学位申請論文

伊藤康人

主論文 1

Miocene Tectonic Movements of Southwest Japan Inferred from Paleomagnetic Studies

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Contents

1. INTRODUCTION

The Japan arc–Japan Sea pair is one of the most intensely studied island arc–back arc basin systems in the western Pacific (Fig. 1). The Japan arc is divided into Southwest Japan, west of the Itoigawa-Shizuoka tectonic line (ISTL), and Northeast Japan, east of the ISTL (Fig. 1), on the basis of Neogene tectonics. Recent paleomagnetic studies (OTOFUJI *et al.*, 1985a,b) have revealed that Southwest Japan and the northern part of Northeast Japan, north of the Tanakura tectonic line (TTL), had undergone clockwise and counterclockwise rotations, respectively, on account of the back-arc opening of the Japan Sea.

Paleomagnetic results obtained from Southwest Japan gave a significant constraint on the opening mode of the western part of the Japan Sea. Using detailed record of paleomagnetic field directions in the San'in area (Fig. 1), OTOFUJI & MATSUDA (1987) concluded that Southwest Japan had rotated clockwise through more than 40° with respect to the eastern margin of Eurasia. Large amount of rotation of Southwest Japan around the pivot fixed at the southwestern end of the arc (Fig. 1) is not explained by the opening in parallel mode linked with the formation of pull-apart basin (LALLEMAND & JOLIVET, 1985) or Atlantic-type marginal basin (TAYLOR & HAYES, 1983). Fan shape opening seems the dominant mode of back-arc opening in case of the western part of the Japan Sea.

Precise determination of the duration and timing of the large amount of clockwise rotation is important to understand the kinematics of fan shape opening and the behavior of asthenosphere beneath the continental margin. OTOFUJI *et al.* (1985a) compiled paleomagnetic data in Southwest Japan and suggested that the climax of the rotation was at 14.9 Ma and its duration was 0.6 m.y. However, widely distributed data in their paper might include unwanted information about the differential block motions in the marginal regions of the arc. Moreover, quite short duration might be affected by systematic error introduced through the compilation of K–Ar, fission track and paleontological ages.

In order to solve above-mentioned problems, the present study is focused on the paleomagnetic data reported from fossiliferous Neogene sections in the Yatsuo area (ITOH, 1986, 1988; ITOH & HAYAKAWA, 1988), a rather limited area (extent of 20km×20km) in the eastern part of Southwest Japan (Figs. 1 and 2). Based on paleomagnetic results obtained from Cretaceous and Neogene rocks, ITOH (1988) suggested that the eastern part of Southwest Japan including Yatsuo area had rotated counterclockwise relative to the central and western parts of

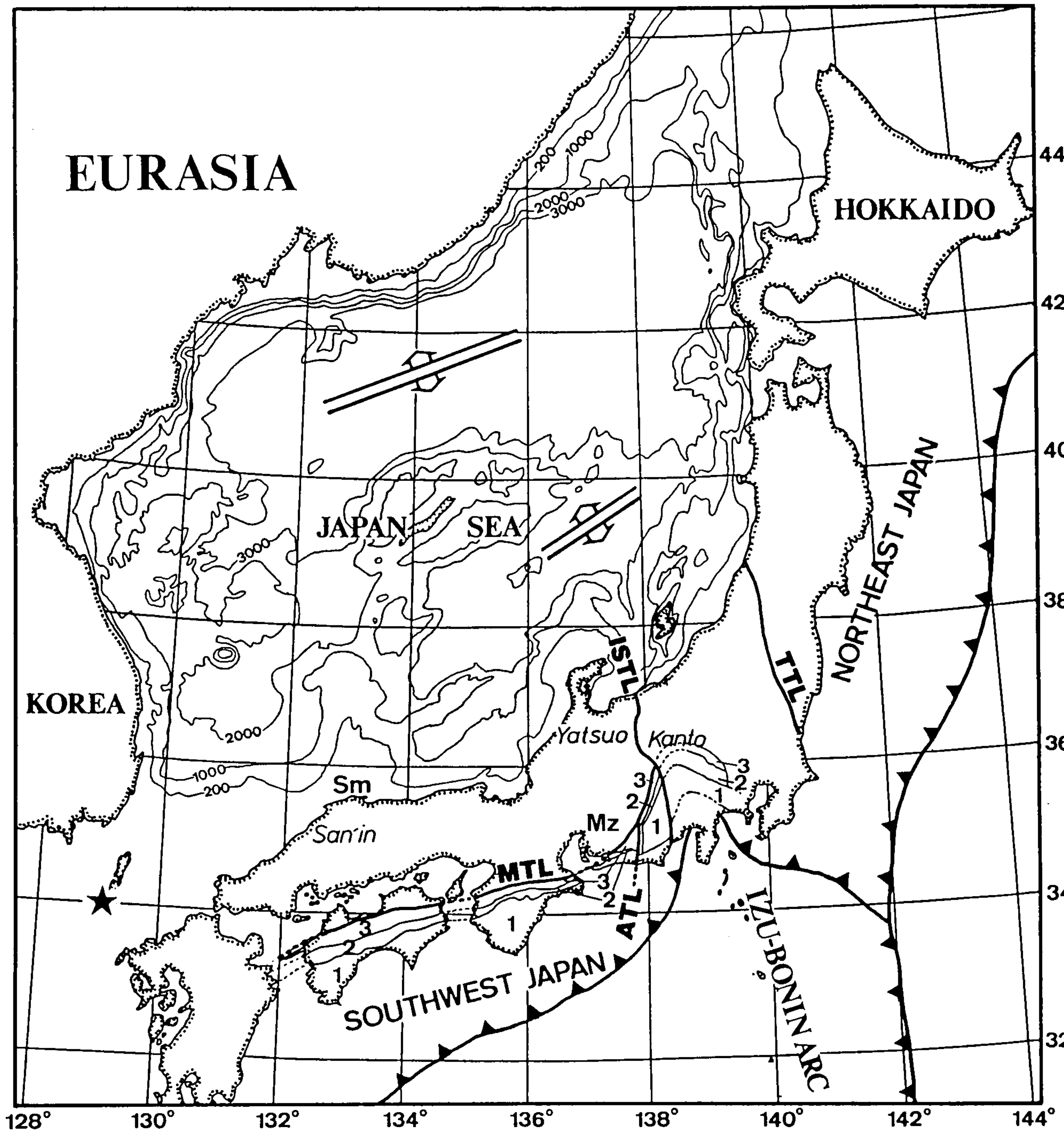


Fig. 1. Index map of geotectonic divisions in Japan with the distribution of pre-Neogene Shimanto (1), Chichibu (2) and Sambagawa (3) terranes (YAMADA *et al.*, 1982). Abbreviations are TTL, Tanakura tectonic line; ISTL, Itoigawa-Shizuoka tectonic line; ATL, Akaishi tectonic line; MTL. Median tectonic line; Mz, Mizunami area; Sm, Shimane peninsula. Base map shows contours and possible position of remnant spreading centers in the Japan Sea (AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS, 1981). The present trench system around the Japanese Islands is also shown. Pivot of clockwise rotation of Southwest Japan is shown by a star at 34°N, 129°E (OTOFUJI & MATSUDA, 1987).

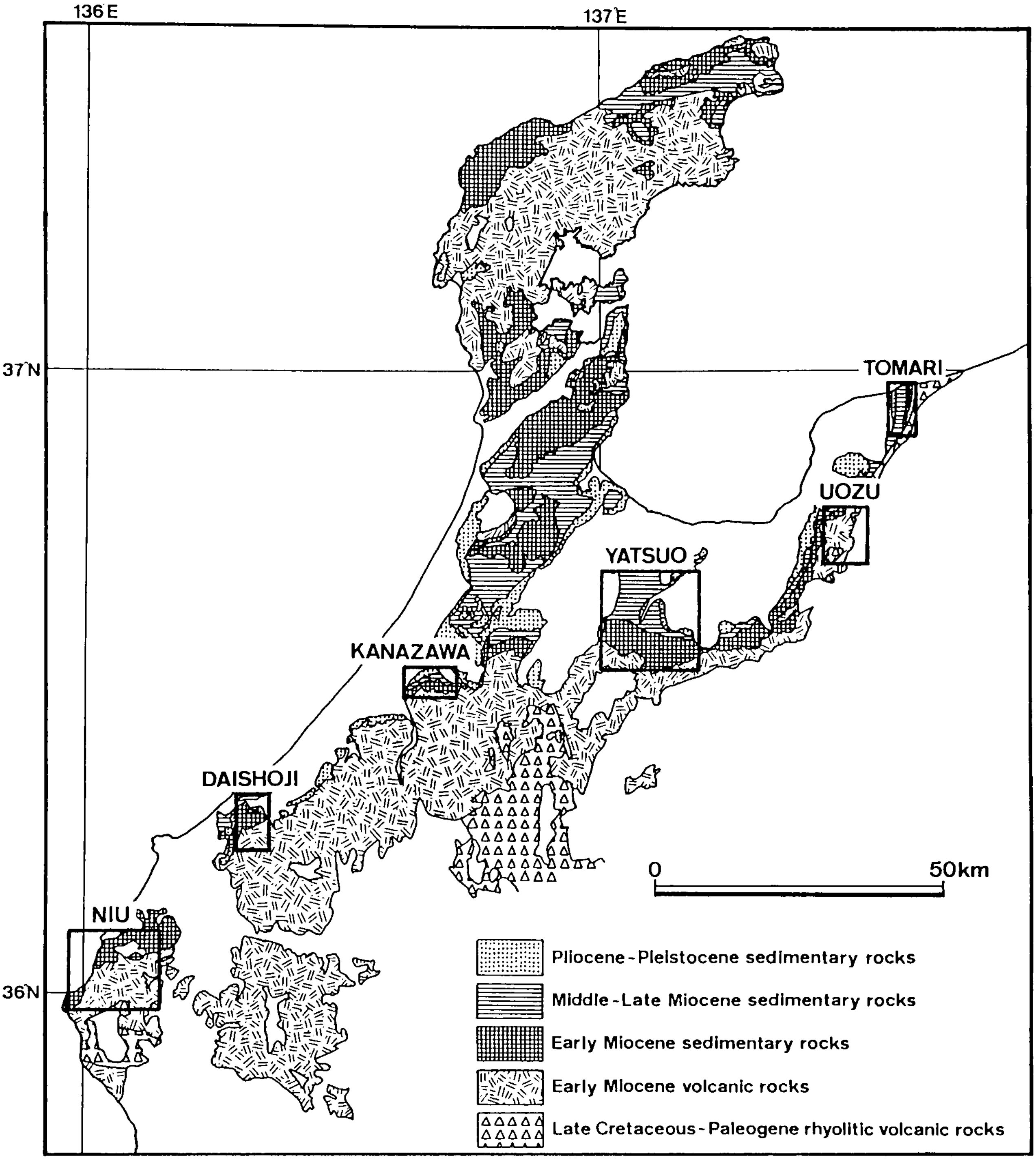


Fig. 2. Distribution of Cretaceous and Tertiary rock units around the eastern part of Southwest Japan (YAMADA *et al.*, 1982). Bold enclosures show the areas of which paleomagnetic data are discussed in this paper.

Southwest Japan succeeding to the coherent clockwise rotation of the arc.

It is, therefore, expected that a reliable data-set compiled from the paleomagnetic data in the Yatsuo area describes clockwise rotation and counterclockwise rotation on account of back-arc opening and intra-arc deformation, respectively. The rotational history of Southwest Japan is established in this study using age estimations by magnetostratigraphy (ITOH & HAYAKAWA, 1988), radiometric method and biostratigraphy (HAYAKAWA & TAKEMURA, 1987) in the Yatsuo area. Paleoenvironment during the clockwise rotation, which is monitored by geological data such as lithofacies and paleodepth inferred from benthic foraminiferal assemblages, sheds light on the understanding for the motive force of continental rifting.

Mode of the intra-arc deformation succeeding to the back-arc opening is also viewed from available paleomagnetic directions reported from six areas (Fig. 2) in the eastern part of Southwest Japan (after NAKAJIMA & HIROOKA, 1986; ITOH, 1986, 1988; ITOH & HAYAKAWA, 1988; ITOH & ITO, H., 1988; ITOH & ITO, Y., 1988; ITOH & WATANABE, 1988) and the Kanto area (HYODO & NIITSUMA, 1986) between the ISTL and TTL (Fig. 1). In this study, the author attempts to describe the comprehensive tectonic movements of Southwest Japan related to the individual rotational motion of above-mentioned areas. Rheology of the continental crust is further argued in regard of the sliver bounded by the ISTL and the Median tectonic line (MTL), respectively on east and south sides (Fig. 1). Since the sliver, which is generally called the inner zone, consists of sedimentary and metamorphic complex which was widely intruded by Cretaceous granite, it can be regarded as a uniform test-piece of granitic crust under tectonic stresses during the Miocene deformation.

2. DATA SELECTION

In order to certify the reliability of rotational movements, the following criteria were adopted to select paleomagnetic data in the Yatsuo area.

(1) Site-mean directions which have a radius of 95% confidence circle smaller than 20° were selected.

