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Neogene stress field in SW Japan and mechanism of deformation during the Sea of Japan opening

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Abstract. We present new structural data from SW Japan and discuss the mechanism of deformation during the opening of the Sea of Japan. We studied the Miocene basins at the southern margin of the Sea of Japan (northern coast of SW Japan) and of the Median Tectonic Line (MTL) by means of fault slip analysis to determine stress field directions during the opening of the Sea of Japan in early and middle Miocene time. On the southern margin, the stress field was extensional or transtensional with a NW-SE trending extension direction. The MTL was a normal fault in Shikoku during early middle Miocene and probably a normal fault with a left-lateral component in central Japan before having been strained by the collisions of the Tanzawa and Izu blocks with central Japan. We combine our results with published data for the Sea of Japan area and show that early and middle Miocene stress field directions are remarkably consistent on the eastern, southern, and western margins of the Sea of Japan with σ_{Hmax} trending NE-SW and σ_{Hmin} trending NW-SE. The stress regime is transpressional or transtensional on the eastern and western margin and almost purely extensional on the southern margin. This stress field distribution is in agreement with the model of the opening of the Sea of Japan in an extensional transfer zone between two N-S right-lateral strike-slip zones proposed by Jolivet et al. (1991). Analogue modelings and kinematic reconstructions showed that this model accounts for 20° to 30° of clockwise rotation in SW Japan, while paleomagnetic rotations reached 40° to 50° during the opening. We present structural data showing that SW Japan was strained during the rotation and did not behave as a rigid block. Our observations suggest that rotations of small blocks may have occurred. We propose that SW Japan has been sheared between the right-lateral strike-slip zones which bound the Sea of Japan and that the missing 10° to 30° of rotation are to be found in its internal deformation. In our model, the MTL is a normal fault with a strike-slip component rotating in a right-lateral shear zone.

Introduction

Paleomagnetism is a very efficient tool to study continental deformation provided that the geometry of crustal blocks and motion along faults that bound them are fully understood [e. g., *Ron et al.*, 1984; *Luyendyk et al.*, 1985]. The case of the Sea of Japan is somewhat controversial because it is difficult to reconcile marine and onland structural data with paleomagnetic data. Two problems arise. The first one is the timing of opening of the Sea of Japan. Paleomagnetic data suggests that SW Japan has been rotated clockwise 40° to 50° as a rigid block between 16 and 14 Ma, causing the fast opening of the Sea of Japan with accretion rates ranging from 20 to 50 cm yr^{-1} [*Otofuji et al.*, 1984, 1985a, 1991; *Otofuji and Matsuda*, 1987; *Hayashida et al.*, 1991]. On the basis of radiometric and micropaleontologic datings of oceanic basalts and sediments drilled during the Ocean Drilling Program (ODP) legs 127 and 128 in the Sea of Japan, *Tamaki et al.* [1992] instead concluded that the Sea of Japan progressively opened between 32 and 11 Ma and that accretion in the Japan Basin occurred between 24 and 17 Ma. *Jolivet et al.* [1995] suggested that the discrepancies between the age of the rotations and the age of accretion are partly because of dating methods. Another possibility is that SW Japan did not rotate as a single rigid block and consequently, that the paleomagnetic rotations are not simply linked with the opening of the Sea of Japan.

The second problem is the incompatibility between rotations and structural data. Two models of opening of the Sea of Japan have been proposed from paleomagnetic data [*Otofuji et al.*, 1985a; *Otofuji and Matsuda*, 1987] and from structural data [*Lallemand and Jolivet,* 1985]. *Otofuji et al.* [1985a] proposed a "bar door" model for the opening of the Sea of Japan with clockwise rotation of SW Japan and counterclockwise rotation of NE Japan (paleomagnetic rotations in Japan since early Miocene are shown in Figure 1). *Lallemand and Jolivet* [1985] instead proposed that the Sea of Japan opened as a pull-apart basin

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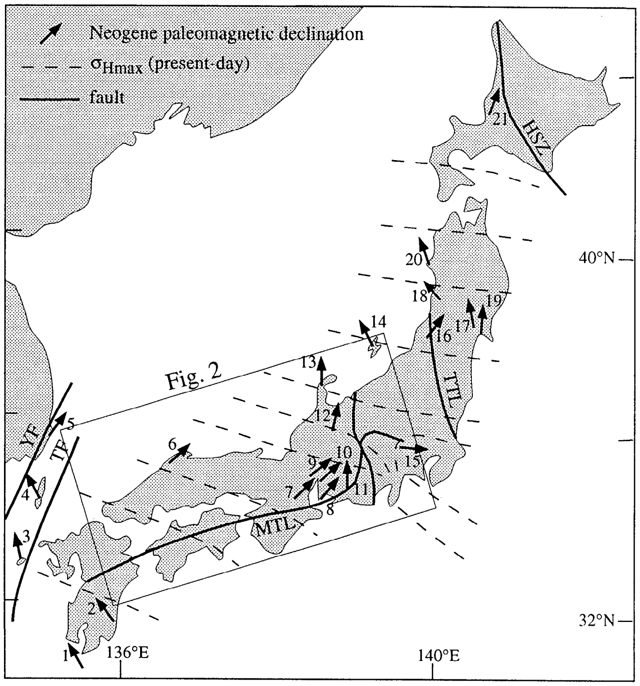

Figure 1. Neogene paleomagnetic declinations and present-day stress field. HSZ is the Hidaka shear zone, MTL is the Median Tectonic Line, TF is the Tsushima fault, TTL is the Tanakura tectonic line, YF is the Yangsan fault. Paleomagnetic declinations are compiled from 1, *Kodama et al.* [1991]; 2, *Kodama and Nakayama* [1993]; 3, *Ishikawa and Tagami* [1991]; 4, *Ishikawa et al.* [1989]; 5, *Kim et al.* [1986]; R. McCabe (unpublished data); 6, *Otofuji et al.* [1991]; 7, *Hayashida and Ito* [1984]; 8 and 9, *Hayashida* [1986]; 10, *Hayashida et al.* [1991]; 11, *Otofuji et al.* [1985]; 12, *Itoh* [1988]; 13 and 14, *Hirooka et al.* [1986]; 15, *Hyodo and Niitsuma* [1986]; 16, 17, and 18, *Otofuji et al.* [1985b]; 19, *Yamazaki* [1989]; 20, *Tosha and Hamano* [1988]; and 21, *Kodama et al.* [1993]. The trajectories of present-day σ_{Hmax} are compiled from *Tsukahara and Kobayashi* [1991], *Tsukahara and Ikeda* [1991], *Ishii et al.* [1983], and *Nakamura and Uyeda* [1980].

between two N-S trending right-lateral strike-slip zones. However, rotations and motions along faults are inseparable components of the deformation, and both must be taken into account in a model of opening. From analogue modeling experiments, *Jolivet et al.* [1991] proposed an improved pull-apart model which took into account a part of the rotations. The structural context of the rotations in SW Japan being poorly known, we decided to survey the Miocene basins of SW Japan. The study of the Neogene stress field from northern Sakhalin to central Honshu by means of fault slip analysis [*Angelier*, 1984] had produced consistent results over a 2000-km-long strike-slip zone, supporting the model of pull-apart opening [*Jolivet and Huchon*, 1989; *Jolivet et al.*, 1991, 1992; *Fournier et al.*, 1994]. In this paper, we extend the Neogene stress field study to SW Japan. We present results for two basins located on the southern margin of the Sea of Japan (northern coast of SW Japan), the basins of the Shimane Peninsula and the Tango Peninsula, and for three basins located along the Median Tectonic Line (MTL), the Ishizuchi, Shidara, and Chichibu basins (Figure 2). Results for the basins of the Noto Peninsula, Yatsuo and Sado, were previously published [*Fournier et al.*, 1994; *Jolivet et al.*, 1991]. The Tsu and Muro basins along the MTL were surveyed without any result because of the lack of outcrops. The stratigraphy of the surveyed basins is compiled in Figure 3.

