dating by *Otofuji and Matsuda* [1983] suggested that most rotation occurred around 15 Ma within a period shorter than can be presently resolved by the available dating techniques.

Some regions of SW Japan nevertheless show different amounts of rotation. The Hokuriku and Chichibu regions are located on both sides of the MTL, which makes a sharp bend from an ENE trend to a more northerly direction west of the collision zone of central Japan. The bend is often attributed to the collision of the Izu arc, assuming that the MTL was straight before the collision. Paleomagnetic data in this region are consistent with this interpretation [*Itoh*, 1988; *Hyodo and Niitsuma*, 1986]. The change in rotation angle is consistent with this model, which assumes that the whole of SW Japan was first rotated clockwise uniformly, and that later its eastern part was rotated back CCW during the indentation of central Japan by the Izu arc. The rotation angle is calculated for the main part of SW Japan by *Otofuji et al.* [1985]. They selected reliable paleomagnetic data with the following criteria: (1) good age assignment, (2) demagnetization with both thermal and alternating field techniques, (3) small 95% confidence circle (<30°), and (4) data correction for tilt. Fitting a function on the selected data gave a finite rotation of 47°. However the estimation

TABLE 1. Paleomagnetic Dpata

Formation	Lat	Long	Age	D	Dcorr	I	N	a	Ref.
SW Japan									
Yoboshiyama	34.6	131.9	33	46.4	36.7	34	2	8.2	1
Hirefuriyama	34.7	131.9	33	49.1	39.4	47	4	21.2	1
Okami	34.8	131.9	33	64.8	55.1	61	3	16.5	1
Hamada	34.9	132.1	32	78.5	68.8	38	5	16.6	1
Harifuku	35	132.2	35	86.3	76.6	46	4	38.1	1
Kawamoto	35	132.5	33	61.6	51.9	53	7	6.4	1
Kawauchi	35	132.5	28	52.2	52.2	34	6	15.3	1
Hata	35.1	132.5	21	69.9	64.3	50	6	14.5	1
Ichishi	34.7	136.4	16.4	44.6	44.6	47	11	11.9	2
Morozaki	34.7	136.8	16	38.2	38.2	56	6	12.7	3
Kani	35.4	137	16.3	-22.2	49.9	53	6	9.7	4
N. Shidara	35.1	137.6	16	47	47	47	4	14	5
NE Japan									
H. Ohtorigawa	38.5	139.8	21	-27.5	-27.5	51	1	...	6
Okatsugawa	39	140.4	25	-40.5	-40.5	54	5	11.6	6
Yunosawagawa	39.1	140.4	33	-43.5	-53.3	63	3	21.4	6
Hatamura	39.2	140.3	21.9	-43.4	-43.4	65	4	24.2	6
Daijima	39.9	139.8	20.8	-45	-45	51	6	9.8	7
Monzen	39.9	139.7	35	-38.3	-48.1	54	6	9.7	6
Nisatai	40.3	141.3	21.8	-78.8	-78.8	43	2	41.2	6
Gongenzaki	41.1	140.3	E.Mio	-64.9	-64.9	56	3	27.7	6
Kunitomi	43	140.9	27.1	-64.2	-64.2	65	2	53.5	6
Fukuyama	46.4	140.2	23	-87.1	-87.1	43	2	2.6	6, 7

Table 1: Paleomagnetic data used in this paper to calculate the mean value of rotation of SW and NE Japan. Lat: Latitude, Long: Longitude, D: declination, Dcorr: declination corrected for the polar wander after *Otofuji et al.* (1985). 1: *Otofuji and Matsuda* [1983, 1984], 2: *Hayashida and Ito* [1984], 3: *Hayashida* [1986], 4: *Hayashida et al.* [1991], 5: *Torii* [1983], 6: *Otofuji et al.* [1985, 1994], 7: *Tosha and Hamano* [1988].

of uncertainties is difficult with this method so we used simple means for paleomagnetic data older than 16 Ma, including some recent data [*Hayashida et al.*, 1991; *Otofuji et al.*, 1991] (Table 1). We obtain a rotation angle of 50.9 ± 7.3° (95% confidence limit).

In contrast to NE Japan the rigid rotation of SW Japan as a single block has been widely accepted because of the limited variations of the paleomagnetic directions and mainly because the geological provinces arranged along the arc south of the MTL are straight and do not show an obvious division into smaller blocks. The only regions with a different trend of magnetization are located near the collision zone as discussed above. The whole of SW Japan has been sampled for paleomagnetic measurement from the forearc region of the Shimanto belt [*Tagami*, 1982] to the backarc side near the Japan Sea. It is difficult to divide SW Japan into smaller blocks without violating the apparent simple arrangement of the area.

Ambiguous Timing of the Rotation of NE Japan Between 22 and 15 Ma

Fewer systematic studies of the paleomagnetism of NE Japan are available in the literature than for SW Japan [*Otofuji et al.*, 1985; *Tosha and Hamano*, 1986, 1988]. These works indicated that counterclockwise rotation occurred sometime between 22 and 15 Ma. *Tosha and Hamano* [1986] and *Tanaka et al.* [1991] showed that the rotation had been completed before 15 Ma. *Yamazaki* [1989] collected samples from the east coast of Honshu and showed that the Matsushima formation (older than 15.7 Ma) has not been rotated. However, despite the observation of both normal and reverse polarities, a secondary remagnetization is still possible. Confusing paleomagnetic results are obtained in the Gongenyama formation 100 km to the northeast [*Momose et al.*, 1990]. The authors concluded that the rotation was not finished before N9 and N10 foraminiferal zones. The result is ascertained through the presence of both reverse and normal polarities and a slight improvement of clustering of data after tilt correction. The remanent magnetic direction close to the present field however leaves the possibility that the demagnetization has not removed all secondary magnetizations. Several other works also suggest that the rotation occurred before 15 Ma and after 22 Ma [*Tosha and Hamano*, 1988]. This makes the rotation older than that postulated by *Otofuji and Matsuda* [1984] for SW Japan. In a more recent paper *Otofuji et al.* [1994] proposed that NE Japan (NE Honshu and SW Hokkaido) rotated counterclockwise as a single block with a "climax" at 15 Ma.

The rotation angle is more difficult to determine by comparison to SW Japan. If we take the mean of data with ages between 20 and 40 Ma from *Otofuji et al.* [1985] and *Tosha and Hamano* [1988] (Table 1), the declination would be -56.1 ± 10.6° (95% confidence limit).

The Double Rotation Model and Japan Sea Opening

Despite a less precisely constrained timing of rotation in NE Japan, *Otofuji et al.* [1985] favored a model with rapid opening of the Japan Sea by rotation of NE and SW Japan about two poles located near the northern and southern ends of the Japan arc in a very short period about 15 Ma. The almost instantaneous rotation leads to implausibly rapid rates of spreading near the hinge between SW and NE Japan (more than 60 cm/year).

Until ODP legs 127 and 128 [*Tamaki et al.*, 1992], there had been no precise dating of oceanic spreading in the Japan Sea. The interval of rifting was rather well constrained by various studies on shore and offshore along the eastern margin in NE Japan but the oceanic basement had never been directly dated. Only in the northern part of the Japan Sea had poorly defined magnetic anomalies been recently discovered [*Kobayashi et al.*, 1988], which suggest an early Miocene spreading older than the proposed fast rotation of SW Japan. The volcanic basement was penetrated in four sites during the two drilling legs, and all results suggest that the Japan Sea was widely opened before 15 Ma. There is an apparent contradiction between the observed age of opening and paleomagnetic data that suggest rapid rigid rotations of two large blocks.