(2) Bedding planes of the strata should be clearly defined so that the paleomagnetic directions can be corrected for the tectonic tilting. Because the Neogene strata within the Yatsuo area generally dip 10°~40° to the north with neither serious

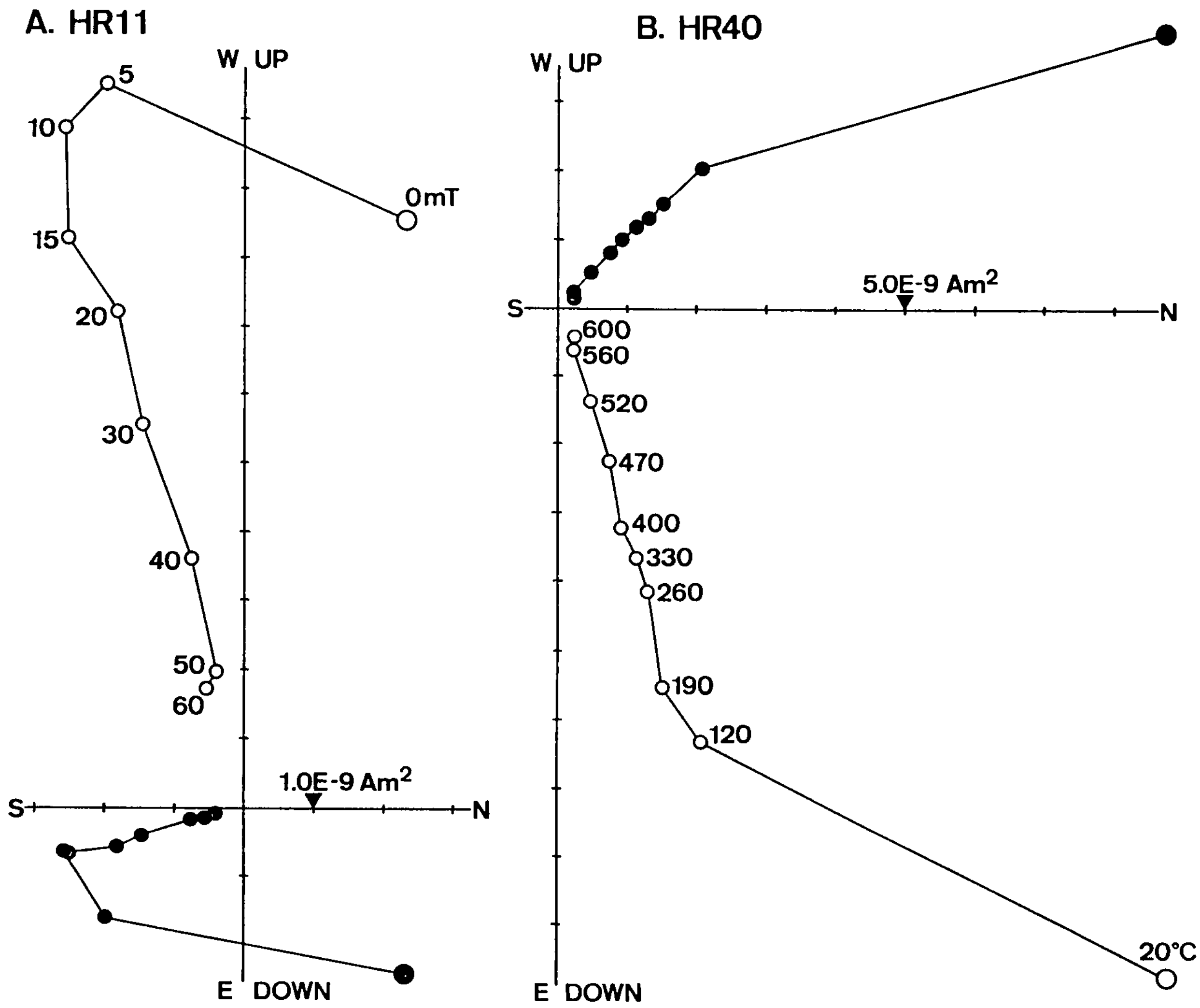


Fig. 3. Typical vector-demagnetization diagrams of progressive alternating field (A) and thermal (B) demagnetization tests for sedimentary rocks obtained from the Yatsuo area. Solid (open) circles are projection of vector endpoints on the horizontal (N-S vertical) plane in in-situ coordinates. Unit of coordinates is bulk remanent intensity. Numbers attached to symbols are demagnetization levels in mT or °C. Progressive change of vector endpoints shows a straight trend indicating stable magnetization.

tectonic disturbance nor slumping structure (HAYAKAWA & TAKEMURA, 1987), tilt-corrected paleomagnetic data are expected to be free from local movements in the investigated area.

(3) Stability of remanent magnetization should have been examined by means of progressive demagnetization using both thermal and alternating field methods. In case that the site-mean direction of stable magnetic component coincided with the present magnetic field direction before tilt correction, the site was rejected because such a magnetization might be of the secondary overprint. Fig. 3 shows the typical results of progressive demagnetization tests. Primary magnetic components are successfully identified as linear trends on the diagrams.

Table 1 is a summary of the Neogene paleomagnetic data which were selected according to the above-mentioned guidelines. As presented in the table, there is no time-dependent change about inclination values within the studied section.

3. MIOCENE ROTATIONAL MOTIONS AROUND THE YATSUO AREA

Fig. 4 shows the temporal change of declination values in the Yatsuo area with their uncertainty defined by KELLOGG & REYNOLDS (1978). As for the paleomagnetic data of the Yatsuo Group, enlarged declination plot is also given in Fig. 5. Based on magneto-biostratigraphic study (ITOH & HAYAKAWA, 1988), the Yatsuo Group is correlated with Chron C5C and C5B of standard geomagnetic polarity time-scale (BERGGREN *et al.*, 1985). The Tonami Group is correlated to the time-scale using fission track ages and biostratigraphic data compiled by HAYAKAWA & TAKEMURA (1987). Declination values shift remarkably from positive (easterly deflected) to negative (westerly deflected) ones in the upper part of the Yatsuo Group. There is no systematic change or significant deflection in declinations obtained from the Tonami Group.

Both of the data with normal and reversed polarities show similar declination shift in the upper part of the Yatsuo Group. On the basis of magnetostratigraphic estimation of sedimentation rate (ITOH & HAYAKAWA, 1988), each site-mean data is considered to be an average direction through more than 1000 years except for samples of volcanic materials. The declination shift is, therefore, not attributed to fluctuation of geomagnetic field linked with the field-reversal or secular variation but to clockwise rotation of the landmass containing the Yatsuo area around a vertical axis. Westerly deflected directions in the uppermost part of the

Table 1. Summary of paleomagnetic data for the Yatsuo area.

Site	DEMAG	D(°)	I(°)	Dc(°)	Ic(°)	N	α_{95}(°)	k	P	λ(°N)	φ(°E)	lithology
Tonami Group												
Otogawa Formation												
HK98***	10mT	148.5	-57.4	177.2	-55.0	12	5.9	54.9	R	-87.5	-157.6	tuff
HK100***	5mT	135.0	-57.6	176.0	-60.1	5	1.9	1650.0	R	-84.6	-76.9	silty tuff
32*	120°C	-38.7	61.2	-6.4	50.8	8	3.2	294.4	N	82.7	5.1	tuff
31*	20mT	-43.4	63.4	-10.4	59.4	11	7.4	39.2	N	81.1	74.2	tuff
16*	10mT	-32.4	75.1	6.9	58.0	10	2.0	572.0	N	84.2	-155.6	tuff
Tenguyama Formation												
18*	10mT	-40.4	71.8	-0.1	53.4	8	4.6	145.1	N	87.3	-41.1	tuff
Yatsuo Group												
Higashibessho Formation												
HR40***	250°C	-45.4	65.4	-19.4	43.3	7	6.8	78.7	N	69.9	18.0	mudstone
YT11***	350°C	130.8	-75.9	170.4	-53.1	8	19.5	9.0	R	-81.6	-150.7	siltstone
HR11***	15mT	142.2	-73.7	177.2	-60.6	9	7.9	43.6	R	-84.6	-65.7	silty tuff
HR43***	200°C	151.2	-69.9	175.6	-54.1	8	9.7	33.5	R	-85.9	-160.6	siltstone
05*	20mT	-143.5	-84.9	-172.5	-51.7	12	3.2	190.1	R	-82.5	79.5	tuff
YT04**	400°C	-36.9	-63.0	-164.9	-73.1	10	5.9	68.9	R	-65.8	-23.7	tuff
YT28***	30mT	-179.3	-53.6	-163.4	-34.2	9	9.5	30.1	R	-67.0	93.3	mudstone
YT25***	200°C	-25.3	42.3	9.3	40.9	8	10.8	27.1	N	74.6	-76.8	shale
Kurosedani Formation												
33*	190°C	171.6	-52.3	-174.0	-45.7	12	4.9	80.1	R	-79.3	107.1	tuff
Iozen Formation												
36*	20mT	42.7	58.2	18.3	48.7	8	2.0	790.8	N	73.2	-113.9	welded tuff
Iwaine Formation												
HK58***	10mT	42.6	55.8	26.5	41.3	12	3.3	176.4	N	63.9	-110.9	andesite
35*	330°C	70.3	61.4	17.9	41.7	9	4.3	143.1	N	70.2	-98.8	andesite
Nirehara Formation												
HK53**	400°C	-70.1	-73.6	-166.8	-60.6	9	4.8	114.2	R	-78.6	16.9	silty tuff
HK50**	10mT	-140.6	-72.9	-160.1	-49.8	12	2.7	262.9	R	-72.4	61.0	siltstone

Note: DEMAG=demagnetization level in °C or millitesla (mT); D, I= mean declination and inclination before tilt correction; Dc, Ic= mean declination and inclination after tilt correction; N=number of specimens; α_{95}=radius of 95% confidence circle; k=Fisher's precision parameter; P=magnetic polarity (N and R are normal and reversed polarity, respectively.); lambda, phi=latitude and longitude of virtual geomagnetic pole position.

* Data from ITOH (1986). ** Data from ITOH (1988). *** Data from ITOH & HAYAKAWA (1988).

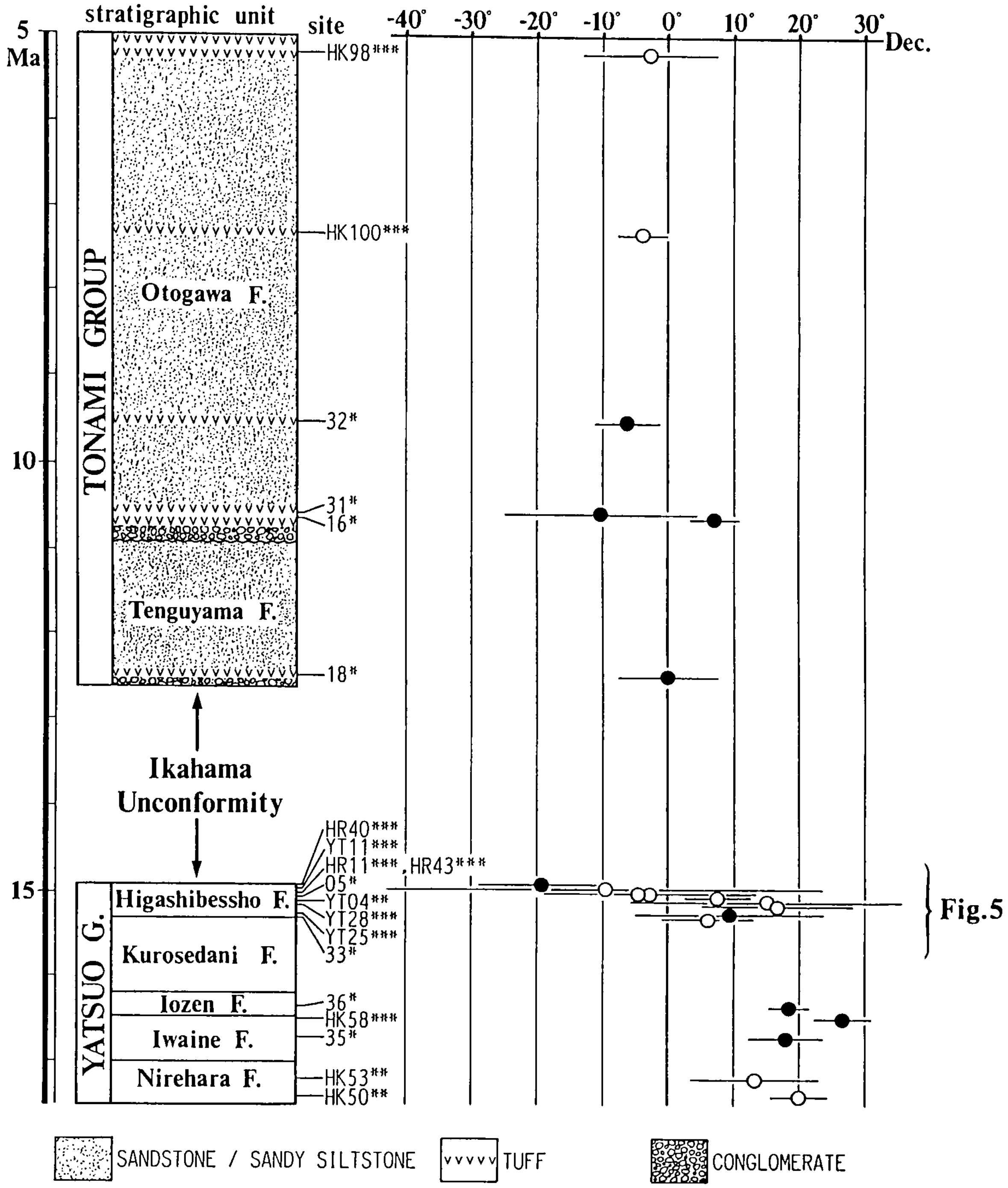


Fig. 4. Declination versus age for the Yatsuo area. Error bars show uncertainty in declinations (defined as $\sin^{-1}[\sin \alpha_{95}/\cos I]$ with α_{95} the radius of 95% confidence circle. I the inclination). Stratigraphy is after HAYAKAWA & TAKEMURA (1987). Solid (open) circles are the data with normal (reversed) polarity. * Data from ITOH (1986). ** Data from ITOH (1988). *** Data from ITOH & HAYAKAWA (1988).