Early to Middle Miocene Transtension on the Southern Margin of the Sea of Japan

Shimane Peninsula Basin

Three formations of early to middle Miocene age are described from the Shimane Peninsula basin, the Hata, Kuri-Kawai, and Omori formations in ascending order (Figure 3). They consist of rhyolitic and dacitic lavas and pyroclatics intercalated with sandstones, conglomerates, and shales. K-Ar ages range from 19 to 15 Ma in the Hata formation [*Kano and Yoshida*, 1984; *Kano and Nakano*, 1985], 18 to 14 Ma in the Kuri-Kawai formation [*Otofuji et al.*, 1991], and 16 to 13 Ma in the Omori formation [*Kano and Yoshida*, 1984; *Kano et al.*, 1991; *Otofuji et al.*, 1991]. The Omori formation is intruded by andesitic dikes radiometrically dated at 9.3 ± 2.4 Ma (K-Ar) [*Kano and Yoshida*, 1984; *Kobayashi*, 1979a].

We carried out fault measurements in the Hata (site 1), Kuri-Kawai (sites 4, 5, 6, 7, 8A, 8B, 13, 14A, 14B, 15, and 16), and Omori (site 9) formations (Figure 4). Three types of paleostress tensors have been obtained. The first one characterizes an extensional stress regime with σ_3 ($\sigma_1 > \sigma_2 > \sigma_3$) trending NW-SE to E-W (sites 1, 5A, 8A, and 14A); the second one characterizes a strike-slip regime with σ_1 trending N-S and σ_3 trending E-W (sites 7, 8B, and 16); and the third one characterizes a compressional stress regime with σ_1 trending N-S to NW-SE (sites 9 and 13).

The upper formation (Omori) is only slightly faulted and records only the compression (site 9). This compression is expressed at a regional scale by large folds with E-W trending axes affecting upper Miocene formations (Figure 4). The same kind of folds have been reported in the Sea of Japan to the northwest of the Shimane Peninsula and are unconformably overlain by unfolded Pliocene deposits [*Tanaka and Ogusa*, 1981; *Yamamoto*, 1993]. The compressional event therefore occurred during the late Miocene.

The Hata and Kuri-Kawai formations were affected by the late Miocene compression and also recorded the extensional and strike-slip deformations. Normal and strike-slip faults are sometimes found on the same outcrop (sites 5A and 8A), and no crosscutting relations between them can be observed. The faults are compatible (the extension directions of stress tensors are not significantly different), and it is difficult to argue for separate tectonic events. Because the late middle Miocene Omori formation was not affected by normal and strike-slip faulting, the extensional and strike-slip deformation is of early to early middle Miocene age. By analogy with the early to middle Miocene deformation on the Tango Peninsula, we consider that it pertains to one single transtensional event.

We therefore have evidence for two successive tectonic events during the Miocene: a transtensional event during

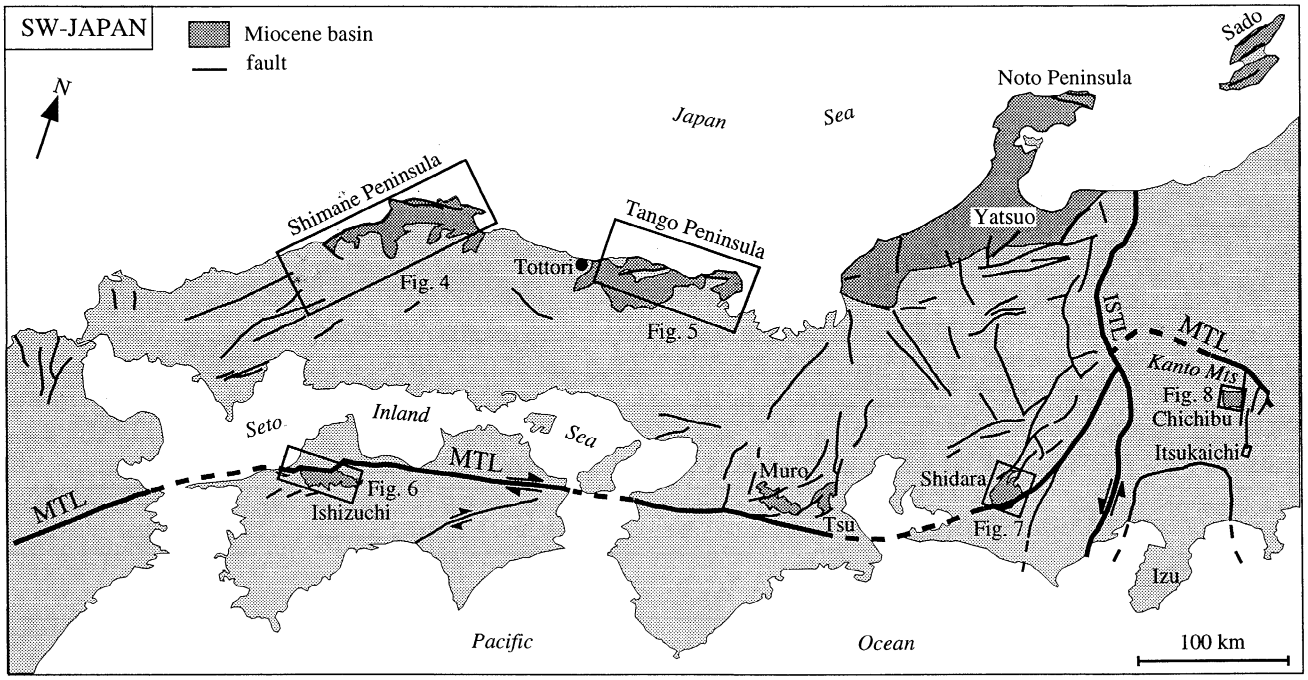

Figure 2. Miocene basins of SW Japan.

early to early middle Miocene and a N-S compressional event during late Miocene. Results obtained in this region are especially important because precise dates of clockwise paleomagnetic rotation are available. According to *Otofuji et al.* [1991], the rotations occurred between 16.1 ± 1.4 Ma (mean K-Ar age of the Kawai formation with a paleomagnetic declination of 39°E ± 15°) and 14.2 ± 0.6 Ma (mean K-Ar age of the Omori formation with a paleomagnetic declination roughly N-S). The extensional and strike-slip deformation observed in the Kuri-Kawai formation, which did not affect the Omori formation, appears to be coeval with the paleomagnetic rotations. As will be discussed in a later section of this paper, the geometry of faulting in the Kuri-Kawai formation suggests that the deformation was taken up by small-blocks rotations.