As we shall see later, it is possible to reconcile the amount and sense of paleomagnetic rotations with the observed deformation of the Japan arc, but not the timing of rotation. Did the rotation actually occur in this short time span, or is it possible that the error on the rotation of SW Japan is larger than usually considered?

Otofuji et al. [1991] give error estimates on the radiometric dating they performed in San'in district. According to them the rotation occurred within a short period of 1.8 ± 1.5 m.y., dated by the non-rotated Omori formation above and the rotated Kawai formation below. The maximum interval for the rotation is 3.3 m.y., which is still shorter than the duration of opening. Ages given for the two formations are means calculated with 8 and 15 different samples coming from various places in each formation. Is it reasonable to calculate a mean age when the individual ages of samples vary widely (from 13.7 ± 0.3 to 18.3 ± 0.4 Ma for the Kawai formation)? If the analytical error is small, there is no reason to deny the obtained ages and to prefer a mean value. Assuming that the mean value represents the age of the Kawai formation is equivalent to supposing that this formation was deposited instantaneously, which is very unlikely. Lithologic features of the Kawai formation are quite variable and its deposition could have lasted longer than supposed by the authors. If the rotation actually occurred in the time interval defined by the two formations, this interval should be defined by the youngest age found in the Kawai formation and the oldest age found in the Omori formation, and not between two mean ages. Furthermore some of the ages obtained in the underlying Kawai formation are younger (13 Ma) than the oldest obtained in the overlying Omori formation. Because some of these ages violate stratigraphic relations, why use them to calculate a mean value?

The authors also calculate average virtual geomagnetic poles (VGP) for each formation and give a 95% confidence interval. If block rotations occurred at a small scale, there could be significant local differences between the rotations of individual sites. As suggested by *Kanaori* [1990] on the basis of field observation in Shimane Peninsula and discussed in a later section of this paper, rotation of smaller scale blocks occurred at the same time as the fast rotation of southwest Japan. What is the meaning of an average VGP in this context? Calculating it, one assumes that the block has rotated rigidly, which is not proven a priori. In their recent paper *Otofuji et al.* [1994] compare the 95% confidence intervals of NE Honshu and SW Hokkaido (considered a priori as two rigid blocks) and conclude that the rotations are statistically identical and thus that the two regions rotated as a single rigid block. These statistics in fact show that the data do not allow separation of the two sets of data, but the inference that they rotated as a single rigid block is only one possible interpretation.

There could thus be an answer to our problem in the way data are treated statistically. If so, many more samples and a much denser sampling procedure is the only way to answer the question of timing and amount of rotation of a complex region; the sampling must also be done in connection with a good structural map where shear zones and other block boundaries are identified. A "statistically rigid" block might be so only because there is no other simple way to consider the numerical data without a priori information on the structure of the concerned region.

An alternative solution is to consider that the observed rotations partly correspond to the internal deformation of the Japan arc. In a classical domino system with a simple geometry crustal blocks rotate by the same amount and it might be impossible to see a difference in the distribution of paleomagnetic rotations between a single rigid block and several dominoes bounded by parallel strike-slip faults. *Kanaori* [1990] suggested that some of the rotation of SW Japan might be accounted for by rotation of large-scale dominoes (Figure 4).

We shall first see that some paleomagnetic data already show that local rotations occur along major shear zones, and then identify these and the strain regime they imply for the Japan arc.

Local Paleomagnetic Rotations along Shear Zones

NE Japan. There are many reports of paleomagnetic directions anomalous with respect to the rigid rotation model of NE Japan. *Otofuji et al.* [1985] themselves reported easterly deflected directions from eastern Asahi, which they attributed to the influence of the Tanakura tectonic line (TTL). *Oda et al.* [1989] observed a 20-30° clockwise rotation south of Sendai city, in the Yanagawa and Takadate area, dated at 15 Ma. They attributed these rotations to drag along the Futaba fault which runs parallel to the TTL in the Abukuma massif. Regional variations of the declination were already discussed based on data from granitic rocks [*Ito and Tokieda*, 1986; *Kawai et al.*, 1971]. It is thus possible that the rotation did not occur with a single rigid block. The basement of NE Japan is also less continuous than in SW Japan. However the data available do not define the size and boundaries of rotating blocks.

Tsushima Strait and Korea peninsula. Two sets of paleomagnetic data show local Miocene rotations. One is the clockwise rotation (45°) of the Guryongpo area on the east coast of the Korean peninsula [*Kim et al.*, 1986] and the second is a counterclockwise rotation of Tsushima island (30°) [*Ishikawa et al.*, 1989]. Both regions are located next to large shear zones and the authors attribute these anomalous direction to local strain. It is noteworthy that the two areas rotated in opposite sense despite the fact that they are located on opposite sides of the same shear zone.

Sakhalin and Hokkaido. Kodama et al. [1993] and *Takeuchi et al.* [1992] analyzed samples from Hokkaido and Sakhalin along the major dextral shear zone that bounds the Japan Sea to the east (east Japan Sea shear zone, EJSSZ). In Sakhalin they obtained reliable measurements on the west side of the Tym-Poronaisk fault, which is a major dextral dislocation that runs N-S for more than 600 km [*Rozhdestvenskiy*, 1982]. Clockwise rotations are observed consistently in the whole area, which the authors attribute to distributed deformation with a simple domino model. There do not seem to be discrete shear zones dividing crustal blocks west of the Tym-Poronaisk fault but rather en echelon folds whose axes are curved clockwise near the fault [*Fournier et al.*, 1994]. The dextral rotation can then be explained as well with a more continuous deformation model.

In a recent paper *Kodama et al.* [1993] describe the results of a sampling campaign in Hokkaido and they show very similar results with dextral rotations, which they attribute to the dextral motion along the axial zone of Hokkaido. The dextral rotations seem to last until the early late Miocene which is later than the end of the Japan Sea opening.

During the opening of the Japan Sea, major strike-slip shear zones were active such as those in central Hokkaido and Sakhalin, and older strike-slip faults such as the MTL or TTL were reactivated. We describe in the following the geometry of deformation of the arc during the opening seen from the view point of the structural geologist and see how it is related to the geometry of opening.

DEFORMATION OF THE JAPAN ARC DURING THE JAPAN SEA OPENING

Oceanic crust occurs in only a restricted area in the northern part of the Japan Sea (Figure 1). Magnetic anomalies identified by *Kobayashi et al.* [1988] suggest that it dates back to the early Miocene. The geometry of anomalies also suggests that the spreading center had been propagating westward during the opening [*Tamaki et al.*, 1992; *Jolivet and Tamaki*, 1992]. This inference is supported by the general triangular shape of the area where oceanic crust is distributed with a wide base along the EJSSZ and a tip further west in the Russian waters. In other regions of the Japan Sea, geophysical surveys have shown that no true oceanic crust is present even in deep basins. The seismic velocity structure of the Tsushima and Yamato basins suggest that they are floored by a thinned continental crust intruded by numerous basaltic sills [*Tokuyama et al.*, 1987]. True continental crust, similar to that of the Japan arc, is found under the Yamato Bank, which has been stranded during the southeastward drift of SW Japan. The Japan Sea can thus be divided into two very different regions. The northern part is characterized by the presence of oceanic crust and a very narrow margin on the Japanese side. Little is known on the Siberian side, but bathymetry also suggests a narrow margin. On the other hand the western part of the Japan Sea was formed by distributed intra-continental extension.