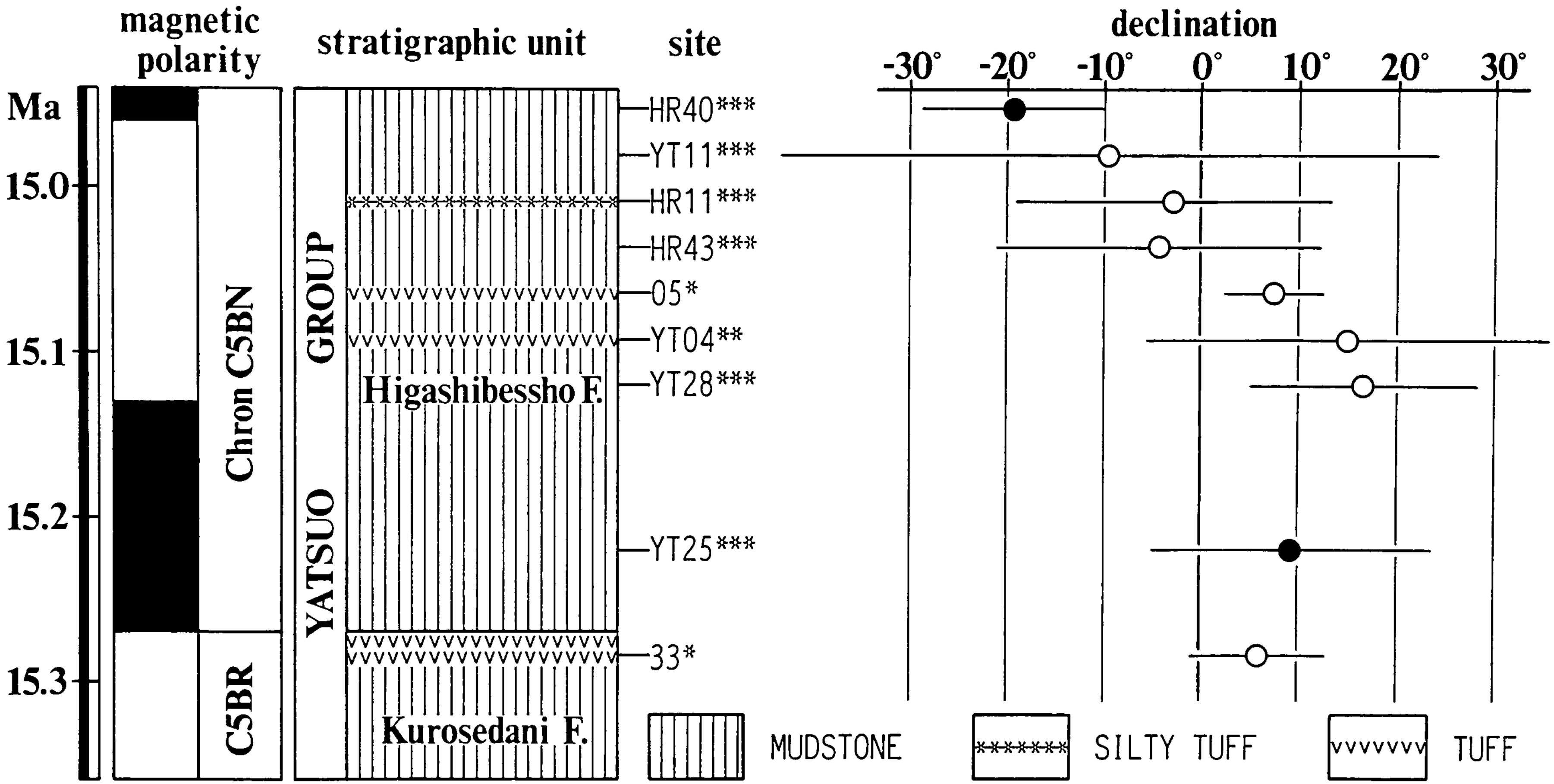


Fig. 5. Enlargement of Fig. 4 around 15 Ma. Magnetostratigraphy of the Yatsuo Group is after ITOH & HAYAKAWA (1988). Stratigraphic positions of the paleomagnetic data within a normal or reversed polarity interval are proportional to the thickness of the sampled section.

group express succeeding counterclockwise rotation of the Yatsuo area relative to Eurasia because the paleomagnetic poles obtained from Eurasia (IRVING & IRVING, 1982) almost coincide with the present geographic pole around 15 Ma. It is most probable that the temporal change of declinations in the Yatsuo Group represents clockwise and counterclockwise rotations around the Yatsuo area.

It is obvious that significant rotation took place during the deposition of the Higashibessho Formation which was correlative to the magnetic Chron C5BN (15.27–14.87 Ma; BERGGREN *et al.*, 1985). The termination of the clockwise rotation is concealed by the unconformity between the Yatsuo and Tonami Groups. Paleomagnetic declinations obtained from the Tonami Group (Fig. 4) suggest that the succeeding counterclockwise rotation occurred during the stage of the Ikahama unconformity ranging in age from 15 to 12 Ma (HAYAKAWA & TAKEMURA, 1987).

Although the process of counterclockwise rotation can not be observed, the amount of differential rotation linked to intra-arc deformation can be determined by comparing early Miocene paleomagnetic directions of the eastern and the western parts of Southwest Japan. Because the apparent polar wandering path (APWP) during last 100 m.y. has been proposed from the San'in area in the western part of Southwest Japan (Fig. 1) by OTOFUJI & MATSUDA (1987), the San'in area is used as a reference to estimate the amount of differential rotation. The mean paleomagnetic declination (D) and inclination (I) of the western part of Southwest Japan are calculated from APWP for the San'in area at the representative location of the Yatsuo area (36°35'N, 137°5'E). For early Miocene, D and I are 62.2° and 47.4°, respectively. A_{95} (circle of 95% confidence about the reference pole) and p (angular distance from the area to reference pole) are 10.9° and 61.4°, respectively. On the other hand, the mean direction of early Miocene data in the Yatsuo area (site-mean data in the Nirehara, Iwaine and Iozen Formations) is $D=19.6°$, $I=48.5°$ and $\alpha_{95}=8.0°$ at the same representative location. Using these data, the angle of relative rotation (R) and its uncertainty (dR) defined by BECK (1980) are given as $-42.6°$ and $17.4°$, respectively. It is concluded that the Yatsuo area has undergone a counterclockwise rotation relative to the western part of Southwest Japan through 43°

4. TECTONIC IMPLICATION OF THE ROTATIONAL MOTIONS

4-A. *Clockwise rotation*

As stated before, the clockwise rotation of the Yatsuo area occurred during deposition of the upper part of the Yatsuo Group (around 15 Ma). It has been shown that easterly deflection in declination decreases within some sequences of the Setouchi Miocene Series, sporadically distributed in Southwest Japan, which can be correlated with the upper part of the Yatsuo Group on the basis of age-diagnostic fossils (TORII, 1983; HAYASHIDA, 1986). The synchronous rotational motions can be attributed to coherent clockwise rotation of Southwest Japan associated with Miocene back-arc opening predicted by geological and geophysical studies (e.g., CHINZEI, 1986; ISEZAKI, 1986).

Declination shift in the Higashibessho Formation exceeds 30°. As the amount of clockwise rotation reported from the central and western parts of Southwest Japan ranges from 40° to 60° (OTOFUJI *et al.*, 1985a; OTOFUJI & MATSUDA, 1987), it seems that more than a half of the rotation had been attained during the short interval (less than 0.4 m.y.). Although the later stage of the rotation is not observed in the studied section, present result suggests that the duration of coherent clockwise rotation is less than 1 m.y. Thus short duration of the rotational motion insisted by OTOFUJI *et al.* (1985a), which implies anomalously rapid back-arc opening, has been reconfirmed through the paleomagnetic data of well-dated Miocene sequence in the Yatsuo area.

4-B. *Counterclockwise rotation*

Counterclockwise rotation in the eastern part of Southwest Japan was also reported from late Cretaceous welded tuffs which were collectively named the Nohi rhyolite (ITOH, 1988). The amount of differential rotation between the San'in area and the area covered by the widespread Nohi rhyolite (see Fig. 6) was calculated as $R=-56.8°$ ($dR=16.6°$). It is, therefore, suggested that the differential rotation of the Yatsuo area is not attributed to the intra-arc deformation only on the coast of the Japan Sea but to the bending motion of whole Southwest Japan during or just after the back-arc opening of the Japan Sea.

Plausible mechanisms of the differential rotation linked to arc bending are presented as the following two models (Fig. 7). In the models, rotational motion of

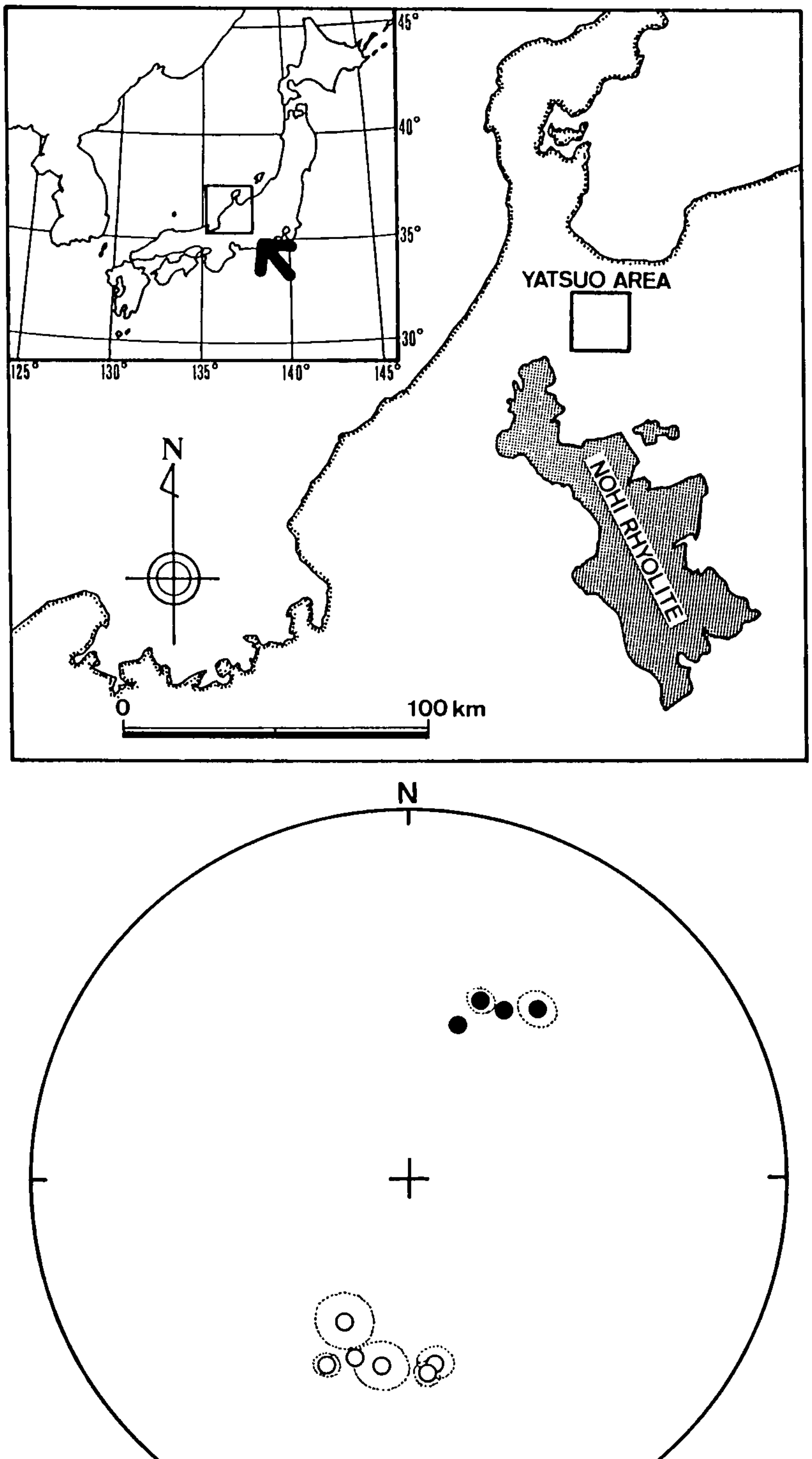


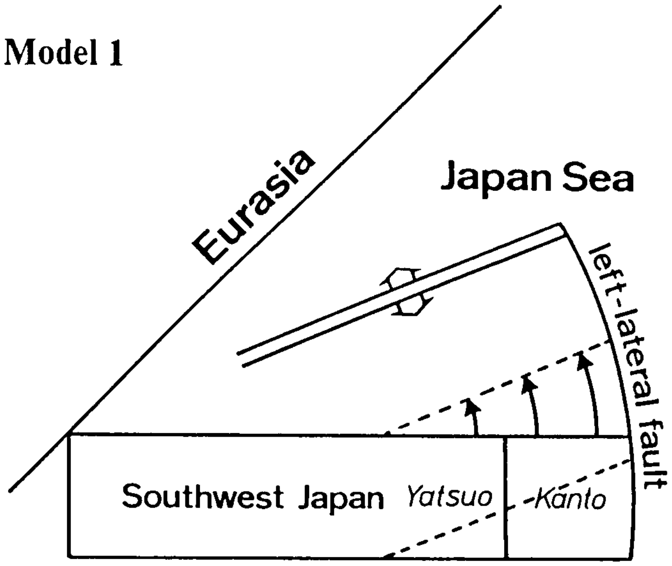
Fig. 6. Map showing the distribution of late Cretaceous Nohi rhyolite and equal-area net showing site-mean directions and their 95% confidence circles of characteristic magnetization (after tilt-correction) obtained from the Nohi rhyolite (ITOH. 1988). Solid (open) symbols are on the lower (upper) hemisphere.

the Kanto area (Fig. 1) is also taken into account because the zonally arranged pre-Neogene terranes of Southwest Japan (see Fig. 1) can be continuously traced as far as the Kanto area, suggesting that the Kanto area was situated in the eastern part of continental sliver which rotated clockwise associated with the back-arc opening in Miocene.

(Model 1) An intense shear drag force may have been produced on the margin of the rotating arc associated with the fan shape opening of the Japan Sea. Because Southwest Japan was rotated clockwise around a pivot fixed at the western end of the arc, left-lateral shear in the eastern margin of the arc caused counterclockwise rotation of the Yatsuo and the Kanto areas.