Tango Peninsula Basin

The early and middle Miocene section of Tango Peninsula basin (Hokutan Group) is composed of four formations, the Yoka, Toyooka, Amino, and Tango formations in ascending order (Figure 3). The Yoka, Amino, and Tango formations consist of basaltic, andesitic, and rhyolitic lavas and breccias, and the Toyooka formation mainly consists of conglomerates, sandstones, and mudstones. The Yoka and Tango formations are intruded by andesitic and basaltic dikes with K-Ar ages of 19-20 Ma and 14-15 Ma, respectively [*Tsunakawa et al.*, 1983a; *Yamamoto and Hoshizumi*, 1988], and the Amino formation recorded an episode of silicic volcanism dated at 15 Ma (K-Ar) [*Yamamoto and Hoshizumi*, 1988]. The Tango formation unconformably

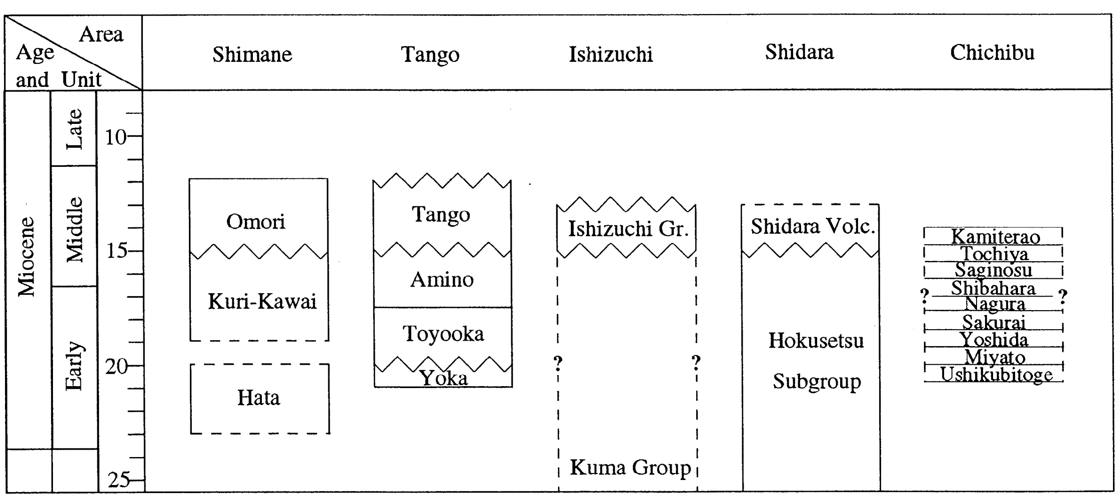

Figure 3. Age of formations of Miocene basins of SW Japan after *Kano et al.* [1991] and *Arai and Kano* [1960].

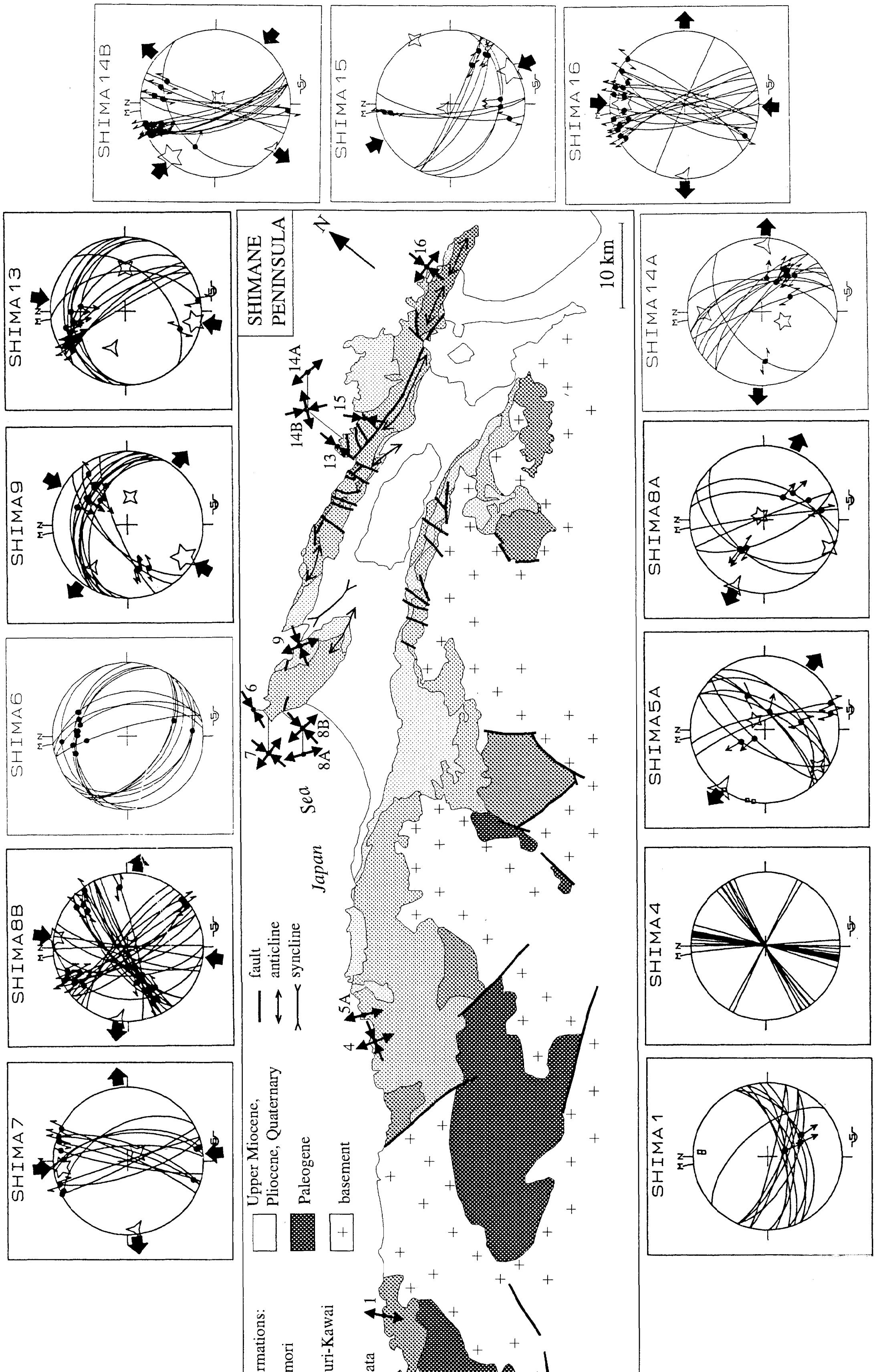

Figure 4. Stress tensors computed for the Shimane Peninsula.

overlies the Amino formation and is unconformably overlain by late Miocene and Pliocene series.

Fault measurements were carried out in the Yoka (sites 10A, 10B, 12, and 14), Toyooka (sites 2, 3, 5, 6, 8, and 17), and Tango (sites 1 and 4) formations (Figure 5). These formations are widely affected by normal and strike-slip faults. The normal faults trend about NE-SW, and the conjugate strike-slip faults trend N-S (right-lateral) and ENE-WSW (left-lateral). Margins of N70°E to N90°E trending dikes that intruded the Yoka formation are reworked as left-lateral strike-slip faults, and the dikes are cut by vertical tension fracture veins trending NE-SW (sites 12 and 14). These structures are compatible with a transtensional stress regime with σ_3 trending NW-SE and σ_1 either vertical or horizontal. The upper Miocene and Pliocene formations are not affected by the transtensional deformation. The transtensional event therefore occurred during early to middle Miocene.

Noto Peninsula and Sado Island

Lower and middle Miocene formations of the Noto Peninsula are affected by normal faults associated with compatible strike-slip faults [*Fournier et al.*, 1994]. Inversion of the data yielded a transtensional middle Miocene regional stress field with σ_3 trending NW-SE. The upper Miocene formations of the Noto Peninsula did not record the transtensional stress regime, but they are affected by late ENE-WSW trending folds as in the Shimane Peninsula.

Similar brittle deformation data were reported by *Jolivet et al.* [1991] on Sado island, east of the Noto Peninsula. There, succession from strike-slip to normal motion was observed on fault planes in lower and middle Miocene formations. However, in the absence of precise stratigraphic data, it was not possible to distinguish two distinct events.