Major Dextral Strike-Slip Shear Zones

As described in several earlier papers [*Lallemand and Jolivet*, 1985; *Jolivet et al.*, 1991; *Jolivet et al.*, 1992; *Fournier et al.*, 1994] the eastern margin of the Japan Sea is paralleled by a major dextral shear zone which trends N-S from the northern tip of Sakhalin to central Japan (Figures 1 and 2). The most obvious zones of strain localization within this shear zone are the Hidaka shear zone (central Hokkaido) and the Tym-Poronaisk fault (central Sakhalin). The Hidaka shear zone runs along 200 km in southern Hokkaido and shows a complete crustal section from brittle to ductile structures compatible with a dextral shear with a component of westward thrusting. Farther north and west, en echelon folds and thrusts [*Kimura et al.*, 1983] form part of the same dextral shear. Radiometric dating of the high temperature metamorphism contemporaneous with the dextral motion, as well as paleostress tensor analysis in the external domains where biostratigraphy allows dating of the successive tectonic events, suggests that the dextral motion has been active from the late Oligocene to the middle Miocene [*Jolivet and Huchon,* 1989]. As discussed above, recent paleomagnetic data [*Kodama et al.*, 1993] in central Hokkaido suggest that the dextral motion might have lasted until the late Miocene though different interpretations of the same data are still probably possible (see discussion in *Jolivet*, 1994). The dextral strike-slip motion stopped sometime in the late Miocene, and the Hidaka shear zone was reworked as a thrust fault, in the hanging wall of which the Hidaka mountains were recently uplifted.

The Tym-Poronaisk fault [*Rozhdestvenskiy*, 1982] divides the island of Sakhalin into two narrow stripes. The western side shows en echelon folds in Cretaceous and early Cenozoic sediments similar to those of Hokkaido which suggest a component of dextral shear. Tectonic analysis of the Tym-Poronaisk fault itself shows that it is made of N-S trending strike-slip segments alternating with NW-SE trending thrust faults. Paleostress analysis near the fault suggests that a transpressional regime has been active during the Miocene until recently; the abrupt change in stress regime seen in Hokkaido is not obvious here though the dextral shear seems less active now [*Jolivet et al.*, 1992, *Fournier et al.*, 1994]. The East Sakhalin mountains are cut by several NE-trending dextral strike-slip faults which branch from the Tym-Poronaisk fault like R-Riedel shears. Counterclockwise rotation of the stripes in between are inferred by *Fournier et al.* [1994], but no paleomagnetic data are yet available to test this hypothesis. A major N-S trending strike-slip fault runs offshore along the western margin of Sakhalin and it led to the formation of second order pull-apart basins in the Tatar Strait.

The transpressional dextral shear zone of Sakhalin and Hokkaido is more than 1000 km long. It is relayed at the latitude of SW Hokkaido by a narrow zone of transtensional dextral shear parallel to the margin of the Japan Sea. En echelon grabens and dextral strike-slip faults are seen offshore. Paleostress analysis in this region from Oga Peninsula to Sado island and Noto peninsula [*Jolivet et al.*, 1991, *Fournier et al.*, 1994] shows that the direction of the extensional principal stress has been oblique on the margin with a NW-SE trend. It is seen in rocks older than the late Miocene. It is then replaced by the E-W compression that is active today, as attested to by the frequent compressional tsunamigenic earthquakes on this side of the Japan arc [*Nakamura,* 1983; *Fukao and Furumoto*, 1975; *DeMets*, 1992]. This zone of transtensional dextral shear divides the NE Japan arc from the oceanic crust of the northern Japan Sea and has been active during its spreading. The Japan Sea is thus bordered on its eastern side by a major dextral shear zone, more than 2000 km long including the transpressional and the transtensional domains, which was active from the late Oligocene to the middle or late Miocene and is still active in the north.

A second dextral strike-slip shear zone is known along the southeastern coast of Korea and in the Tsushima Strait [*Otsuki and Ehiro*, 1978]. The NE-trending Yangsan fault offsets the Cretaceous Bulgugsa granites by several tens of kilometers. It also offsets metallogenic belts of Korea, which are then offset again dextrally on the Japanese side of the Tsushima Strait [*Sillitoe*, 1977]. The direction of early Miocene basaltic dykes intruding the Miocene Pohang basin is compatible with dextral motion along the Yangsan fault [*Lee*, 1988]. Paleostress analysis in the Cretaceous Gyongsan basin and the Miocene Pohang Basin shows two successive stages of dextral motion during the late Oligocene and early Miocene [*Hwang*, 1992]. This shear zone was thus active while the Japan Sea was opening.

The geology of Tsushima island is puzzling in this context. It clearly shows en echelon folds and thrusts formed inside a left-lateral shear zone parallel to the dextral one previously described. Recent observations by *Fabbri and Charvet* [1994] suggest that this compressional deformation occurred more recently than the Japan Sea opening (from 15 Ma onward) and was preceded by a phase of dextral shear. What is more puzzling is that focal mechanisms of earthquakes in the western part of the Japan Sea [*Jun*, 1990] are compatible with a mixture of shortening perpendicular to the Yangsan fault and dextral strike-slip. Similar mechanisms are seen further inland in the gulf of Bohai [*Chen and Nabelek*, 1988]. The left-lateral event is thus bracketed between two episodes of right-lateral motion.

Reactivated Shear Zones

Formed initially as a left-lateral strike-slip fault in the Late Cretaceous and early Cenozoic the Tanakura tectonic line was reactivated as a dextral shear zone during the Miocene [*Otsuki and Ehiro*, 1978] though the Miocene offset is probably small. Parallel faults cut through the basement of the Abukuma massif such as the Futaba fault.

The Median Tectonic Line is a very large shear zone which runs E-W between the inner and outer zones of SW Japan [*Ichikawa*, 1980]. It was most active during the Late Cretaceous and early Cenozoic as a left-lateral fault. Ductile deformation is observed on its northern side in the granitoids of the Cretaceous Ryoke belt. It is active today as a dextral strike-slip shear zone that accommodates the dextral component of the oblique subduction of the Philippine Sea Plate under SW Japan.

Very little is known on the behavior of the MTL during the Miocene. *Jolivet et al.* [1989] suggested that it had already reversed its motion to a dextral shear because of the apparent dextral torsion of paleomagnetic directions near the fault. Recent observations of trend of Miocene dikes by *Takeshita* (oral communication, 1990) on the contrary suggest that it was left-lateral around 15 Ma. *Fournier*'s [1994] recent observations confirm Takeshita's findings. Not only do the trends of Miocene basaltic dikes imply a left-lateral component of motion, but also the fault set analysis we performed in Miocene basins distributed along the fault is compatible with this sense of motion with an additional component of extension perpendicular to the fault. Observation in the west (Shikoku) shows the MTL as a normal fault while in the east (Shidara basin) it has a significant left-lateral component. No evidence is known for the amount of relative left-lateral displacement during the Miocene

Distributed Deformation in SW Japan

The rotations of dominoes can produce an apparently homogenous strain field if only rotations are taken into account and the dominoes are not identified. The linearity of the MTL and other boundaries between the belts of SW Japan precludes major internal strain in a first approach. Linearity is, however, a characteristic of strike-slip shear zones and, because outcrops of SW Japan are far from continuous, some important shear zones bounding dominoes might have been missed by geologists. Already *Kanaori* [1990] recognized large-scale fault-bounded blocks in SW Japan.