(Model 2) Collision of the landmasses on the Philippine Sea plate is a possible cause of the deformation of the island arc. Though the present length of the slab under the Japan arc suggests that the subduction of the Philippine Sea plate can go back to 5 Ma (MATSUBARA, 1980), the subduction in middle Miocene is surmised from the ages of ophiolite and surrounding rocks in the Mineoka belt (OGAWA, 1983). Back-arc opening of the Japan Sea would be the direct cause of middle Miocene subduction of the Philippine Sea plate. On account of the subduction, the Izu-Bonin arc on the Philippine Sea plate collided against the island arc which had been separated from the margin of Eurasia. Such collision caused counterclockwise rotation of the Yatsuo area and clockwise rotation of the Kanto area.

Model 1 seems not to be realistic because the model requests the accretionary prism of Paleogene Shimanto terrane to be abruptly bent around the Kanto area before Miocene intra-arc deformation (see Fig. 1). Moreover, the paleomagnetic data obtained from the Kanto area prefer Model 2. HYODO & NIITSUMA (1986), who studied paleomagnetism of the early Miocene Series in the Chichibu Basin of the Kanto Mountains, revealed that the mean direction of the sedimentary rocks which were correlated to BLOW's zone N8 (16.5−15.5 Ma) showed easterly deflection as much as 94° They attributed half of the deflection to the rotation of Southwest Japan (about 47°) and the remainder to the differential rotation between the Kanto Mountains and Southwest Japan after 15 Ma. Therefore it is concluded that the differential rotations of the Yatsuo and the Kanto areas occurred in consequence of collision of the Izu-Bonin arc in middle Miocene. Since the collision event, the Yatsuo and the Kanto areas have belonged to different tectonic domains and the eastern limit of Southwest Japan has been situated around the ISTL (Fig. 1).



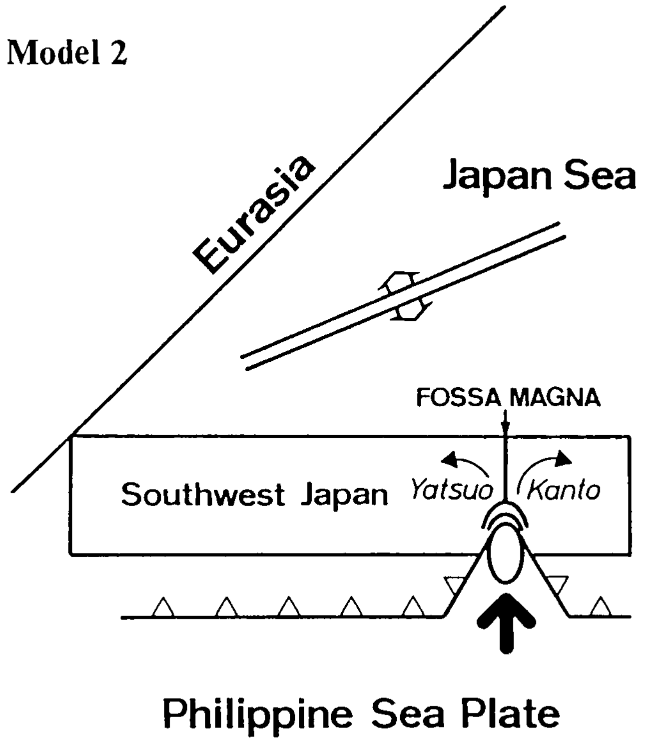


Fig. 7. Two models for the mechanism of the differential rotation as confirmed by paleomagnetic data in the Yatsuo area. (Model 1) Left-lateral shear is produced on the margin of a rotating arc, resulting in counterclockwise rotation of the Yatsuo and Kanto areas. (Model 2) Landmasses on the Philippine Sea plate collide against the Japan arc, resulting in counterclockwise rotation of the Yatsuo area and clockwise rotation of the Kanto area.

5. ENVIRONMENTAL CHANGES DURING THE ROTATIONAL MOTIONS

5-A. *Clockwise rotation*

The thick (1500–1800 m) sequence of fining-upward sediments in the Kurosedani and Higashibessho Formations yields the benthic foraminifers which suggest that the Miocene sedimentary basin in the Yatsuo area changed its depth considerably as shown in Fig. 8-D (CHIJI, 1986). On the basis of magnetostratigraphy (ITOH & HAYAKAWA, 1988), it has been confirmed that the sedimentation was accelerated within the upper part of the Yatsuo Group and the massive fine-grained sediments in the Higashibessho Formation accumulated at extremely high rates of 4–3 m per 1000 years (Fig. 8-C). These data suggest active block-faulting and subsidence around the margin of continental sliver of Southwest Japan during the rifting and breakup of the continental lithosphere related to the clockwise rotation because the global sea level change around 15 Ma was in negligible amount (HAQ *et al.*, 1987).

Synchronous subsidence has been reported from some areas within Southwest Japan. TAI (1973) showed that the Miocene sedimentary basin in the Shimane peninsula (see Fig. 1) had rapidly subsided in middle Miocene. Using foraminiferal biostratigraphy (NOMURA, 1986), the stage of rapid subsidence (Josoji Formation) can be correlated with the Higashibessho Formation in the upper part of the Yatsuo Group. TAI (1975) also stated that the remnants of coeval marine sediments of Bihoku Group scattered in the mountain ranges and inner-arc basins of Southwest Japan. SHIBATA (1985) suggested that the middle Miocene Oidawara Formation in the Mizunami area (Fig. 1), which was correlated with the Higashibessho Formation on the basis of diatom biostratigraphy (KOIZUMI, 1981), had been formed by distinct marine transgression. These data seem to denote that the whole of the southwestern Japan arc was subsiding during the clockwise rotation.

5-B. *Counterclockwise rotation*

Based on the paleomagnetic data, a paleogeographic reconstruction of the pre-Neogene terranes in Southwest Japan and the western part of Northeast Japan can be made for the period before the differential rotation. Fig. 9 delineates the distribution of the Sambagawa terrane, showing the typical trend of the terranes

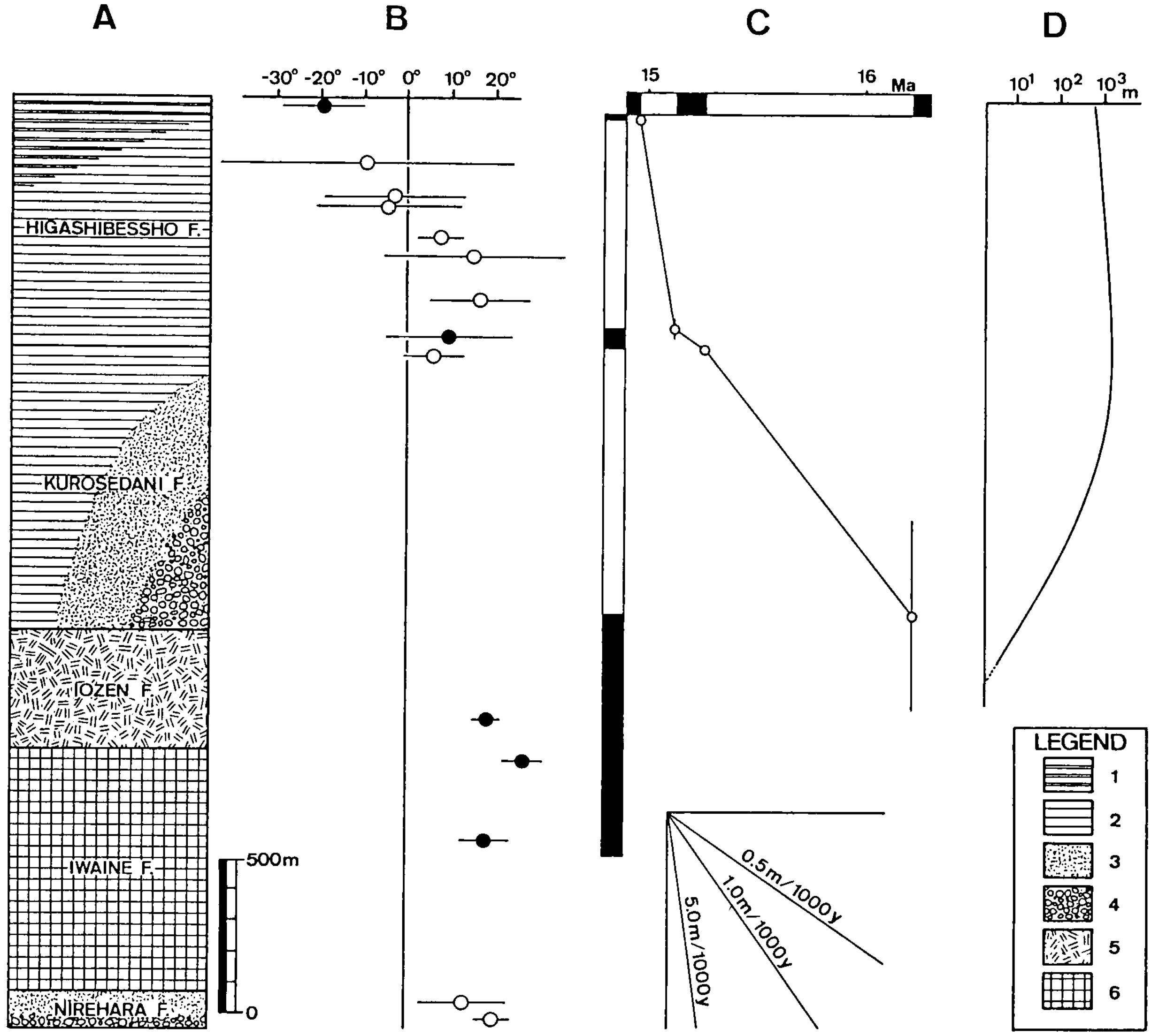


Fig. 8. Summary of stratigraphic, paleomagnetic and environmental data obtained from the Yatsuo Group. A: Lithostratigraphy (1=bedded mudstone; 2=siltstone; 3=sandstone; 4=conglomerate; 5=rhyolitic volcanics; 6=andesitic volcanics) after HAYAKAWA & TAKEMURA (1987). B: Plot of declination versus thickness. C: Sedimentation rate on the basis of magnetostratigraphy (ITOH & HAYAKAWA, 1988). D: Paleodepth inferred from benthic foraminiferal assemblage (CHIJI, 1986).

(Ryoke, Sambagawa, Chichibu and Shimanto). On the paleomagnetically distinct three segments of the terrane, horizontal components of the mean paleomagnetic directions in early Miocene are plotted as arrows. Paleomagnetic data of the central part of Southwest Japan (OTOFUJI & MATSUDA, 1987), the Yatsuo area (ITOH, 1988) and the Kanto area (HYODO & NIITSUMA, 1986) are assigned to segments a, b and c, respectively. Even if some differential rotations occurred between the Yatsuo area and segment b of the Sambagawa terrane, the rotation angle is supposed to have been of a negligible amount because the rotational motion of the area covered by the Nohi rhyolite is comparable to that of the Yatsuo area as shown in Chapters 3 and 4. To obtain the paleoposition, segment b is rotated so as to parallel the arrow on it with the arrow on segment a. Then the segment is translated toward segment b' so as to cancel the offset of the terrane along the Akaishi tectonic line, which is estimated to be 60 km (MATSUSHIMA, 1973). As for the reconstruction of segment c, it is rotated toward segment c' so as to parallel the arrow on it with the arrow on the segment a around the pivot of rotation (pivot C). Pivot C is tentatively situated at 35.8°N, 140.5°E, where the Sambagawa crystalline schist has been confirmed by the results of deep drilling (YAMADA *et al.*, 1982). As clearly shown in Fig. 9, reconstructed segments a, b' and c' stand almost on a straight line. This result suggests that the rotational event of the Yatsuo and the Kanto areas associated with arc-arc collision is equivalent to the formation of northward bending structure of the pre-Neogene terranes.