Conclusions

From the Shimane Peninsula to Sado island, the southern margin of the Sea of Japan recorded a transtensional event during early to middle Miocene with compatible normal and strike-slip faults. It is characterized by a NW-SE to WNW-ESE extension direction, the vertical axis of the stress tensor being either σ_1 or σ_2. This transtension affects formations of early to early middle Miocene age, the Kuri-Kawai formation in the Shimane Peninsula basin, the Amino and Tango formations in the Tango Peninsula basin, and the Yatsuo formation in the Noto Peninsula basin, and this transtension lasted at least until 15 Ma according to the radiometric ages of these formations [*Kano et al.*, 1991]. This transtensional event is also known farther west on the southern margin of the Sea of Japan, on northern Kyushu, and Goto islands.

During late Miocene, an almost N-S compression prevailed on the southern margin of the Sea of Japan, expressed by E-W to ENE-WSW trending folds. This compressional event is also documented in the Korea Strait where it is responsible for left-lateral motions along NNE-SSW trending faults during late Miocene [*Fabbri and Charvet*, 1994].

Miocene Normal and Left-Lateral Motion Along the Median Tectonic Line

The MTL is the most prominent dislocation in SW Japan, but its motion during the opening of the Sea of Japan remains poorly constrained. During Latest Cretaceous to Paleogene, the MTL was a left-lateral fault as suggested by the en echelon arrangement of folds and faults in the Izumi group (Campanian-Maastrichtian) along the fault, which are not observed in the Kuma group that was deposited between late Eocene and early middle Miocene [*Ichikawa*, 1980; *Miyata et al.*, 1980]. Since latest Pliocene, the MTL has been a right-lateral strike-slip fault, and its rate of motion is estimated from the offset of Quaternary terraces at 5 to 10 mm yr^{-1} in its fastest portion (eastern Shikoku) [*Okada*, 1980, 1992]. We conducted a structural study of Neogene basins distributed along the MTL to determine the stress field and the motion of the MTL during the opening of the Sea of Japan.

Ishizuchi Basin (Shikoku)

The Tertiary Ishizuchi basin consists of conglomerates, sandstones, and mudstones (Kuma Group), overlain by middle Miocene volcanics (Ishizuchi Group) (Figure 3). The Kuma Group is considered of late Eocene age and the contact with the Ishizuchi volcanics is described as an uncomformity. However, tuff layers at the base of the volcanics are locally intercalated with the Kuma Group sandstones suggesting a progressive early middle Miocene transition. In the eastern part of the basin, these formations are intruded by granodioritic stocks dated at 14 Ma (K-Ar) [*Shibata and Nozawa*, 1967; *Yoshida*, 1984] and by an andesitic dike swarm of the same age [*Kobayashi*, 1979b; *Yoshida*, 1984].

The Ishizuchi basin is bounded to the north by the northward dipping MTL which brings into contact the Kuma group with upper Cretaceous sandstones (Izumi Group) [*Takahashi*, 1986, 1992; *Takeshita*, 1991]. *Takagi et al.* [1992] described northward dipping normal shear bands in the MTL fault zone and dated the foliated fault gouge at 14.7 Ma (K-Ar). They concluded to normal motion along the MTL during middle Miocene.

We carried out fault measurements in the Kuma and Ishizuchi Groups and in the MTL fault zone (Tobe Thrust type locality). Normal faulting prevails in all sites (Figure 6). It is associated with compatible strike-slip faulting in site 5 only. The stress regime is extensional, with σ_3 trending N-S to NW-SE. This stress regime is mechanically consistent with the injection of the E-W trending andesitic dike swarm. We consider that the extension inferred from the fault is coeval with the dike emplacement (14 Ma) and, following *Takagi et al.* [1992], that the MTL was a normal fault during early middle Miocene.

Shidara Basin (Central Japan)

The lower series of Shidara basin consists of Oligocene to early Miocene tuffaceous sandstones and mudstones (Hokusetsu subgroup). They are overlain by rhyolitic and dacitic lavas (Shidara volcanics) (Figure 3) [*Kogi,* 1983]. These formations were intruded by andesitic dikes dated at

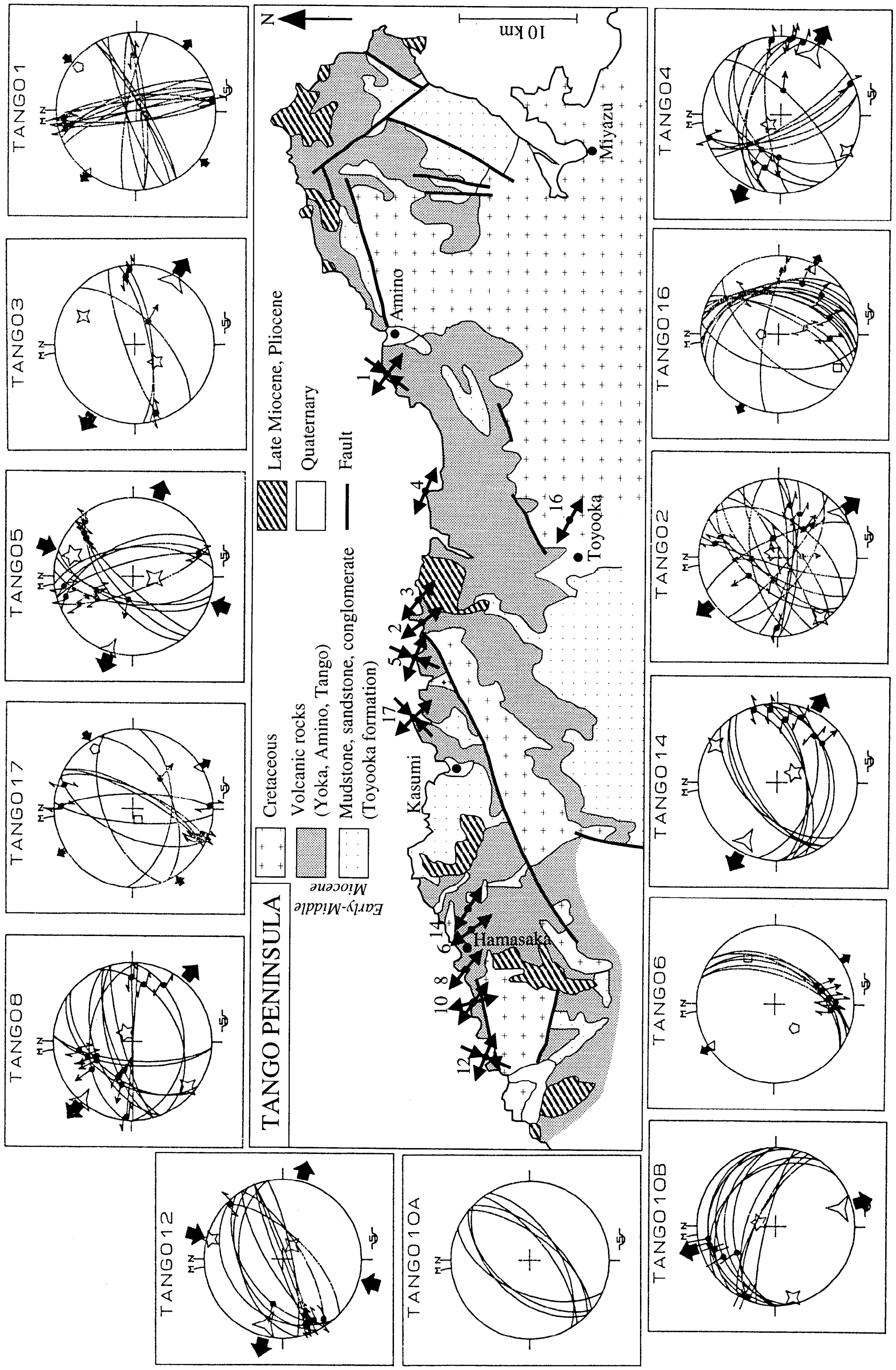

Figure 5. Stress tensors computed for the Tango Peninsula.