To approach this problem we surveyed the San'in district (central SW Japan on the backarc side) where *Otofuji et al.* [1991] have recognized a fast clockwise rotation at about 15 Ma. The deformation is very different depending upon the observed stratigraphic level. Miocene strata older than 15 Ma show both normal and strike-slip faults and the inferred direction of extension varies from WNW-ESE to NW-SE. Shimane peninsula (Figures 1 and 5) is the area where *Otofuji et al.* [1991] obtained some of the measurements indicating a fast rotation of SW Japan at 15 Ma. *Fournier* [1994] has performed paleostress analysis using fault sets with *Angelier*'s [1984] method. The paleostress tensors are shown on Figure 5. A mixture of strike-slip and extensional tensors is observed plus some additional compressional ones that are related to the recent compression. The mean direction of extension (Figure 5) is NW-SE, which is compatible with the general dextral pull-apart geometry. Figure 6 shows a simplified block diagram of a measured site on the western tip of the Shimane peninsula where pure N150°E dextral strike-slip faults and N50°E left-lateral and normal faults were observed. The computed stress tensor [*Angelier*, 1984] (Figure 7) implies a strike-slip regime with σ_1 and σ_3 horizontal. This outcrop is a good example of how the brittle deformation is distributed in the older Miocene strata. Here N150°E dextral strike-slip faults are regularly spaced every two meters. These are large fault planes, several tens of meters long. Oblique to this first set is a second one that trends N50°E on average and which corresponds to oblique slip faults with a component of left-lateral slip and a component of normal slip. These planes are also regularly spaced every meter or so and are never longer than 2 or 3 m. They show normal offsets of approximately 30 cm. The offsets induced by the first set of faults are not seen in the outcrop. Inside the blocks defined by these two sets of faults a third set (N20°E) with very small offsets are observed. These are dextral faults but no striae could be seen. The two largest sets of faults define regularly spaced dominoes and the geometry implies a clockwise rotation (Figure 6). Similar outcrops were observed along the coastline of the San'in district with the same regular spacing of faults and several sets with smaller offsets on smaller faults [*Fournier*, 1994]. This deformation is characteristic of the Kawai-Kuri and older formations. The Kawai-Kuri formation is dated by *Otofuji et al.* [1991] as 16.0 ± 1.4 Ma.

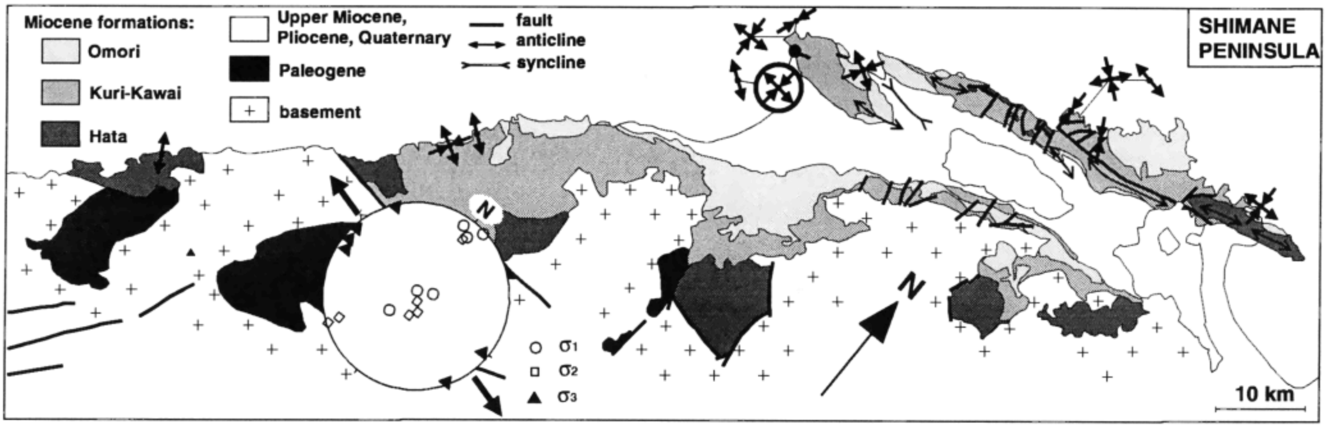

Fig. 5. Simplified geological map of Shimane peninsula (see Figure 1 for location) and paleostress tensors deduced from inversion of fault kinematic data [*Angelier*, 1984]. The site discussed detailed in Figures 6 and 7 is located by a black dot and the computed tensor is circled. Insert: 6 stress tensors with σ_3 horizontal showing a mean direction of extension ENE-WSW [after *Fournier*, 1994].

Younger formations such as the Omori formation (14.2 ± 0.6 Ma) do not show this deformation. Most of the outcrops are little deformed and show only tilting and long wavelength folding which can be attributed to very recent deformation. Only one outcrop in the Omori formation showed a set of faults that indicates a NE-trending compression, which could be compatible with the NW-trending extension described above. It could also be the local result of folding and thus have no relation with the older deformation. Except for this outcrop, all formations younger than the Kawai-Kuri formation are little deformed and never show the fault-bounded domino geometry seen below.

According to *Otofuji et al.* [1991], the Omori formation did not suffer the clockwise rotation observed in the underlying rocks; this allowed them to constrain the timing of rotational motion of SW Japan to a very short period about 15 Ma. We see from this example that the rotation was locally accompanied by a strong internal deformation with a domino geometry. Because the outcrops are not continuous enough to draw a complete map of these structures it is impossible to quantify the amount of finite internal deformation of SW Japan. Furthermore the blocks we have seen might be only second or third order blocks within larger ones which are more difficult to see. We can only conclude that some internal deformation of SW Japan occurred during the paleomagnetic rotation and thus that the 50° rotation is only partly rigid. *Kanaori* [1990] proposed a similar geometry at the scale of central Japan.

STRIKE-SLIP SHEAR ZONES AND PALEOMAGNETIC ROTATIONS

Jolivet et al. [1991] used the internal structure of the Japan Sea to close it back to its pre-opening position. One of the constraints was the shape of the northern side of the Yamato Bank, which fits reasonably with the 2000 m isobath of a portion of the Siberian coast. This allowed them to calculate an approximate pole of rotation which falls in the Tsushima Strait. The same authors used the same geometry to rotate SW Japan back to its position before opening and obtained a finite rotation about the same pole of 30° clockwise. This was based upon the assumption that the Yamato basin was floored with oceanic crust, which has since been proved wrong. [*Tamaki et al.*, 1992]. The 30° of rotation completely closes the Yamato basin and the western part of the Japan basin. The presence of highly stretched continental crust instead of oceanic crust is an argument to reduce the finite rotation. However the thickness of the Japan arc crust before the Japan Sea opening is not known precisely enough and it is then impossible to calculate the thinning factor. We shall then consider that 30° of clockwise rigid rotation of SW Japan is a maximum. The remaining 20° must be found in the internal strain we have described above.