It seems that collision of the Izu-Bonin arc in middle Miocene brought about not only bending but also uplift within the Japan arc. The Tonami Group is mostly composed of coarse clastic rocks deposited in the shallow water (Fig. 4) with some interruptions of sedimentation (HAYAKAWA & TAKEMURA, 1987), which contrasts with rapidly deposited fine sediments in the underlying Yatsuo Group. Using diatom biostratigraphy, ITO (1986) detected similar environmental change in the Neogene System distributed along the Japan Sea coast of the eastern part of Southwest Japan. Fig. 10 illustrates the principal Neogene sedimentary basins (Ichishi, Morozaki, Mizunami, Shidara, Yatsuo, Kanazawa, Kakegawa and Chichibu) which are settled on the pre-Neogene terranes and distributed around the southern Fossa Magna, highly deformed region in front of the colliding Izu-Bonin arc. In these Neogene basins, sedimentary rocks were deposited dominantly under marine conditions during late Early Miocene. However, all of the Neogene sequences in the basins are cut off abruptly at the horizons assigned to the zone N8 or N9 of BLOW (1969) (TSUCHI, 1981; ITO, 1986; HAYAKAWA & TAKEMURA, 1987). The remarkable environmental change around these areas is not attributed to eustatic sea level changes but to tectonic uplift on account of the

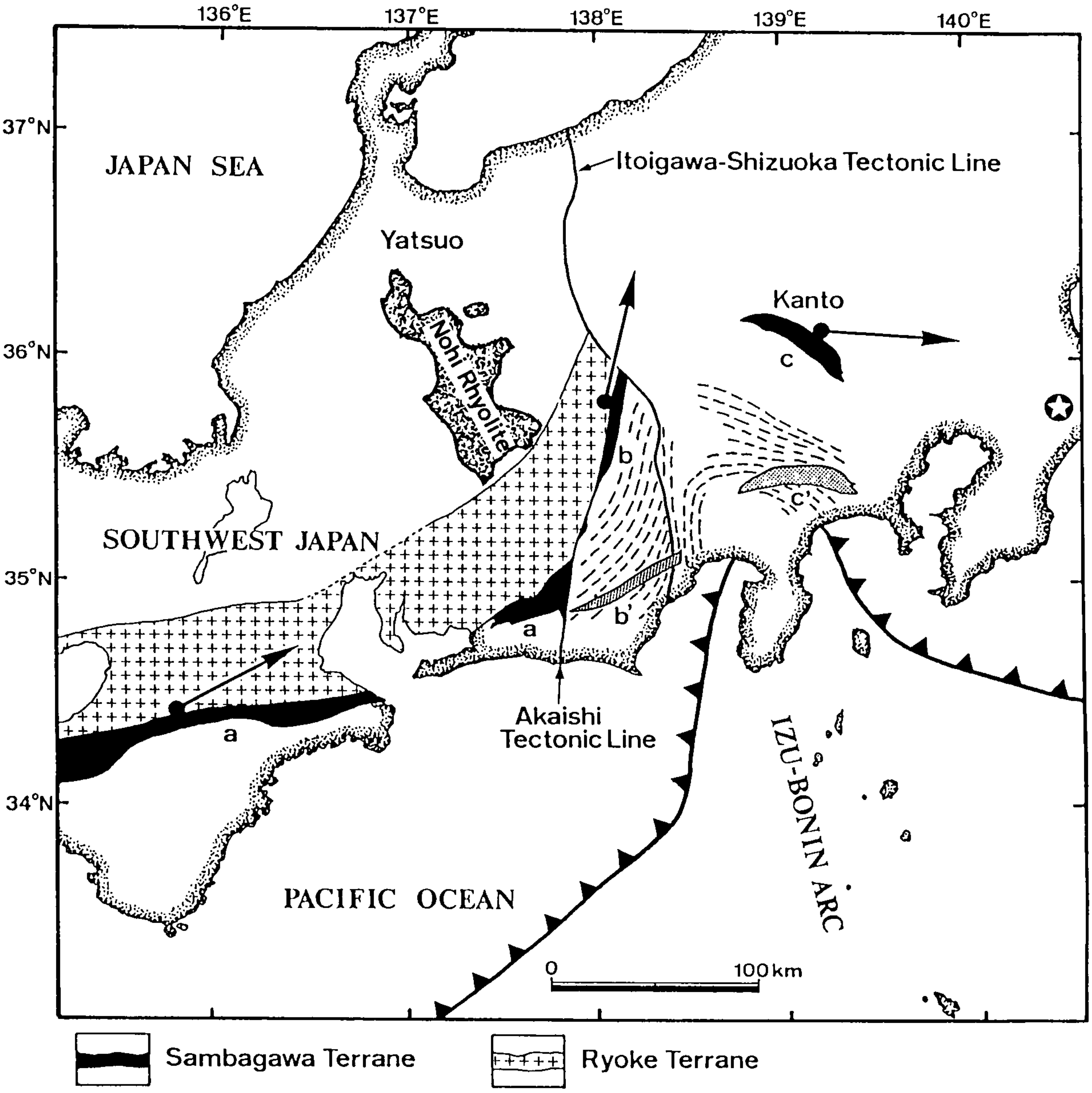


Fig. 9. Rearrangement of the pre-Neogene Sambagawa Terrane before differential rotation of the Yatsuo and Kanto areas. Segments a, b and c, which belong to three paleomagnetically distinct parts (central part of Southwest Japan, Yatsuo and Kanto), show the present arrangement of the Sambagawa Terrane. Structural trends of late Mesozoic and Cenozoic strata around southern Fossa Magna are also shown by short dashes. Arrow attached to each segment shows horizontal component of mean paleomagnetic direction of the part in early Miocene. Data source of the arrow on segment a is OTOFUJI & MATSUDA (1987), on segment b is ITOH (1988) and on segment c is HYODO & NIITSUMA (1986). Segments b and c are rotated to the rearranged position of the terrane (segments b' and c') so as to parallel the three arrows on the segments. Star shows the rotation pivot for segment c (pivot C).

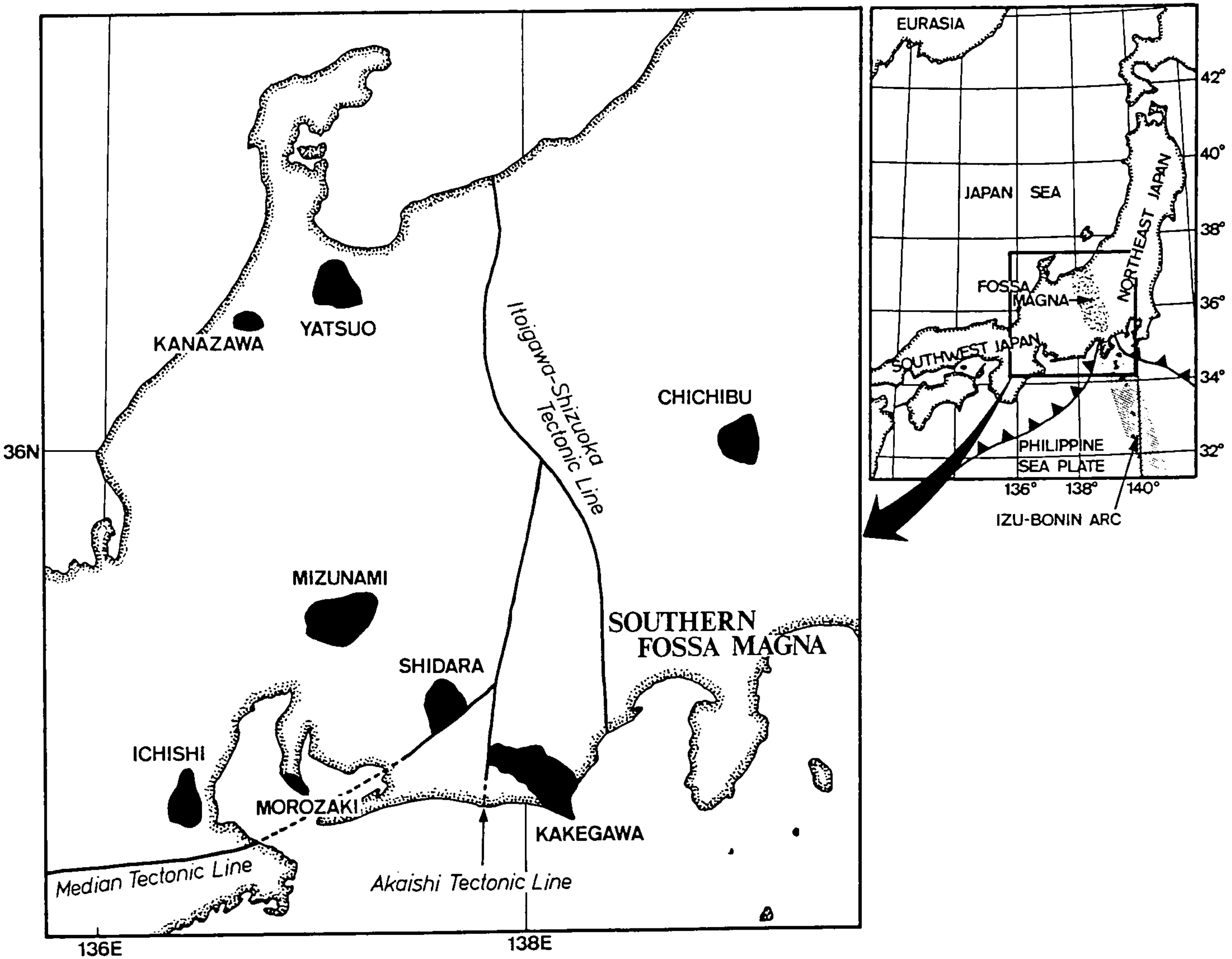


Fig. 10. Principal Neogene sedimentary basins (darkened area) settled on the pre-Neogene terranes and distributed around the southern Fossa Magna.

collision event since the biostratigraphic studies (e.g., NOMURA, 1986) have not detected coeval interruption of sedimentation within Miocene sequences on the western part of Southwest Japan. The uplift would be brought about by buoyant subduction of the Izu-Bonin arc as suggested by ISHIBASHI (1986) and thickening of the crust on account of arc bending.

6. POSSIBLE MODEL FOR BACK-ARC OPENING IN THE JAPAN SEA

The extensive subsidence described in Chapter 5 can be attributed to tensional stress of Southwest Japan associated with the back-arc opening. This is contradictory to previous opinion about the stress state of Southwest Japan. Based on the azimuth of dike swarms dated by K–Ar method and fault mechanism, TSUNAKAWA (1986) stated that Southwest Japan had been under compressional stress directed nearly orthogonal to the morphological elongation of the arc between 15 and 12 Ma. The compression was related to the viscous force of mantle convection beneath the continental margin (SLEEP & TOKSOZ, 1971) during the back-arc opening. However, it is difficult to select the dike swarms intruded in the stage of opening because the present paleomagnetic result has clarified that the duration of the opening is shorter than 1 m.y. Middle Miocene stress field inferred from dike swarms would be affected by succeeding arc-arc collision event in the period between 15 and 12 Ma. Hence tensional field prevailed in Southwest Japan during rapid opening of the western part of the Japan Sea.

Tension in the drifting Southwest Japan is a significant clue to inference for the model which can explain the extensional tectonics of the Japan Sea. In this case, mantle convection generated by the drag of downgoing slab did not play any important role in splitting the continental rim because viscous force induced by the convection should result in compression around the drifting continental sliver (TSUNAKAWA, 1986). The tensional stress seems to be explained by the trench suction force (CHASE, 1978) which is raised alternatively by motion of the overriding plate away from the downgoing slab anchored in the mantle (UYEDA & KANAMORI, 1979) or oceanward rollback of the hinge of the downgoing plate (MOLNAR & ATWATER, 1978). The large amount of clockwise rotation of Southwest Japan suggests directly that the back-arc opening of the western part of the Japan Sea in fan shape mode was raised by hinge migration of the oceanic plate which was downgoing along the continental margin.

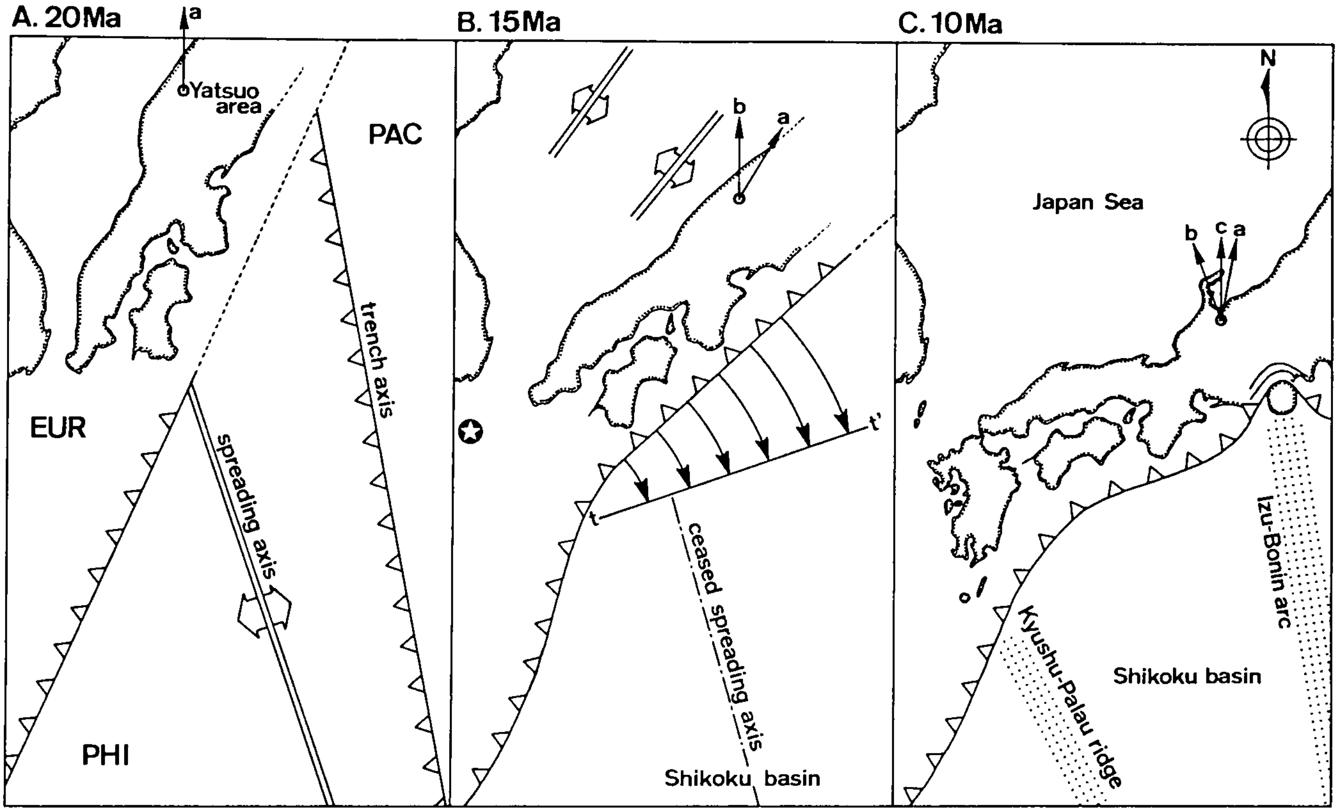


Fig. 11. Schematic reconstruction around Southwest Japan before, during and after the back-arc opening of the Japan Sea in middle Miocene. A: Pre-opening stage (20 Ma). Paleopositions of Southwest Japan and the plate boundary are adapted from OTOFUJI & MATSUDA (1987) and SENO & MARUYAMA (1984), respectively. EUR=Eurasia plate; PAC=Pacific plate; PHI=Philippine Sea plate. B: Opening stage (about 15 Ma). Southwest Japan is rotating clockwise associated with rapid hinge rollback of the downgoing Philippine Sea plate. t-t' shows the final position of hinge. Star represents the pivot of rotation (OTOFUJI & MATSUDA, 1987). C: Post-opening stage (10 Ma). Differential rotations within Southwest Japan raised by the collision of the Izu-Bonin arc have already finished, too. Arrows a and b show horizontal components of paleomagnetic directions in the lower and uppermost part of the Yatsuo Group, respectively. Arrow c corresponds to paleomagnetic data in the Tonami Group acquired after the clockwise and counterclockwise rotations of the Yatsuo area.