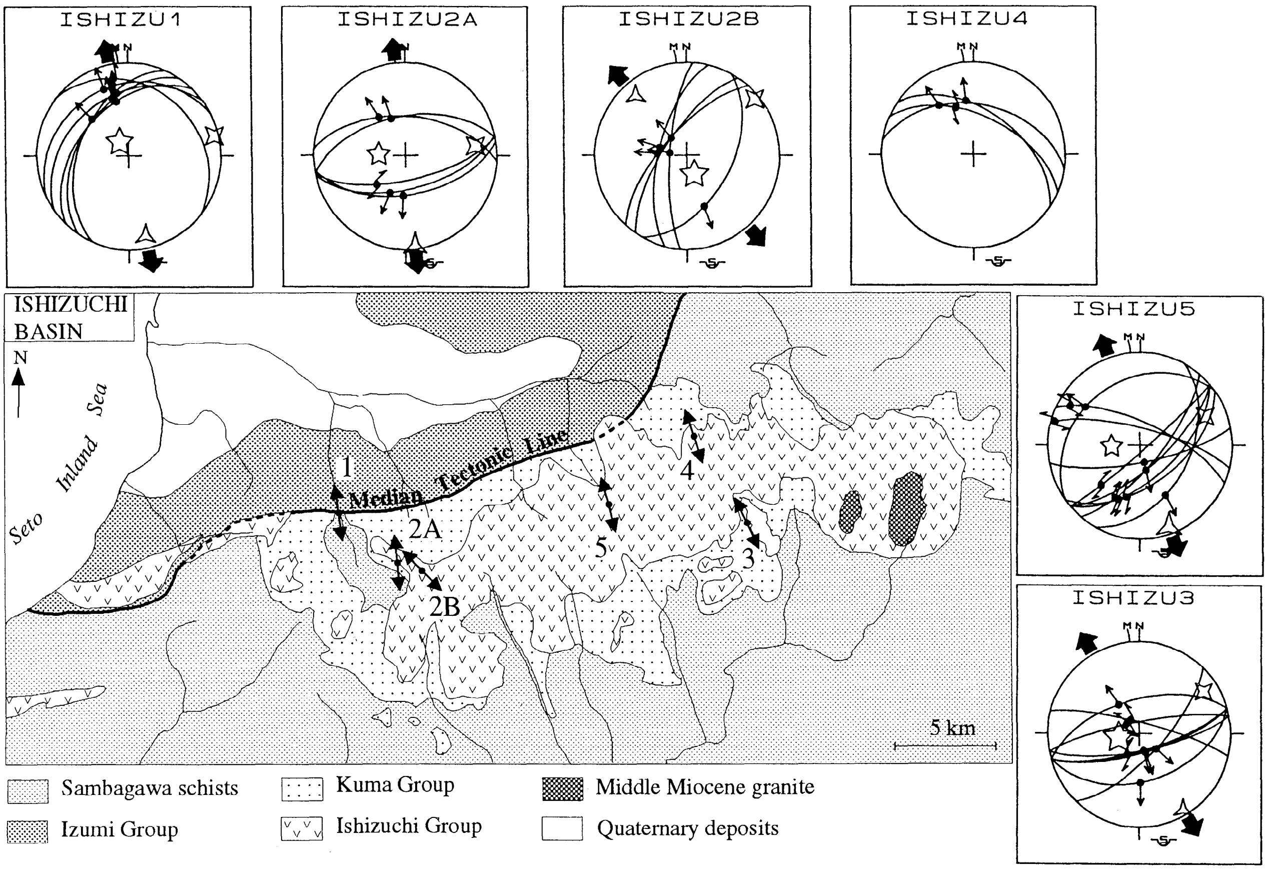

Figure 6. Stress tensors computed for the Ishizuchi basin.

16.5-14.9 Ma (K-Ar) [*Tsunakawa et al.*, 1983a; *Takada*, 1987a, b]. N-S paleomagnetic declinations measured in the andesitic dikes suggest that no rotation occurred since their emplacement [*Torii*, 1983]. The basin is bounded to the south by the MTL which is steeply dipping toward the north [*Ui*, 1980].

Fault measurements (Figure 7) were carried out in the Oligocene to early Miocene series (sites 7, 9, 11, 13A, 13B, and 14), in cataclasites along the MTL (sites 2A, 2B, 3, and 5), and in the Cretaceous basement (sites 8 and 12). The Shidara volcanics are nearly devoid of faults. Two systems of conjugate normal faults have been observed. The first one trends N-S to NNW-SSE and is sometimes associated with compatible strike-slip faults (sites 2A, 5, 7, 8, and 13A). The stress regime is extensional or transtensional with σ_3 trending E-W to WSW-ENE and σ_1 either vertical or horizontal. The extension direction is compatible with the emplacement of the N-S to N20°E trending andesitic dikes in the basin [*Kogi*, 1983]. We then consider that the extension inferred from the faults is coeval with the dike emplacement (16.5-14.9 Ma). The extension direction is slightly oblique to the trend of the MTL (N50°E) suggesting a normal motion with left-lateral strike-slip component along it. The dike swarm geometry, with respect to the MTL to the south and the Tsugu fault to the north, also suggests that it was emplaced in an extensional transfer zone between the two left-lateral strike-slip faults.

The second system of conjugate normal faults trends NE-SW (sites 2B, 9, 10, and 11) and pertains to an extensional stress regime with σ_3 trending NW-SE. This fault system is observed in coarse deposits at the base of the basin (sites 9, 10, and 11). Synsedimentary faulting shows that extension accompanied sedimentation during the Oligocene to early Miocene. The extension direction is compatible with purely normal motion along the MTL.

Two extensional events are therefore recognized in the Shidara basin, a NW-SE extension during the Oligocene to early Miocene and a WSW-ENE extension coeval with the andesitic dike emplacement during late early to early middle Miocene (16.5-14.9 Ma). The extension directions are compatible with a purely normal motion along the MTL during the Oligocene to early Miocene and with an oblique-slip motion with a left-lateral component during late early to early middle Miocene.

Chichibu Basin (Central Japan)

The MTL and the external zones of SW Japan (Tertiary accretionary prisms) are bent in central Japan to the north of the Izu Peninsula (Figure 2) owing to the successive collisions of the Tanzawa and Izu blocks of the Philippine Sea Plate with Japan [*Niitsuma and Matsuda*, 1985; *Taira et al.*, 1989]. The age of the Tanzawa collision is poorly constrained. *Takahashi and Nomura* [1989] showed that paleomagnetic declinations of the Chichibu quartzite (6-8 Ma) in the Kanto mountains (Figure 2) are not deflected and dated the Tanzawa collision as late Miocene or earlier. From paleomagnetic measurements in Upper Cretaceous to middle Miocene rocks of central Japan, *Itoh* [1988]