The rigid clockwise rotation of SW Japan is compatible with a left-lateral motion along the MTL in a simple domino model. SW Japan inner zones and outer zones can be considered as 600 km long dominoes, bounded by left-

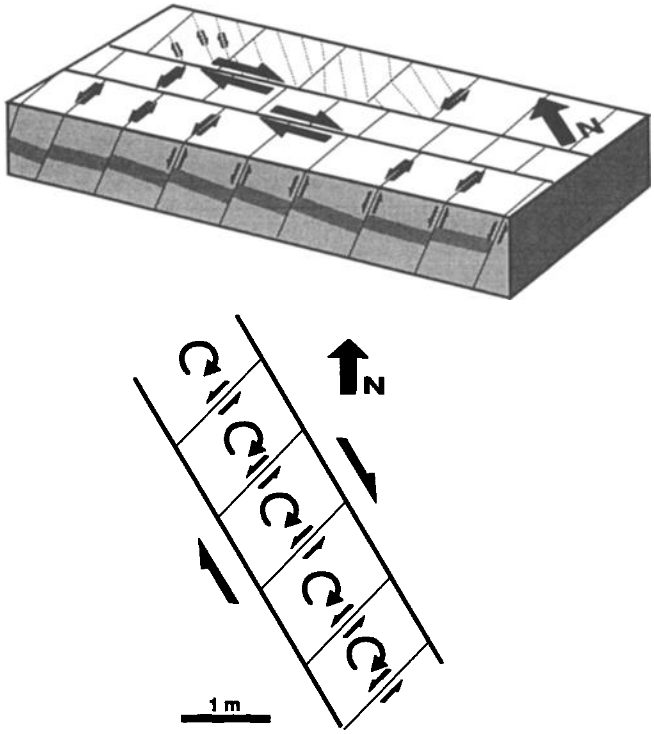

Fig. 6. Schematic representation of an outcrop in the Kawai-Kuri formation in Shimane peninsula showing the distribution of strain along the boundaries of small blocks and implying dextral rotation.

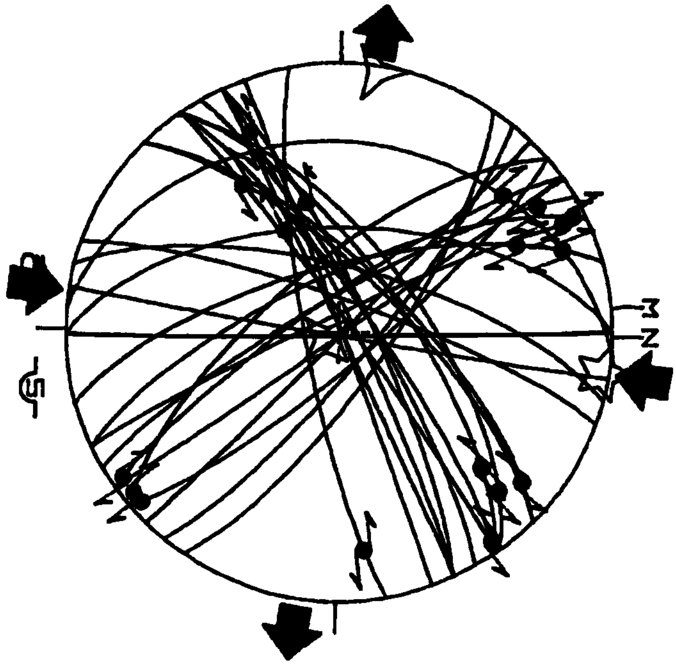

Fig. 7. Stress tensor inferred from the faults measured on the outcrop shown in Figure 6 with *Angelier*'s method [1984].

lateral E-W cross faults (MTL) and N-S dextral master faults.

To properly close the northern part of the Japan Sea, a 20° counterclockwise rotation was used in *Jolivet et al.* [1991]. This number is similar to what is given by paleomagnetic data for this region.

We can already conclude that if one accepts that a part of the clockwise rotation of SW Japan is due to internal strain actually observed at the time of paleomagnetic rotations, there is no major conflict between paleomagnetic data and the dextral pull-apart model.

Paleomagnetic studies along the major shear zones have shown that local rotation occurs and can be related to the observed deformation in Hokkaido and Sakhalin. Local rotation effects are also observed along less important shear zones such as the Tanakura tectonic line.

RECONSTRUCTIONS

The reconstructions shown here (Figure 8) are simplified from those described in *Jolivet and Tamaki* [1992]. The entire Japan Sea is considered as a wide dextral pull-apart zone between two major dextral strike-slip shear zones. The largest one is along the eastern margin of the Japan Sea and in Hokkaido and Sakhalin. A second one divides the Korean peninsula from SW Japan. The 30° of clockwise rotation of SW Japan accommodates the difference in the amount of offset on these two shear zones. In the reconstructions 400 km of dextral offset are imposed on the eastern shear zone and only 150 km on the western one. Extension is distributed in the domain of relay between these two shear zones; it eventually localizes at the southern tip of the eastern transpressional domain and finally leads to a complete rupture of the crust and formation of oceanic crust in a triangular zone. The geometry of the oceanic domain is that of a crustal-scale tension crack propagating westward near the end of a strike-slip shear zone. Crustal thinning continues even after the initiation of the spreading center, in the southern part of the Japan Sea. On the reconstructions only the rigid rotations are shown. Local rotations along the major shear zones occur in the meantime. Extension, spreading and strike-slip motion last until the middle Miocene, with strike-slip motion alone until recent time in the north (Sakhalin). After 10 Ma, a compressional stress field forms in NE Japan and the deformation progressively localizes along the eastern margin where compressional earthquakes