Since paleomagnetic results indicated that the clockwise rotation had taken place during Chron C5B, the event of hinge rollback postdated the spreading of the Shikoku basin (Fig. 11) which had ceased by Chron C5C at the latest after KOBAYASHI & NAKADA (1978). In this case, therefore, the oceanic plate in front of the rotating Southwest Japan was the Philippine Sea plate. It seems difficult to bring about the rapid rollback by gravitational subsidence (MOLNAR & ATWATER, 1978) of the young and buoyant oceanic lithosphere within the Shikoku basin. The rollback event would be caused by asthenospheric flow beneath the continental margin inferred from Miocene volcanism in the Japan arc (NOHDA *et al.*, 1988; TATSUMI *et al.*, 1988). Asthenospheric material could be injected into the mantle wedge and eventually raise the oceanward migration of dam-up slab of the Philippine Sea plate.

7. DUCTILE DEFORMATION OF THE JAPAN ARC

7-A. *Deformation mode of Southwest Japan revealed by paleomagnetism*

In order to clarify the deformation mode of Southwest Japan during middle Miocene linked to collision of the Izu-Bonin arc, reliable paleomagnetic directions of Paleogene or early Miocene are compiled in six areas (Fig. 2) distributed around the deformation zone predicted by the Cretaceous and Neogene paleomagnetic data (ITOH, 1988). The criteria for selecting reliable paleomagnetic data were as follows.

(1) Ages of sampled rock units must have been determined by radiometric dating or by biostratigraphic age assignments using marine planktonic microfossils or by magnetostratigraphy.

(2) Estimated age is older than 15.5 Ma (assigned to the upper part of BLOW's foraminiferal zone N8) at which the coherent clockwise rotation of Southwest Japan had not started.

(3) Bedding planes of the strata are defined in each site so that the paleomagnetic directions are corrected for the tectonic tilting. As the strata in the six areas have not been subjected to serious tectonic disturbance, mean direction of tilt-corrected paleomagnetic data of each area reflects rotational movement around the area free from local deformation within area.

(4) Stability of magnetization must have been examined by means of progressive

Table 2. Tectonic parameters (R, F) and their uncertainties defined by BECK (1980) on N sites of each area in Fig. 2.

Area	Age*	representative point lat.(N)	long.(E)	N	R(°)	F(°)	Ref.**
Tomari***	N8	36°55'	137°35'	3	-107.3±15.4 (-52.1±29.0)	-8.4±13.7	1
Uozu	59Ma(FT)	36°45'	137°30'	5	-50.6±21.1	3.7±13.4	2
Yatsuo	17-16Ma(MG)	36°35'	137°05'	5	-42.6±17.4	-1.1±15.2	3
Kanazawa	N8	36°30'	136°40'	7	-36.4±21.0	-2.3±17.1	4
Daishoji	N8	36°15'	136°20'	6	-25.2±16.0	-7.3±14.5	4
Niu	27-19Ma(FT)	36°00'	136°05'	10	-14.9±26.8	-5.4±19.6	5

* FT and MG mean age estimations on the basis of fission track dating and magnetostratigraphic study, respectively.

** References: 1-ITOH & WATANABE (1988); 2-ITOH & ITO, H. (1988); 3-ITOH (1986, 1988), ITOH & HAYAKAWA (1988); 4-ITOH & ITO, Y. (1988); 5-NAKAJIMA & HIROOKA (1986).

*** R value in parentheses for the easternmost Tomari area shows the data eliminating the effect of local rotational motions since late Pliocene observed between the ISTL and Tomari area (ITOH & WATANABE, 1988).

demagnetization using alternating field and/or thermal methods.

Mean paleomagnetic direction calculated for each area in Fig. 2 (see Table 2 for data sources) is compared with the contemporaneous geomagnetic direction which is expected from the apparent polar wandering path of the San'in area (OTOFUJI & MATSUDA, 1987) at the representative point of the area (see Table 2) in order to reveal the intra-arc deformation of Southwest Japan. As clearly shown in Table 2, significant F values (N−S transportation) are not obtained from the studied areas. On the contrary, significant negative R values, which correspond to counterclockwise rotations around vertical axes, are detected within all areas excepting the Niu area.

Fig. 12 delineates the R values of the discussed areas versus longitudinal value which represents the geographic distribution of the areas along approximate elongation of the arc. As for the Tomari area, the effect of counterclockwise rotation since late Pliocene, which had occurred between the Tomari area and the ISTL (ITOH & WATANABE, 1988), is corrected (as much as 55°) in the figure. A major point which can be noticed in the results from all the areas is that the absolute value of R becomes greater gradually from the westernmost Niu area toward the east. Another remarkable feature is that the R value in the Niu area seems to be insignificant, suggesting that the counterclockwise rotation which was related to the arc-arc collision event in middle Miocene mainly occurred between 136°E and 138°E, that is, in a rather restricted portion of the uniform continental sliver of the inner zone from 130°E to 138°E (as long as 750 km).

7-B. *Rheology of the continental crust of the Japan arc*

Apparently the paleomagnetic directions obtained from the supracrustal brittle layer basically follow the motion of deeper part of the crust because there has not been detected any significant Cenozoic transportation associated with superficial nappe in the inner zone of Southwest Japan. Petrologic investigations have shown that the mantle wedge beneath the volcanic arc is partially melted (TATSUMI *et al.*, 1983). Therefore gradual change in R values, together with the absence of remarkable faults around the investigated areas, suggests that the continental crust of the sliver, which is bounded by the ISTL and MTL and underlain by fluidal mantle, had deformed ductilely during the arc-arc collision event between 15 and 12 Ma.

Based on a long-term creep test of rocks, ITO (1979) pointed out that granitic rock has a vanishingly small yield stress and it can be regarded rheologically as a

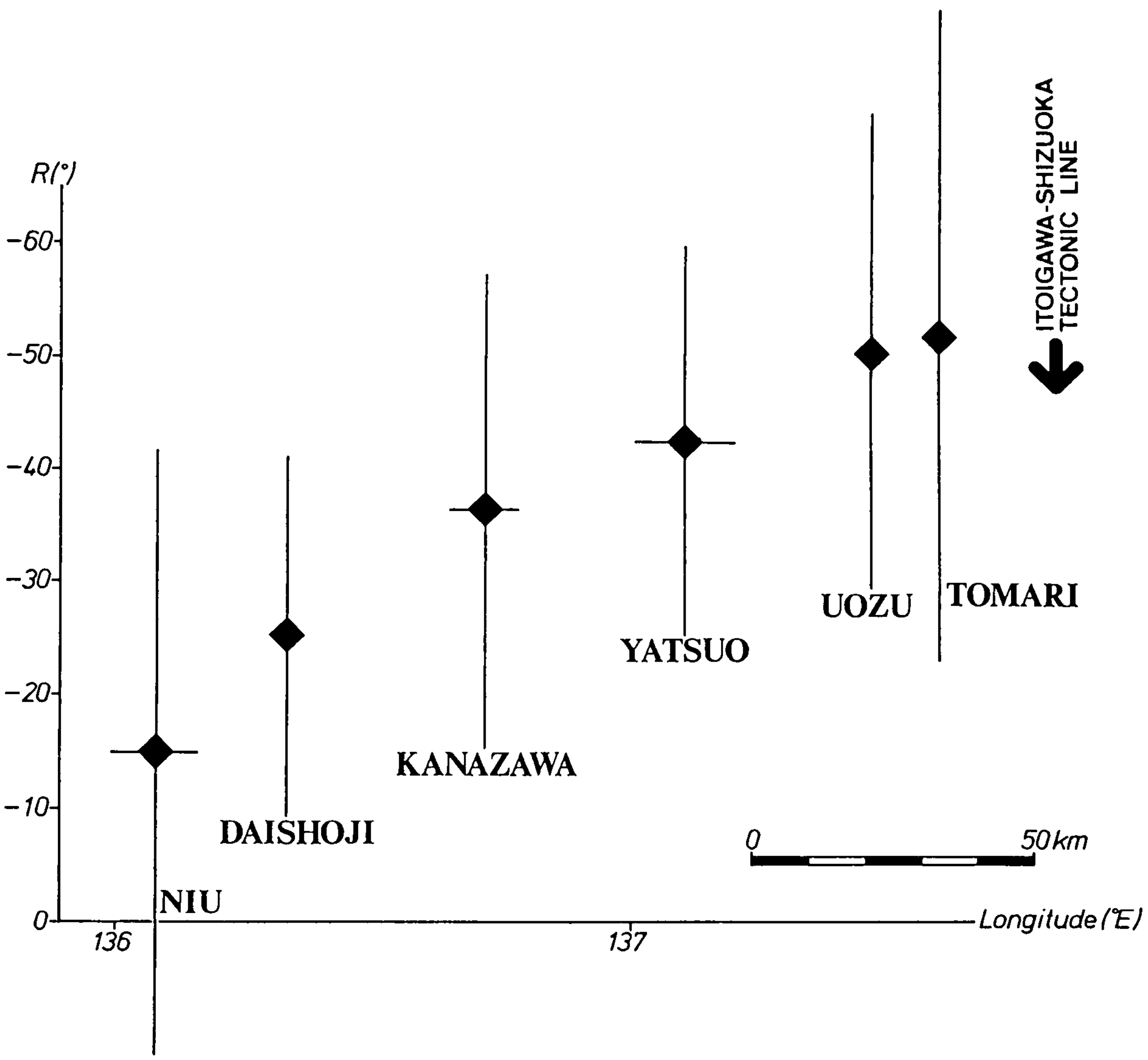


Fig. 12. Plot of R values versus longitude about the areas listed in Table 2. Errors in R show uncertainty defined by BECK (1980).

Maxwell liquid. The granitic crust under external forces will behave as a Newtonian liquid over a long period of time in case that the maximum shearing stress is smaller than the shearing strength of the crust (about 100 bar). He estimated that the crust of Southwest Japan had been flowing with a viscosity of 10^{22} poise under a compressional regime on account of global plate motions during Quaternary. The present paleomagnetic result indicates that middle Miocene deformation of the Japan arc linked to the arc-arc collision was also governed by viscous flow of the crust without fracture.

7-C. *Tectonic stress inferred from confined deformation*

As stated in Chapter 7-A, the intra-arc deformation in middle Miocene mainly occurred around the eastern part of the continuous sliver of Southwest Japan. Confined mode of the deformation can not be attributed to the inhomogeneity in the continental sliver because it consists of Paleozoic and Mesozoic terranes intruded entirely by Cretaceous-Paleogene granites. This fact leads us to the concept of irregular horizontal compression on fore-arc side linked to the collision of the Izu-Bonin arc settled on the subducting Philippine Sea plate. A working hypothesis is assumed that resisting compressive force is induced along the back-arc side of the Japan arc associated with the irregular compression on fore-arc side. Tectonic feature within the Shimane peninsula (see Fig. 1) affords a clear illustration of such resistance. TAI (1973) showed that the E–W trending folded zone and reverse fault in the Shimane peninsula had started to develop in middle Miocene. It is, therefore, probable that compression directed orthogonal to the elongation of Southwest Japan existed on back-arc side during the collision event on fore-arc side.

Fig. 13 is a cartoon showing a possible mechanism of confined ductile deformation in the Japan arc. Shaded parts in Fig. 13-A indicate indenters on the Philippine Sea plate. The inner zone, a fault-bounded uniform sliver as stated in Chapter 1, is regarded as a beam of continental crust of 750 km in length, 200 km in width and 20 km in thickness (Fig. 13-B). The beam is floating on inviscid mantle and normally loaded by the indenters which are assumed to have the same thickness as the beam. Let us adopt a pressure of 100 bar in front of the Izu-Bonin arc (frontal area is about 10^9 m^2), which is the recent compressive stress in the Japan arc estimated from the in-situ rock stress measurements and stress releases of earthquake faults (ITO, 1979). Philippine Sea plate does not affect the Japan arc except in the shaded areas in Fig. 13 because compressive stress raised by