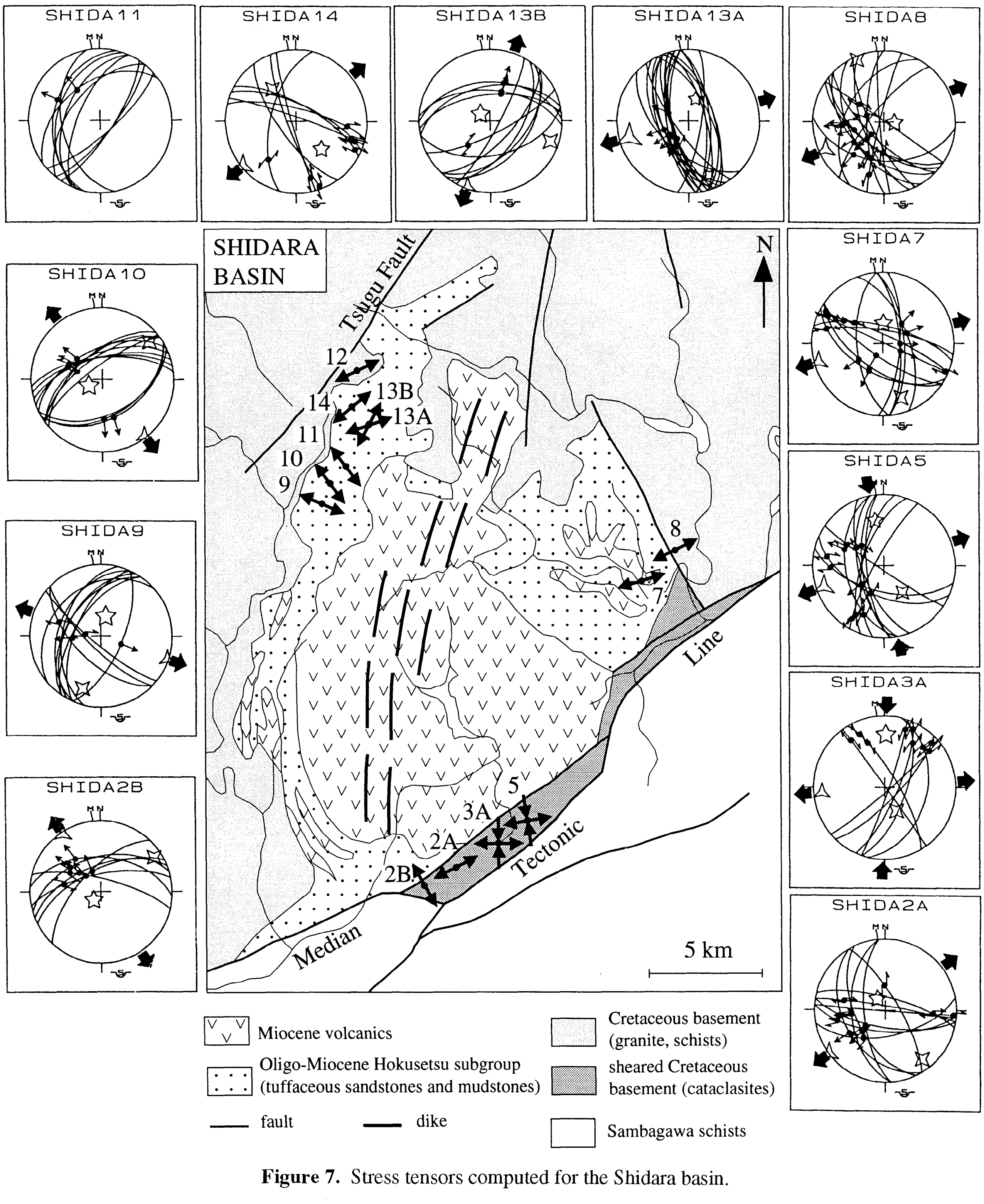

Figure 7. Stress tensors computed for the Shidara basin.

concluded that the bending of external zones of SW Japan occurred between 15 and 12 Ma. The Izu collision started during the Quaternary [*Huchon and Kitazato*, 1984].

The Chichibu basin is a square basin filled with Neogene deposits as thick as 5 km in its southern part and folded in a broad synform with a NE-SW axis (Figure 8) [*Arai and Kanno*, 1960]. The Neogene series uncomformably overlies the Mesozoic basement of the Kanto Mountains. The age of the lower formations in the basin is not well constrained but is suggested to be late Oligocene-early Miocene [*Arai and Kanno*, 1960]. Ages of the upper formations are correlated with the planktonic foraminiferal zone N8 of *Blow* [1969], which is late early to early middle Miocene in age [*Saito and Maiya*, 1973] and thus younger than about 16.3 Ma (Figure 3) [*Harland et al.*, 1990]. Paleomagnetic declinations measured in the Miyato and Yoshida formations (Figure 8) show a CW rotation of about 90° of the basin since its formation

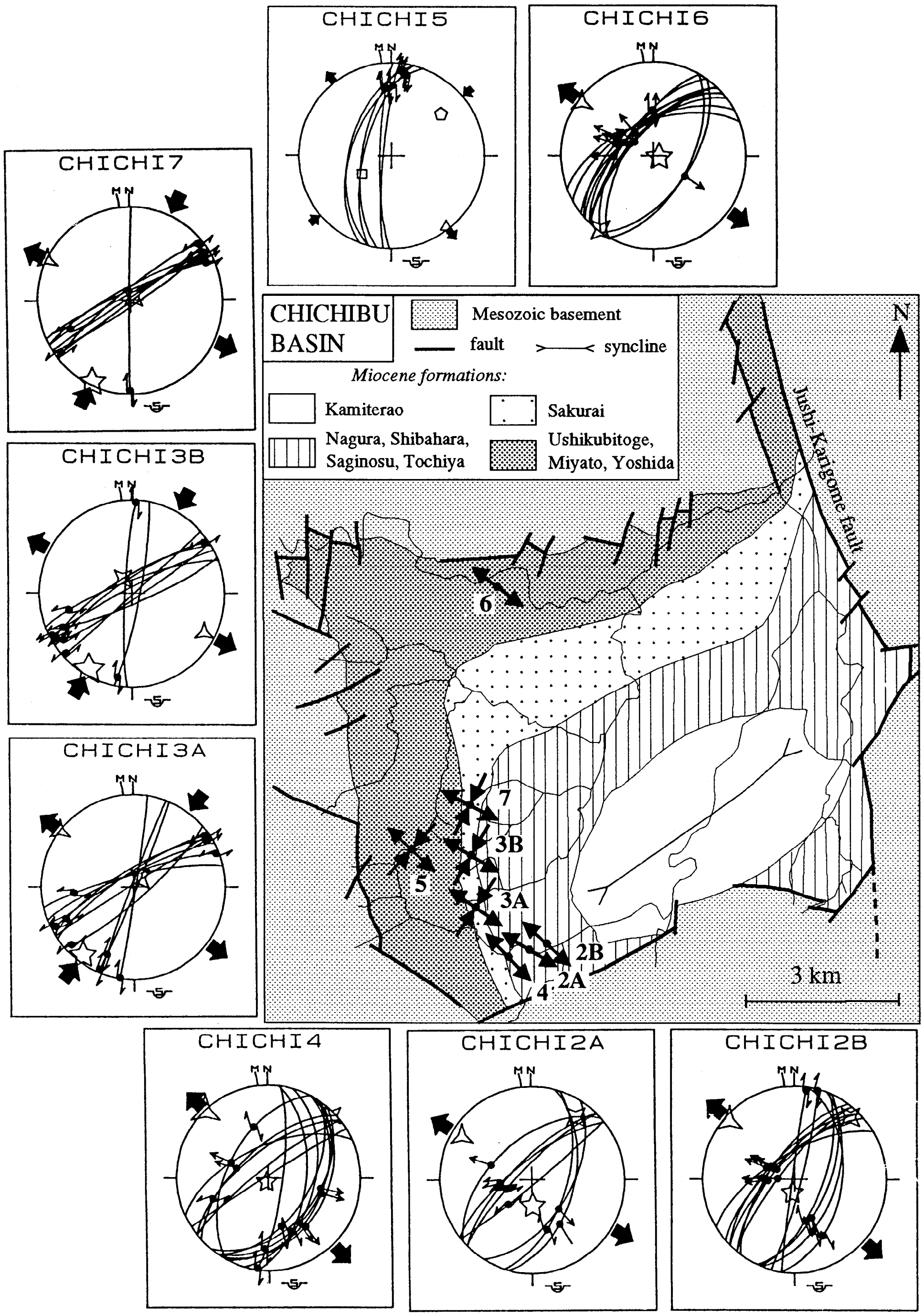

Figure 8. Stress tensors computed for the Chichibu basin.