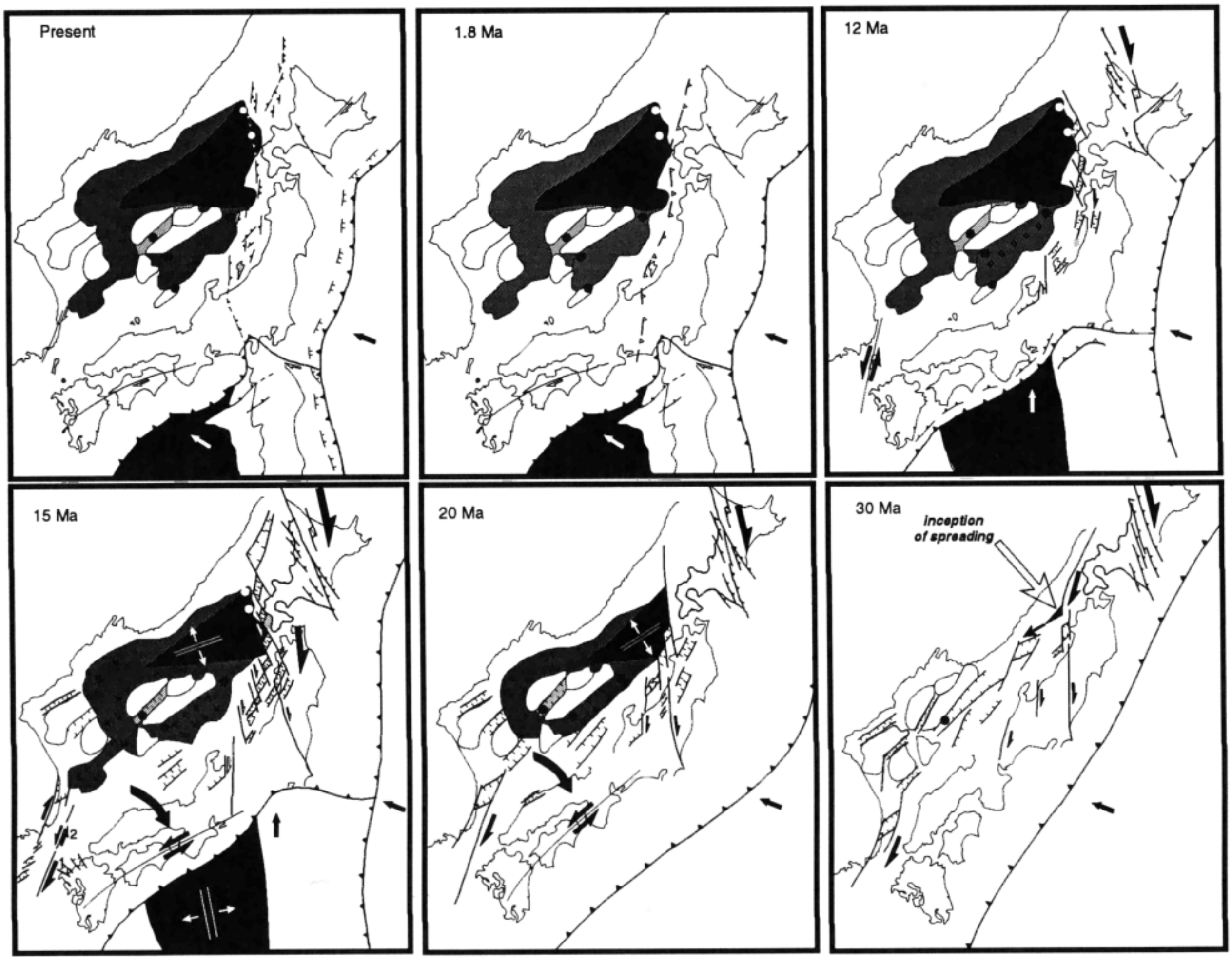

Fig. 8. Reconstructions of the Japan Sea evolution from 30 Ma to the present. Oceanic crust is shown in black and stretched continental crust in gray. Black and white dots represents ODP legs 127 and 128 drilling sites.

are recorded nowadays. This zone has been interpreted as a future subduction zone by *Nakamura* [1983].

CONCLUSION

This paper shows that the pull-apart model and the amounts of paleomagnetic rotations of SW and NE Japan can be compatible. The left-lateral behavior of the MTL during the Miocene accommodated the clockwise rotation of SW Japan between the two major dextral strike-slip faults, one along Sakhalin, Hokkaido, and NE Japan, and one between the Korean peninsula and SW Japan. One has, however, to accept that a part of the 50° of clockwise rotation of SW Japan is due to internal deformation of the rotating blocks with second order dominoes. The observation of such distributed brittle deformation in San'in district is in favor of this conclusion.

Local dextral rotations are seen along the major dextral shear zones in Sakhalin and Hokkaido, as well as along the Tanakura tectonic line and the Futaba fault. This geometry shows that rotations involve blocks of different sizes, major blocks such as SW Japan, smaller blocks along the major shear zones, or inside the major blocks as we have seen in San'in district. It is thus most important that the paleomagnetic sampling is made in connection with a precise identification of block boundaries.

The timing of rotation remains difficult to reconcile with other evidence for the age of opening. It is inescapable that the clockwise rotation of a 600 km block must leave a hole of the size of the Japan Sea, and thus the rotation and the basin formation should have the same age. The evidence for rifting and spreading before the given age for the rotation cannot be ignored. There must then be a problem in the timing of rotation. The discussion of radiometric dating in San'in suggest that the error bar might be much larger than suspected by *Otofuji et al.* [1991]. We suggest that the data be reconsidered without averaging the ages nor the declinations, and that measurements be made on the basis of a structural map showing the possible tectonic boundaries in order to differentiate between first and second order rotations. This job might be difficult to do in Japan because of poor outcrop conditions, but this difficulty must be taken into account when giving uncertainties on the values and ages of rotation.

Acknowledgments. This short discussion comes after many years of research in Japan in the field as well as onboard oceanographic vessels. Laurent Jolivet is indebted to many of his colleagues in Japan, among them M. Nakagawa, N. Kito, T. Bamba, S. Miyashita and his family, G. Kimura. Special thanks to K. Tamaki for his efforts to promote ODP drilling in the Japan Sea and his help to understand the geometry of opening of the Japan Sea. Thanks also to J. P. Cadet, J. Charvet, X. le Pichon, P. Huchon, P. Davy, J. P. Brun and C. Rangin. Thanks to V. Rozhdestvenskiy, K. Sergeyev, O. Melnikov, R. Kovalenko and H. Gnibidenko for the help they provided in the field in Sakhalin. We benefited also from discussions with T. Ohguchi, K. Kaneko, Y. I. Otofuji, R. Tada and A. Yamaji. S. Uyeda and J. F. Dewey have also encouraged this work. Y. Otofuji kindly suggested to us papers to read and provided us with data before these were published.

REFERENCES

Amano, K., and H. Sato, Neogene tectonics of the central part of the Northeast Honshu arc, *Mem. Soc. Geol. Jpn.*, 32, 81-96, 1989.

Angelier, J., Tectonic analysis of faultslip data sets, *J. Geophys. Res.*, 89, 5835-5848, 1984.

Charvet, J., K. Grimm, J. Griffin, L. Jolivet, and A. Pouclet, Structural features in ODP leg 128 cores: relationship with the tectonic evolution of the Japan Sea, in *Proc. ODP, Sci. Results, 127-128*, part 2, edited by K. Tamaki, K. Suyehiro, J. Allan and M. McWilliams, pp. 1175-1193, Ocean Drilling Program, College Station, TX, 1992.

Chen, W. P., and J. Nabelek, Seismogenic strike-slip faulting and the development of the North China basin, *Tectonics*, *7*, 975-989, 1988.

De Mets, C., A test of present-day plate geometries for northeast Asia and Japan, *J. Geophys. Res.*, *12*, 17,627-17,636, 1992.

Fabbri, O., and J. Charvet, Paleocontraintes et mouvements decrochants dans le détroit de Corée d'après l'exemple des îles Tsushima (Japon Sud-Ouest), *C. R. Acad. Sci. Paris*, *318*, 397-404, 1994.

Fournier, M., Ouverture de bassins marginaux et déformation continentale: l'exemple de la Mer du Japon, Thèse Université Pierre et Marie Curie, Paris, 1994.

Fournier, M., L. Jolivet, P. Huchon, V. S. Rozhdestvensky, K. F. Sergeyev, and L. Oscorbin, Dextral motion in Sakhalin, and the Japan Sea opening, *J. Geophys. Res.*, *99*, 2701-2725, 1994.

Fujioka, K., Synthesis of Neogene explosive volcanism of the Tohoku arc, deduced from the marine tephra drilled around the Japan trench region, Deep Sea Drilling Project Legs 56, 57 and 87B, in *Init. Repts. DSDP*, 87, H. Kagami, D. E. Karig, W. T. Colbourn, et al., pp. 703-721, U.S. Govt. Printing Office, Washington D.C., 1986.

Fukao, Y., and M. Furumoto, Mechanisms of large earthquakes along the eastern margin of the Japan sea, *Tectonophysics*, *25*, 247-266, 1975.

Hayashida, A., Timing of rotational motion of southwest Japan inferred from paleomagnetism of the Setouchi Miocene series, *J. Geomagn. Geoelectr.*, *38*, 295-310, 1986.

Hayashida, A., and I. Y. Ito, Paleoposition of southwest Japan at 16 Ma: implication from magnetism of the Miocene Ichishi group, *Earth Planet. Sci. Lett.*, *68*, 335-342, 1984.

Hayashida, A., T. Fukui, and M. Torii, Paleomagnetism of the early Miocene Kano Group in Southwest Japan and its implication for the opening of the Japan Sea, *Geophys. Res. Lett.*, *18*, 1095-1098, 1991.

Hirooka, K., H. Sakai, T. Takahashi, H. Kinoto, and A. Takeuchi, Tertiary tectonic movement of central Japan inferred from paleomagnetic studies, *J. Geomagn. Geoelectr.*, *38*, 311-323, 1986.