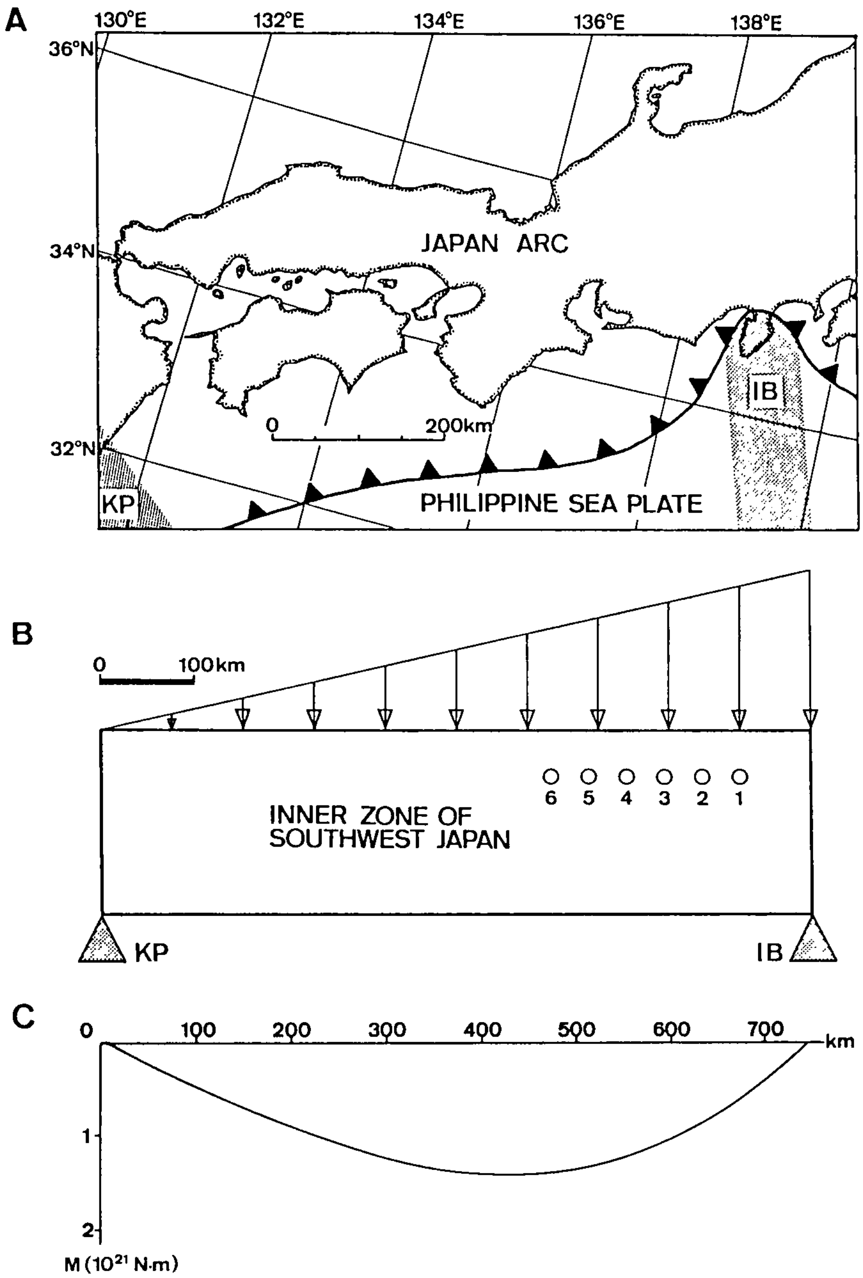


Fig. 13. Possible mechanism of the confined deformation within the Japan arc. A: Index map showing Southwest Japan and probable indenters (shaded parts) on the Philippine Sea plate (IB, Izu- Bonin arc: KP, Kyushu-Palau ridge). B: Simplified model of the inner zone of Southwest Japan before the intra-arc deformation. Open circles show the approximate positions of the discussed areas on the pre-deforming arc (1, Tomari area: 2, Uozu area; 3. Yatsuo area: 4. Kanazawa area: 5. Daishoji area; 6, Niu area). Arrows delineate relative intensity of assumed resistance acted on the back-arc side. C: Distribution of bending moment (M) within the simplified beam of crust. External forces loaded on the Japan arc are described in the text.

conventional subduction of an oceanic plate is not transmitted far into the overriding plate (NAKAMURA & UYEDA, 1980). Assuming that Southwest Japan is kept in equilibrium and resisting force on the back-arc side increases linearly toward east and reaches its maximum around the collisional zone of the Izu-Bonin arc (Fig. 13-B), the distribution of bending moment within the beam is calculated as shown in Fig. 13-C. Under these conditions, maximum shearing stress upon the surface of the beam is determined to be 54 bar, suggesting that the tectonic stress is low enough to allow the granitic beam to flow without fracture (ITO, 1979).

The normal strain, ε, on any cross-section of a bent beam is given by:

$$\varepsilon = yk \tag{1}$$

where y is the distance from neutral plane of the beam, and k is the curvature. The present result suggests that the beam of the Japan arc was bending during middle Miocene associated with viscous flow. Substituting the value of ε from eqn.(1) into the rheological equation of a Newtonian liquid, $\sigma = 3\eta(d\varepsilon/dt)$ (σ is the normal stress, η is the viscosity), we obtain:

$$\sigma = 3\eta y(dk/dt) \tag{2}$$

Bending moment, M, can be calculated by integrating the normal stress, σ, over the cross-section of the beam. Substituting eqn.(2) into σ, bending moment is given by:

$$M = 3\eta I(dk/dt) \tag{3}$$

where I is the moment of inertia of the cross-section of a beam with respect to its neutral plane. In the case that the bending moment is not a function of t, integrating both sides of eqn.(3) with respect to t, we obtain:

$$Mt = 3\eta Ik \tag{4}$$

Table 3 lists the approximate curvature of the bent Japan arc estimated for each interval terminated by neighboring two areas in Fig. 2. It is obvious that the curvature decreases toward the eastern Tomari area, which is concordant with eqn.(4) considering the distribution of M (Fig. 13-C) around the paleomagnetically investigated six areas (Fig. 13-B).

Let us assume in eqn.(4) that:

$M = 10^{21}$ Nm, $t = 10^{14}$ sec (approx. 3 m.y.), $\eta = 10^{22}$ poise and $I = 1.3\times10^{19}$ m^4

then k is 2.6×10^{-3} /km, which is comparable with actual curvature listed in Table 3. This result indicates that the present intra-arc deformation can be made by viscous flow of the crust within a few million years. Thus it is confirmed that the ductile deformation of the Japan arc occurred in a rather short interval as predicted by a previous paleomagnetic study (15−12 Ma; ITOH, 1988) under plausible tectonic stress. Ductile bending seems to be a common phenomenon for an island arc even

Table 3. Deformation of the Japan arc estimated from paleomagnetic data. *

Interval	dR(°)	a(km)	k(/km)
Tomari-Uozu	1.5	25.3	0.00103
Uozu-Yatsuo	8.0	39.3	0.00355
Yatsuo-Kanazawa	6.2	38.1	0.00284
Kanazawa-Daishoji	11.2	41.0	0.00476
Daishoji-Niu	10.3	35.9	0.00500

* Columns give the interval terminated by neighboring two areas in Fig. 2, difference in R between the two areas (dR), distance between the central points of the two areas (a), curvature of the bent arc around the interval (k) which is approximately given by [2sin(dR/2)]/a.

where an intense deformation is brought about by arc-arc collision.

8. SUMMARY

Tectonic movements of Southwest Japan have been clarified using reliable paleomagnetic directions obtained from well-dated Cenozoic strata.

(1) Based on plot of the declinations in respect to the age, it is shown that the Yatsuo area, in the eastern part of Southwest Japan, had rapidly rotated clockwise at about 15 Ma and then rotated counterclockwise between 15 and 12 Ma. Geological and geophysical data around the Japan arc suggest that the clockwise and counterclockwise rotations of the Yatsuo area were brought about by back-arc opening of the Japan Sea in fan shape mode and intra-arc deformation associated with collision of the Izu-Bonin arc on the Philippine Sea plate, respectively.

(2) The Yatsuo area was considerably subsiding in the short period (less than 1 m.y.) of the clockwise rotation associated with the back-arc opening. On the basis of biostratigraphic correlation, synchronous subsidences are detected in some areas sporadically distributed in Southwest Japan, suggesting that the arc was under tensional stress during the rapid back-arc opening. Predominant tension could be attributed to the rifting and drifting of Southwest Japan from the margin of Eurasia due to hinge rollback of the downgoing Philippine Sea plate.

(3) Based on early Miocene paleomagnetic data, a paleogeographic reconstruction of the pre-Neogene terranes in Southwest Japan and the western part of Northeast Japan can be made for the period before the counterclockwise rotation of the Yatsuo area associated with collision of the Izu-Bonin arc. Reconstructed segments of pre-Neogene Sambagawa terrane stand almost on a straight line, suggesting that the rotation of the Yatsuo area related to the collision event is equivalent to the formation of northward bending structure of the pre-Neogene terranes around the southern Fossa Magna. The arc-arc collision raised not only differential rotation but also uplift around the Yatsuo area recognized as remarkable environmental change in middle Miocene.

(4) Mode of the deformation of Southwest Japan on account of the collision event is also described using reliable paleomagnetic directions reported from six areas around the eastern part of Southwest Japan (Niu, Daishoji, Kanazawa, Yatsuo, Uozu, Tomari). Paleogene or early Miocene paleomagnetic data of the six areas distributed along the E–W trending morphological elongation of Southwest Japan

indicate that the angle of counterclockwise rotation relative to the western part of Southwest Japan increases gradually toward the east. Because there has not been detected any Cenozoic transportation associated with superficial nappe around the studied areas, the paleomagnetic result and the absence of remarkable faults to compensate differential rotations imply that whole of the granitic crust of Southwest Japan was ductilely bending during the collision event. It is also suggested that significant rotation related to ductile bending occurred in eastern confined portion of the uniform continental crust of the inner zone of Southwest Japan. The confined deformation of the continental sliver floating on inviscid mantle wedge would be attributed to the irregular compressive force in front of the colliding landmasses on the subducting Philippine Sea plate on fore-arc side and the resisting force induced on back-arc side. Under the supposed tectonic stress which is lower than the breaking strength of the crust, the actual amount of deformation around the studied areas can be attained within a few million years as predicted by the paleomagnetic results in the Yatsuo area. The granitic crust of Southwest Japan was flowing as a Newtonian liquid during the period of intense intra-arc deformation.

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* in Japanese with English abstract

** in Japanese

Appendix 1

In Chapters 3, 4 and 7 of this study, differential movements within Southwest Japan have been described using R and F values defined by BECK (1980). Observed mean direction (Do, Io) and expected direction (Dx, Ix), calculated from the appropriate reference pole, are used to determine values of R (rotation) and F (flattening). R, F and their uncertainties (dR, dF) are defined mathematically below:

$$R = Do - Dx \quad (A1)$$

$$F = Ix - Io \quad (A2)$$

$$dR = (dDo^2 + dDx^2)^{\frac{1}{2}} \quad (A3)$$

$$dF = (dIx^2 + dIo^2)^{\frac{1}{2}} \quad (A4)$$

$$dDo = \sin^{-1}(\sin \alpha_{95} / \cos Io) \quad (A5)$$

$$dDx = \sin^{-1}(\sin A_{95} / \sin p) \quad (A6)$$

$$dIo = \alpha_{95} \quad (A7)$$

$$dIx = 2A_{95} / (1 + 3\cos^2 p) \quad (A8)$$

where α_{95} is the circle of 95% confidence about the observed direction, A_{95} is the equivalent circle about the reference pole and p is the ancient colatitude (angular distance from sampling area to reference pole). Positive R implies clockwise rotation of the sampling area in relation to the reference area. Positive F implies relative northward transport.

Appendix 2

Paleomagnetic data obtained from the Tomari, Uozu, Kanazawa and Daishoji areas.

Tomari area (ITOH & WATANABE, 1988)

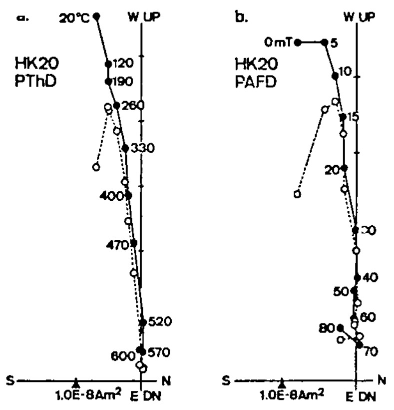

Fig. 3. Typical vector-demagnetization diagrams of progressive demagnetization tests. Solid (open) circles are projection of vector end-points on horizontal (N-S vertical) plane in in-situ coordinates. Numbers attached to symbols are demagnetization levels in °C & mT.

Site	N	DMG	D(°)	I(°)	α_{95}(°)	Λ(°N)	Φ(°E)	R(°)	F(°)	Lithology
					Late Pliocene					
HK72	8	400°C	123.0	-49.6	14.4	-42.8	-122.8	-57.0±22.6	6.8±14.4	siltstone
HK22	8	260°C	123.4	-60.2	7.1	-46.6	-108.7	-56.6±14.4	-3.8± 7.1	siltstone
					Middle Miocene					
HR19	8	20mT	129.1	-65.4	5.6	-51.6	-99.9	-50.9±13.6	-9.0± 5.6	andesite
					Early Miocene					
HK20	8	10mT	134.4	-58.3	2.5	-54.4	-114.8	-108.1±13.4	-10.3±13.0	tuff
HK71	8	250°C	134.4	-52.7	16.2	-52.9	-124.1	-108.1±30.1	-4.7±20.6	shale
HK18	8	10mT	-43.0	58.2	3.2	56.3	64.3	-105.5±13.9	-10.2±13.1	rhyolite

Table 2. Tilt-corrected site-mean directions in the Tomari area.

DMG: demagnetization level, D,I: mean declination & inclination, α_{95}: radius of 95% confidence circle, Λ,Φ: latitude & longitude of VGP position, R,F: tectonic parameters defined by BECK (1980).

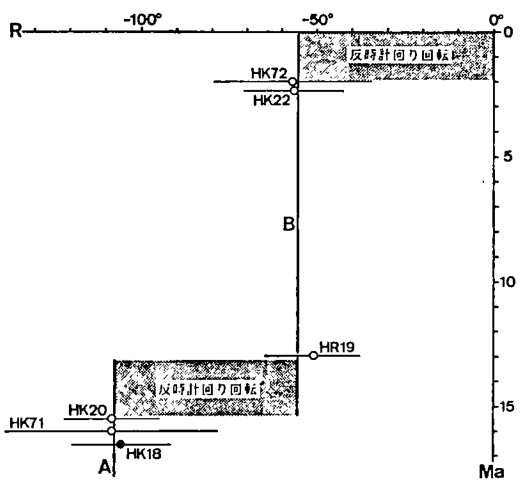

Fig. 4. R value versus age for the Tomari area. Error bars are uncertainty in R defined by BECK (1980). Solid (open) symbols are data with normal (reversed) polarity.