[*Hyodo and Niitsuma*, 1986]. *Hyodo and Niitsuma* [1986] attributed this rotation partly to the rotation of SW Japan during the opening of the Sea of Japan and partly to the Tanzawa and Izu collisions since the middle or late Miocene.

The present-day σ_{Hmax} deduced from in situ measurements and earthquake focal mechanisms is trending NNE-SSW in the Kanto mountains and WNW-ESE immediately north of the Kanto mountains (Figure 1) [*Tsukahara and Ikeda*, 1991]. The northern boundary of the Kanto mountains coincides with the northern boundary of the zone of stress field perturbation induced by the Izu collision.

We measured sets of faults in sandstones of the lower part of the basin (Yoshida, Sakurai, and Nagura formations). We could not calculate stress tensors for the upper part of the basin, although we observed normal faults in the Saginosu formation. The paleostress tensors in Figure 8 are shown after tilt correction of the strata. Normal faulting dominates at sites 2A, 2B, 4, and 6, with conjugate normal faults trending NE-SW, and strike-slip faulting prevails in sites 3A, 3B, 5, and 7, with conjugate strike-slip faults trending N-S (right-lateral) and N60°E (left-lateral). This system of conjugate strike-slip faults has already been described by *Kuwahara* [1982] and *Sato* [1986]. In all sites, σ_3 consistently trends NW-SE and σ_1

is either vertical (extensional stress regime) or horizontal (strike-slip stress regime); it is not possible to differentiate two distinct events. Note that, with the exception of synsedimentary structures [*Latt*, 1989], we did not observe any compressional structures in the basin which appear to have been sheltered from the effects of the collisions.

Faults are observed in early to early middle Miocene formations and predate tilting of the strata. According to *Latt* [1989], initial tilting was coeval with the deposition of the upper basin formations, which constrains the age of the measured stress field to early middle Miocene or earlier. It therefore predated the basin rotation owing to the Tanzawa collision.

North of the Kanto Mountains, the MTL trends N110°E (Figure 2). In its vicinity (Yorii-Ogawa area), *Kuwahara and Sato* [1981] and *Kuwahara* [1982] described fault systems in early to early middle Miocene formations similar to those of Chichibu basin. The regional early to early middle Miocene stress field is then characterized by a direction of extension NW-SE which is compatible with a normal motion with a left-lateral slip component along the MTL, as in the Shidara basin. By comparison with the early middle Miocene stress field of the Shidara basin, the stress field of the Chichibu basin is rotated clockwise by about 60°, as is the MTL which trends N110°E instead of N50°E adjacent to the Shidara basin. The paleostress field and the fault were probably rotated during the Tanzawa and Izu collisions.

The Chichibu basin is bounded to the east by the NNE-trending Jushi-Karigome fault [*Arai and Kanno*, 1960] which links southward with the Naguri fault and the Itsukaichi basin (Figure 2). During early to early middle Miocene, these faults may have accommodated right-lateral motions. The Chichibu basin, with its square shape, might be a dextral pull-apart basin as proposed by *Kuwahara* [1982].

Synthesis of MTL Basin Results

The study of the MTL Miocene basins yields stress field directions which correlate with dike swarm emplacement during early middle Miocene. An extensional stress regime with σ_3 trending N-S prevailed in the Ishizuchi basin, a transtensional regime with σ_3 trending WSW-ENE prevailed in the Shidara basin, and a transtensional regime with σ_3 trending NW-SE prevailed in the Chichibu basin. In central Japan, the Tanzawa and Izu collisions caused local rotations which are not well understood. In the Shidara basin, the N-S declinations measured in the andesitic dikes emplaced at 16.5-14.9 Ma [*Otofuji et al.*, 1985a] might be interpreted as the sum of two successive rotations of reverse sense which nullify each other, related to the opening of the Sea of Japan and to the Tanzawa and Izu collisions. In the Chichibu basin, the timing and the rate of rotation due to the opening of the Sea of Japan and to the Tanzawa and Izu collisions are not well constrained. In the absence of precise rotation rates and datings in central Japan, the scattering of the stress field directions cannot be further discussed. Nevertheless, the likely sense of motion of the MTL remains a relevant result as the fault and the paleostress field directions underwent the same rotation. During early middle Miocene, the MTL appears to have been a normal fault in the Ishizuchi basin and a normal fault with a left-lateral strike-slip component in the Shidara basin and in the Chichibu basin area. This normal and left-lateral motion is coeval with the clockwise rotation of SW Japan [*Otofuji et al.*, 1991; *Hayashida et al.*, 1991]. As will be discussed later, this motion is compatible with the clockwise rotation of the MTL in a right-lateral shear zone at the scale of the Sea of Japan.

Summary: Early to Middle Miocene Stress Field in the Sea of Japan Area

Results concerning the early and middle Miocene stress field in the Sea of Japan area are collected in Figure 9. For each study area in SW Japan we determined a mean regional stress field from the computed stress tensors (Table 1). We did the same for the areas of Sakhalin and NE Japan which had been previously studied by *Jolivet and Huchon* [1989], *Jolivet et al.* [1991], and *Fournier et al.* [1994]. We also plotted in Figure 9 the stress field directions determined from fault slip analysis in the Pohang Tertiary basin in Korea (label 6 in Figure 9 [*Hwang*, 1992]) and in the Sea of Japan during the ODP leg 128 (label 7) [*Charvet et al.*, 1992], and the results of vein and dike strike statistics in Japan (labels 8, 9, and 10 [*Yamagishi and Watanabe*, 1986; *Otsuki*, 1990]).(References are given in Table 2.)

On the Sea of Japan margins, the directions of σ_{Hmax} and σ_{Hmin} deduced from fault analysis and vein strike statistics are remarkably consistent, that is, NE-SW and NW-SE, respectively. On the eastern margin, the stress regime is transpressional in the north in Sakhalin and Hokkaido and is transtensional in the south along the western coast of NE Honshu. It is almost purely extensional on the southern margin, and it is again transtensional on the western Korean margin. The northern margin of the Sea of Japan remains poorly known. This stress field distribution is in agreement with the model of opening of the Sea of Japan in an extensional transfer zone between two N-S right-lateral strike-slip zones proposed by *Lallemand and Jolivet* [1985] and *Jolivet et al.* [1991]. This model requires a specific stress field and strain distribution on the Sea of Japan margins, that is, extension on the southern and northern margins and strike-slip deformation on the western and eastern margins, which is verified on our map of the regional stress field (Figure 9).