Hyodo, H., and N. Niitsuma, Tectonic rotation of the Kanto mountains, related with the opening of the Japan Sea and collision of the Tanzawa block since Middle Miocene, *J. Geomagn. Geoelectr.*, *38*, 335-348, 1986.

Hwang, J. H., L'évolution tectonique post-Jurassique de la Corée: apport des reconstitutions des paleocontraintes dans les bassins Crétacé méridionaux, Thèse université Pierre et Marie Curie, Paris, 1992.

Ichikawa, K., Geohistory of the Median Tectonic Line of Southwest Japan, *Mem. Geol. Soc. Jpn.*, *18*, 187-212, 1980.

Iijima, A., and R. Tada, Evolution of Tertiary sedimentary basins of Japan in reference to opening of the Japan Sea, *J. Fac. Sci., Tokyo Univ.*, 22, 121-171, 1990.

Ingle, C. J., Subsidence of the Japan Sea: stratigraphic evidence from ODP sites and onshore sections, in *Proc. ODP, Sci. Results, 127/128*, K. Tamaki, K. Suyehiro, J. Allan, M. McWilliams, et al., pp. 1197-1218, Ocean Drilling Program, College Station, TX, 1992.

Ishikawa, N., and T. Tagami, Paleomagnetism and fission-track geochronology on the Goto and Tsushima islands in the Tsushima Strait area: implications for the opening mode of the Japan Sea, *J. Geomagn. Geoelectr.*, *43*, 229-253, 1991.

Ishikawa, N., M. Torii, and K. Koga, Paleomagnetic study of the Tsushima Islands, southern margin of the Japan Sea, *J. Geomagn. Geoelectr.*, *41*, 797-811, 1989.

Ito, H., and K. Tokieda, An interpretation of paleomagnetic results from Cretaceous granites in South Korea, *J. Geomagn. Geoelectr.*, *32*, 275-284, 1980.

Ito, H., and K. Tokieda, K., Tilting movements of the Japanese islands inferred from Cretaceous and Early Tertiary paleomagnetic data, *J. Geomagn. Geoelectr.*, *38*, 361-386, 1986.

Ito, H., K. Tokieda, and Y. Notsu, A paleomagnetic approach to possible tilting movements of Kitakami mountains and Oshima peninsula of Hokkaido, *Rock Mag. Paleogeophys.*, *7*, 113-117, 1980.

Itoh, Y., Differential rotation of the eastern part of southwest Japan inferred from paleomagnetism of Cretaceous and Neogene rocks, *J. Geophys. Res.*, *93*, 3401-3411, 1988.

Jolivet, L., Comment on "Clockwise tectonic rotation of Tertiary sedimentary basins in central Hokkaido, northern Japan," by K. Kodama, T. Takeuchi and T. Ozawa, *Geology*, 21, 431-434, 1993, *Geology, 22*, 94-95, 1994.

Jolivet, L., and Ph. Huchon, Crustal scale strike-slip deformation in Hokkaido, Northeast Japan, *J. Struct. Geol.*, *11*, 509-522, 1989.

Jolivet, L., and K. Tamaki, Neogene kinematics in the Japan Sea region and the volcanic activity of the Northeast Japan arc, in *Proc. ODP, Sci. Results, 127/128*, K. Tamaki, K. Suyehiro, J. Allan, M. McWilliams, et al., pp. 1311-1331, Ocean Drilling Program, College Station, TX, 1992.

Jolivet, L., P. Huchon, and C. Rangin, Tectonic setting of Western Pacific marginal basins, *Tectonophysics*, *160*, 23-47, 1989.

Jolivet, L., Ph. Huchon, J. P. Brun, N. Chamot-Rooke, X. Le Pichon, and J. C. Thomas, Arc deformation and marginal basin opening, Japan Sea as a case study, *J. Geophys. Res.*, *96*, 4367-4384, 1991.

Jolivet, L., M. Fournier, P. Huchon, V. S. Rozhdestvenskiy, K. F. Sergeyev, and L. S. Oscorbin, Cenozoic intracontinental dextral motion in the Okhotsk-Japan Sea region, *Tectonics*, *11*, 968-977, 1992.

Jun, M. S., Source parameters of shallow intraplate earthquakes in and around the Korean peninsula and their tectonic implication, *Acta Universitatis Upsaliensis, Comprehensive Summaries of Uppsala Dissertation from the Faculty of Science*, *285*, Uppsala, 1990.

Kanaori, Y., Late Mesozoic - Cenozoic strike-slip and block rotation in the inner belt of Southwest Japan, *Tectonophysics*, *177*, 381-399, 1990.

Kawai, N., H. Ito, and S. Kume, Deformation of the Japanese islands as inferred from rock magnetism, *Geophys. J. R. Astron. Soc.*, *6*, 124-130, 1961.

Kawai, N., K. Hirooka, and T. Nakajima, Paleomagnetic and potassium-argon age information supporting Cretaceous-Tertiary hypothetic bend of the main island, Japan, *Palaeogeogr. Palaeoclim. Palaeoecol.*, *6*, 277-282, 1969.

Kawai, N., T. Nakajima, and K. Hirooka, The evolution of the island arc of Japan and the formation of granites in the circum Pacific belt, *J. Geomagn. Geoelectr.*, *23*, 267-293, 1971.

Kim, K. H., J. K. Won, J. Matsuda, K. Nagao, and M. W. Lee, Paleomagnetism and K-Ar age of volcanic rocks from Guryongpo area, Korea, *J. Korean Inst. Mining Geol.*, 19, 231-237, 1986.

Kimura G., S. Miyashita, and S. Miyasaka, Collision tectonics in Hokkaido and Sakhalin, in *Accretion Tectonics in the Circum Pacific Regions*, edited by M. Hashimoto and S. Uyeda, pp. 117-128, Terrapub, Tokyo, 1983.

Kobayashi, K., K. Tamaki, M. Nakanishi, N. Isezaki, and K. Sayanagi, Complex pseudofault pattern of the Japan Sea - results of detailed geomagnetic survey, *EOS Trans. AGU*, *67*, 1227, 1988.

Kodama, K., and K. Nakayama, Paleomagnetic evidence for post-Late Miocene intra-arc rotation of south Kyushu, Japan, *Tectonics*, *12*, 35-47, 1993.

Kodama, K., T. Ozawa, K. Inoue, Y. Maeda, and T. Tohru, Paleomagnetism and post-Middle Miocene counter-clockwise rotation of Tanegashima island off Kyushu, Japan, *J. Geomagn. Geoelectr.*, *43*, 721-740, 1991.

Kodama, K., T. Takeuchi, and T. Ozawa, Clockwise tectonic rotation of Tertiary sedimentary basins in central Hokkaido, northern Japan, *Geology, 21*, 431-434, 1993.

Lallemand, S., and L. Jolivet, Japan Sea: a pull apart basin. *Earth Planet. Sci. Lett.*, *76*, 375-389, 1985.

Lee, J. S., Pétrologie et relations structurales des volcanites Crétacé à Cénozoïques de la Corée du Sud: implications géodynamiques sur la marge est-eurasiatique, Thèse Université d'Orléans, 1988.

Momose, H., M. Torii, and H. Tanaka, Counterclockwise paleomagnetic direction from the Gongenyama Formation (N9-N10) on the coastal area of Northeast Japan, *Rock. Mag. Paleogeophys.*, *17*, 47-50, 1990.