Uozu area (ITOH & ITO, H., 1988)

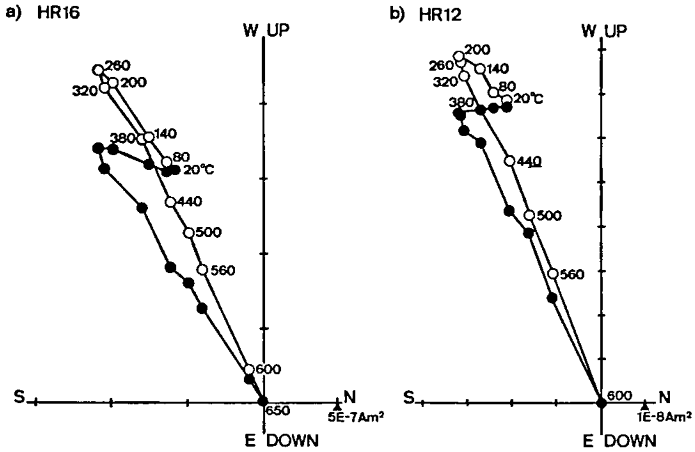

Fig. 3. Typical vector-demagnetization diagrams of progressive thermal demagnetization. Solid (open) circles are projection of vector end-points on horizontal (N–S vertical) plane in in-situ coordinate. Numbers attached to symbols are temperature in °C. Progressive change of vector end-points shows a straight trend indicating stable magnetization. In (a), spectrum of blocking temperature indicates that stable magnetization is carried by magnetite and hematite. In (b), stable magnetization is carried by magnetite.

Table 1. Paleomagnetic site-mean directions obtained from the Futomiyama Group in the Uozu area.

Site	DEMAG	Dc	Ic	N	α_{95}	k	Lat(N)	Lon(E)
HR12	260°C	-161.1	-53.2	9	3.5	221.5	-74.3	52.7
HR13	15mT	-146.0	-51.4	8	1.7	1126.9	-61.7	46.8
HR14	15mT	-154.9	-66.7	10	2.0	574.2	-67.9	4.9
HR15	10mT	-153.9	-48.5	8	2.1	694.0	-67.1	58.3
HR16	440°C	-159.0	-57.7	8	1.5	1305.8	-73.3	35.7
mean		25.2	55.6	5	7.5	106.2		

DEMAG : demagnetization level, Dc, Ic mean declination and inclination in degrees after tilt correction, N : number of specimens, α_{95} : radius of 95% confidence circle in degrees, k : Fisher's precision parameter, Lat(N), Lon(E) : north latitude and east longitude of virtual geomagnetic pole position in degrees.

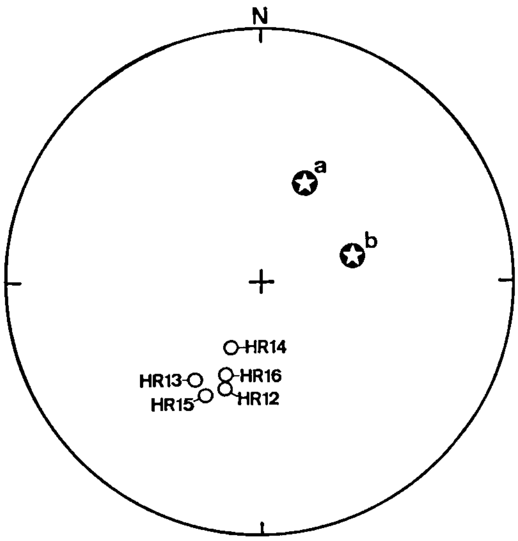

Fig. 4. Equal-area plots of paleomagnetic directions. Open circles show site-mean directions obtained from the Futomiyama Group after tilt correction (on the upper hemisphere). Stars show average paleomagnetic directions for the Futomiyama Group (59 Ma) in the Uozu area (a) and the Sakurae Group (63—58 Ma) in the San'in area (b) (lower hemisphere). Direction for Sakurae Group is after OTOFUJI & MATSUDA (1987). Average directions (a,b) are presented as the values at the representative point of the eastern part of Southwest Japan (36°N, 137°E).

Kanazawa and Daishoji areas (ITOH & ITO, Y., in press)

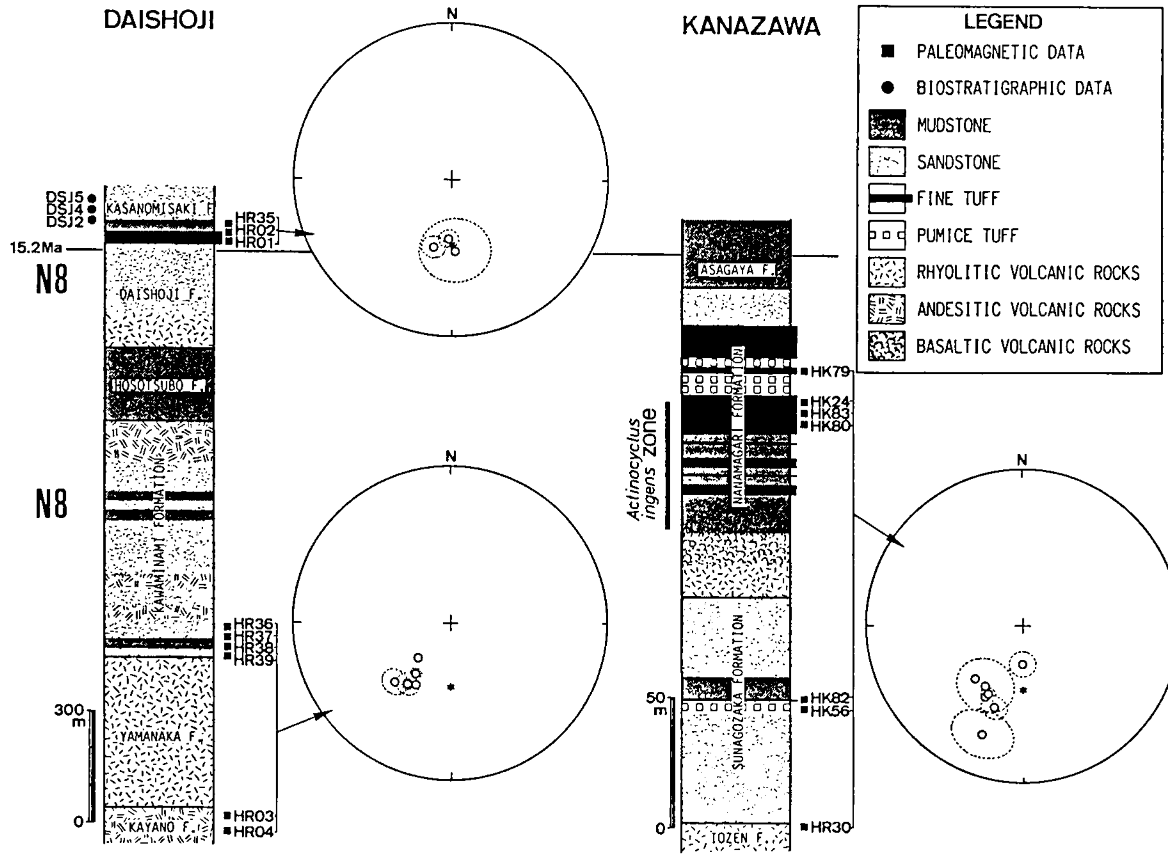

Fig. 3. Stratigraphic successions in the Kanazawa and Daishoji areas after Sugimoto (1983) and Bito et al. (1980). Possible horizon of planktonic foraminiferal N8/N9 boundary (15.2 Ma) is shown on the basis of biostratigraphic data. Equal-area plots of site-means after tilt correction are also shown with 95% confidence circles. Asterisk represents axial dipole field direction. All the directions are plotted on the upper hemisphere.

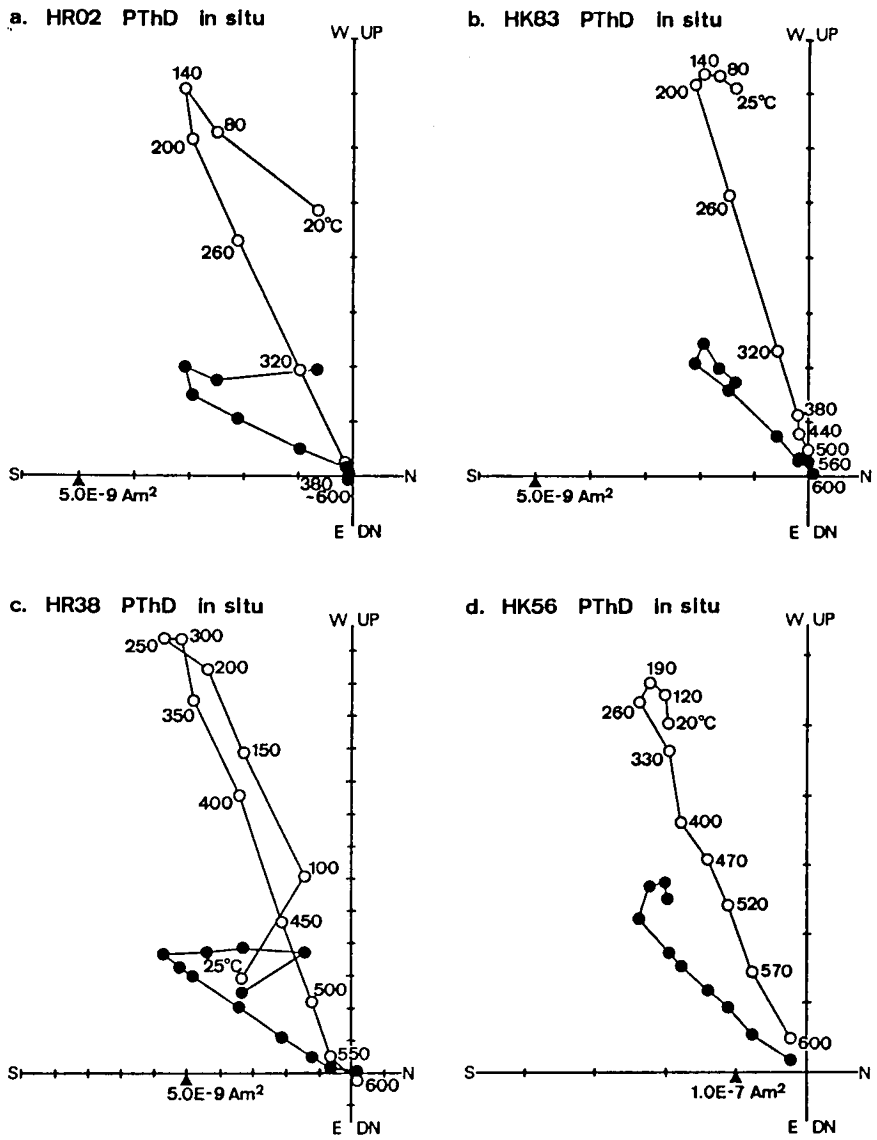

Fig. 5. Typical vector-demagnetization diagrams of progressive thermal demagnetization. Solid (open) circles are projection of vector endpoints on the horizontal (N-S vertical) plane in in-situ coordinates. Unit of coordinates is bulk intensity of the remanence. Numbers attached to symbols are temperature in centigrade. Progressive change of vector endpoints above 260°C shows a straight trend indicating stable characteristic remanent magnetization.

Formation	Site	DEMAG	n	Dc(°)	Ic(°)	α_{95}(°)	k	Locality lat.(N)	Locality long.(E)	Lithology
					KANAZAWA AREA					
Nanamagari	HK79	300°C	9	-179.3	-70.0	6.8	58.9	36°30.1'	136°42.4'	fine tuff
	HK24	330°C	8	-160.3	-43.8	6.4	75.4	36°30.1'	136°43.6'	fine tuff
	HK83	200°C	8	-137.9	-52.4	2.5	479.0	36°30.0'	136°41.7'	fine tuff
	HK80	300°C	10	-159.1	-26.9	14.2	12.5	36°30.1'	136°42.4'	fine tuff
Sunagozaka	HK82	250°C	8	-147.9	-52.5	14.5	15.6	36°30.8'	136°46.0'	tuff
	HK56	300°C	11	-152.0	-47.3	1.5	923.4	36°30.1'	136°43.9'	tuff
Iozen	HR30	25mT	8	-152.7	-49.4	3.9	202.0	36°29.5'	136°42.1'	tuff
TOTAL&MEAN			N=7	25.6	49.3	11.0	31.1			
					DAISHOJI AREA					
Kasano-misaki	HR35	200°C	8	-165.2	-53.1	6.0	86.3	36°18.8'	136°17.9'	fine tuff
	HR02	40mT	8	-177.1	-58.8	5.1	119.2	36°18.8'	136°17.9'	fine tuff
	HR01	320°C	8	177.4	-52.1	17.6	10.9	36°18.8'	136°17.9'	fine tuff
TOTAL&MEAN			N=3	5.1	54.9	9.7	162.0			
Kawaminami	HR36	250°C	9	-144.8	-50.3	2.9	311.5	36°15.2'	136°20.0'	siltstone
	HR37	15mT	8	-145.5	-57.6	3.2	302.9	36°15.2'	136°20.0'	siltstone
	HR38	200°C	8	-150.8	-52.7	1.7	1028.7	36°15.2'	136°20.0'	siltstone
	HR39	15mT	9	-145.0	-50.4	5.9	77.1	36°15.2'	136°20.0'	siltstone
Kayano	HR03	260°C	12	-137.4	-65.0	2.4	328.4	36°13.7'	136°21.8'	tuff
	HR04	10mT	10	-136.8	-46.9	6.8	51.6	36°13.4'	136°20.9'	tuff
TOTAL&MEAN			N=6	36.5	53.9	6.0	125.7			

TABLE 2

Paleomagnetic site-means obtained from the studied areas*

* Columns give the formation name, site name, demagnetization level (DEMAG), number of specimens (n), declination (Dc) and inclination (Ic) of site-means after tectonic tilt correction, radius of 95% confidence circle (α_{95}) and Fisher's precision parameter (k), locality of sampling site, lithology of samples.