Nakamura, K., Possible nascent trench along the eastern Japan sea as the convergent boundary between Eurasia and North American plates (in Japanese), *Bull. Earthquake Res. Inst.*, *58*, 721-732, 1983.

Nakamura, K., and S. Uyeda, Stress gradient in back arc regions and plate subduction, *J. Geophys. Res.*, *85*, 6419-6428, 1980.

Oda, H., M. Torii, and A. Hayashida, Paleomagnetic study and fission-track dating in Yanagawa and Takadate area, Northeast Japan, *Rock Mag. Paleogeophys.*, *19*, 231-237, 1989.

Otofuji, Y., and T. Matsuda, Paleomagnetic evidence for the clockwise rotation of Southwest Japan, *Earth. Planet. Sci. Lett.*, *62*, 349-359, 1983.

Otofuji, Y., and T. Matsuda, Timing of rotational motion of Southwest Japan inferred from paleomagnetism, *Earth Planet. Sci. Lett.*, *70*, 373-382, 1984.

Otofuji ,Y., and T. Matsuda, Amount of clockwise rotation of Southwest Japan - fan shape opening of the southwestern part of the Japan Sea, *Earth Planet. Sci. Lett.*, *85*, 289-301, 1987.

Otofuji, Y., T. Matsuda, and S. Nohda, Paleomagnetic evidences for the Miocene counterclockwise rotation of northeast Japan - rifting process of the Japan arc, *Earth Planet. Sci. Lett.*, *75*, 265-277, 1985.

Otofuji, Y., T. Itaya, and T. Matsuda, Rapid rotation of southwest Japan - paleomagnetism and K-Ar ages of Miocene volcanic rocks of southwest Japan, *Geophys. J. Int.*, *105*, 397-405, 1991.

Otofuji, Y., A. Kambara, T. Matsuda, and S. Nohda, Counterclockwise rotation of northeast Japan: paleomagnetic evidence for regional extent and timing of rotation, *Earth Planet. Sci. Lett.*, *121*, 503-518, 1994.

Otsuki, K., Reconstruction of Neogene tectonic stress field of Northeast Honshu arc from metalliferous veins, *Mem. Soc. Geol. Jpn.*, *32*, 281-304, 1989.

Otsuki K., and M. Ehiro, Major strike slip faults and their bearing on the spreading of the Japan Sea, *J. Phys. Earth, supplement issue, 26*, 537-555, 1978.

Rozhdestvenskiy, V. S., The role of wrench faults in the structure of Sakhalin, *Geotectonics*, *16*, 323-332, 1982.

Sillitoe, R. H., Metallogeny of an Andean type continental margin in South Korea, implications for opening of the Japan Sea, in *Island Arcs, Deep Sea Trenches and Back Arc Basins, Maurice Ewing Ser.*, vol. 1, edited by M. Talwani and W. C. Pitman III, pp. 303-310, AGU, Washington, D. C., 1977.

Sugi, N., K. Chinzei, and S. Uyeda, Vertical crustal movements of northeast Japan since middle Miocene, in *Geodynamics of the Western Pacific and Indonesian Region, Geodynamic Ser.*, vol. 11, edited by W. C. T. Hilde and S. Uyeda, pp. 317-329, AGU, Washington, D.C., 1983.

Sugimura, A., T. Matsuda, K. Chinzei, and K. Nakamura, Quantitative distribution of late Cenozoic volcanic material in Japan, *Bull. Volcanol.*, *26*, 125-140, 1963.

Suzuki, K., On the Late Cenozoic history in the southern part of northeast Honshu in Japan, *Mem. Geol. Soc. Jpn.*, *32*, 97-112, 1989.

Tagami, T., Paleomagnetism and fission-track ages of the Kumano acidic rocks, *News of Osaka Micropaleontologists*, *9*, 23-32, 1982.

Takeuchi, T., T. Ozawa, and K. Kodama, Paleomagnetism of the Late Cretaceous to Neogene deposits in central Hokkaido, Japan and south Sakhalin of the USSR: multiple rotations caused by transcurrent faults (abstract), 29th International Geological Congress, Kyoto, 24 August-3 September 1992, 108, 1992.

Tamaki, K., Age estimation of the Japan sea on the basis of stratigraphy, basement depth and heat flow data, *J. Geomagn. Geoelectr.*, *38*, 427-446, 1986.

Tamaki, K., Geological structure of the Japan sea and its tectonic implications, *Bull. Geol. Surv. Jpn.*, *39*, 269-365, 1988.

Tamaki, K., K. Suyehiro, J. Allan, J. C. Ingle, and K. Pisciotto, Tectonic synthesis and implications of Japan Sea ODP drilling, in *Proc. ODP, Sci. Results, 127/128*, K. Tamaki, K. Suyehiro, J. Allan, M. McWilliams, et al., pp. 1333-1350, Ocean Drilling Program, College Station, TX, 1992.

Tokuyama, H., M. Suyemasu, K. Tamaki, E. Nishiyama, S. Kuramoto, K. Suyehiro, H. Kinoshita, and A. Taira, Report on DELP cruises in the Japan Sea, Part III: seismic reflection studies in the Yamato Basin and the Yamato Rise area, *Bull. Earthq. Res. Inst., Univ. Tokyo*, *62*, 367-390, 1987.

Torii, M., Paleomagnetism of Miocene rocks in the Setouchi province: evidence for rapid clockwise rotation of Southwest Japan in middle Miocene time, Ph. D. Thesis, Kyoto Univ., 1983.

Tosha, T., and Y. Hamano, Paleomagnetic study on the dyke swarm in the Oga peninsula, Northeast Honshu island, *J. Geomagn. Geoelectr.*, *38*, 349-360, 1986.

Tosha, T., and Y. Hamano, Paleomagnetism of Tertiary rocks from the Oga peninsula and the rotation of northeast Japan, *Tectonics*, *7*, 653-662, 1988.

Tsuchiya, N., Submarine basalt volcanism of Miocene Aosawa formation in the Akita-Yamagata oil filed basin, back-arc region of northeast Japan, *Mem. Geol. Soc. Jpn.*, *32*, 399-408, 1989.

Tsuchiya, N., Middle Miocene back-arc rift magmatism of basalt in the Northeast Japan arc, *Bull. Geol. Surv. Jpn.*, *41*, 473-505, 1990.

Usuta, M., Geotectonic history of the southern part of Akita prefecture, Northeast Japan, *Mem. Geol. Soc. Jpn.*, *32*, 57-80, 1989.

Yamaji, A., Geology of Atsumi area and early Miocene rifting in the Uetsu district, northeast Japan, *Mem. Geol. Soc. Jpn.*, *32*, 305-320, 1989.

Yamaji, A., Rapid intra-arc rifting in Miocene northeast Japan, *Tectonics*, *9*, 365-378, 1990.

Yamazaki, T., Paleomagnetism of Miocene sedimentary rocks around Matsushima Bay, Northeast Japan and its implication for the time of the rotation of Northeast Japan, *J. Geomagn. Geoelectr.*, *41*, 533-548, 1989.

Yaskawa, K., On the paleomagnetic approach to the origin of the Japan Sea, *Nihon Kai (Japan Sea)*, *10*, 120-126, 1979, in Japanese.

L. Jolivet, and M. Fournier, Laboratoire de Géologie, Ecole Normale Supérieure, 24 rue Lhomond, 75231 Paris cedex 05, France

H. Shibuya, Department of Earth Sciences, University of Osaka Prefecture, Sakai 593, Japan