Paleomagnetic data show that SW and NE Japan have been rotated clockwise and counterclockwise, respectively, during the opening of the Sea of Japan [*Otofuji et al.*, 1991; *Hayashida et al.* 1991; *Tosha and Hamano*, 1988]. The consistency of the stress field principal directions around the Sea of Japan suggests that the measured stress field did not undergo these differential rotations and therefore postdate them. If so, it is coeval with the end of opening of the Sea of Japan (15-11 Ma). However, data scattering in places (see for example the results of the Tango Peninsula) does not allow us to rule out the possibility of a progressive rotation of the measured stress field. In the absence of precise stratigraphic data, a progressive rotation cannot be constrained. Moreover, as Angelier's [1984] method uses a slip criteria on preexisting faults, the final stress tensor is generally obtained. Only if the stress regime completely changes, for instance, from pure strike-slip to extensional,

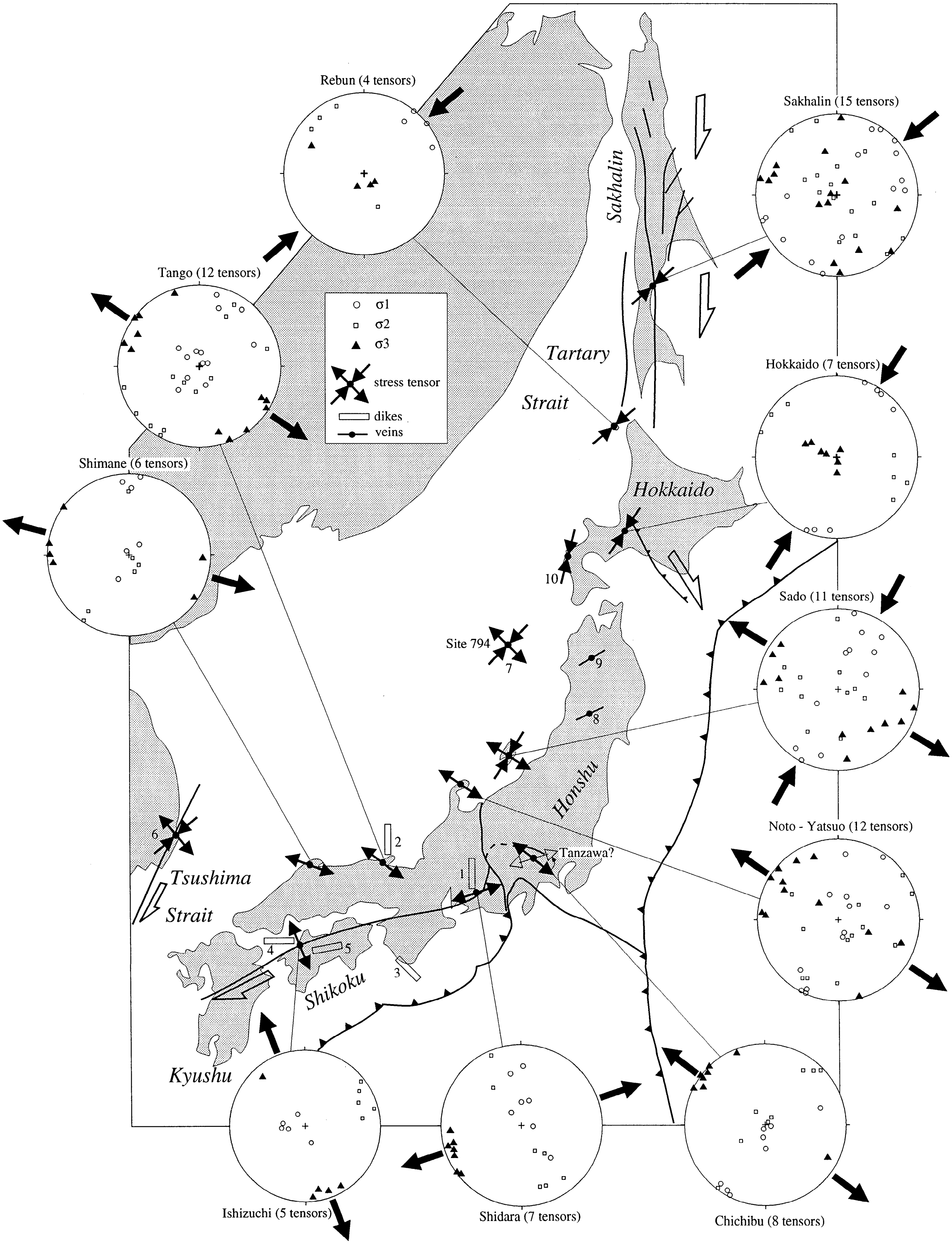

Figure 9. Middle Miocene stress field in the Japan Sea area. References for middle Miocene dike swarms (labels 1 to 5) are given in Table 2. References for the other labels are as follows: 6, *Hwang* [1992]; 7, *Charvet et al.* [1992]; 8 and 9, *Otsuki* [1990]; and 10, *Yamagishi and Watanabe* [1986].

Table 1. Stress Tensors Used to Derive Regional Stress Field in Figure 9

Site	σ_1	σ_2	σ_3	Φ^*	Formation	Age, Ma
Shimane						
1					Hata	15-19
4					Kuri-Kawai	14-18
5A	044-75	216-15	306-02	0.853	Kuri-Kawai	14-18
7	355-11	140-76	263-08	0.424	Kuri-Kawai?	14-18
8A	340-86	214-02	124-03	0.571	Kuri-Kawai	14-18
8B	008-03	144-86	278-03	0.575	Kuri-Kawai	14-18
9	211-14	096-59	308-27	0.166	Omori	13-16
13	189-09	090-42	289-46	0.378	Kuri-Kawai	14-18
14A	205-64	359-23	093-10	0.645	Kuri-Kawai	14-18
14B	309-07	113-83	218-02	0.202	Kuri-Kawai	14-18
15	151-08	061-01	322-82	0.133	Kuri-Kawai	14-18
16	002-18	166-72	270-05	0.418	Kuri-Kawai	14-18
Tango						
1	037-10	226-71	307-01	0,499	Tango	middle Miocene
2	042-83	234-07	144-02	0,783	Toyooka	early Miocene
3	220-62	029-27	122-04	0,956	Toyooka	early Miocene
4	320-74	209-06	117-15	0,940	Tango	middle Miocene
5	019-21	184-68	287-05	0,524	Toyooka	early Miocene
6	228-76	074-13	343-06	0,559	Toyooka	early Miocene
7	119-23	303-67	210-01	0,277	Yoka	early Miocene
8	055-79	219-11	310-03	0,698	Toyooka	early Miocene
10B	013-72	256-08	164-16	0,870	Yoka	early Miocene
12	015-06	124-73	284-16	0,854	Yoka	early Miocene
13	354-20	190-69	086-05	0,582	Yoka	early Miocene
14	151-71	030-10	298-17	0,728	Yoka	early Miocene
16	359 72	209-16	117-08	0,543	Tango	middle Miocene
17	067-25	252-65	158-02	0,799	Toyooka	early Miocene
Ishizuchi						
1	328-75	077-05	168-14	0.365	Tobe thrust	14.7
2A	273-66	082-24	174-04	0.560	Ishizuchi	14
2B	158-72	051-06	319-17	0.327	Ishizuchi	14
3	260-71	057-17	149-07	0.212	Kuma	Eocene - middle Miocene
4					Ishizuchi	14
5	268-65	066-24	160-08	0.670	Ishizuchi	14
Shidara						
2A	324-74	142-16	233-01	0.610	cataclasites	Cretaceous
2B	221-78	058-12	327-03	0.532	cataclasites	Cretaceous
3A	002-27	153-60	265-13	0.448	cataclasites	Cretaceous
5	349-35	145-52	250-12	0.749	cataclasites	Cretaceous
7	001-67	162-22	254-07	0.569	Hokusetsu	Oligocene - early Miocene
8	094-78	336-06	245-10	0.641	Ryoke	Cretaceous
9	014-67	200-23	109-02	0.389	Hokusetsu	Oligocene - early Miocene
10	245-73	052-17	143-04	0.402	Hokusetsu	Oligocene - early Miocene
13A	018-64	159-21	255-15	0.931	Hokusetsu	Oligocene - early Miocene
13B	305-77	109-13	200-04	0.502	Hokusetsu	Oligocene - early Miocene
14	138-46	323-43	231-03	0.676	Hokusetsu	Oligocene - early Miocene
15B	304-76	112-13	203-03	0.733	Hokusetsu	Oligocene - early Miocene
Chichibu						
2A	179-67	036-18	301-13	0.511	Nagura	early Miocene
2B	190-78	043-10	312-06	0.689	Nagura	early Miocene
3A	217-09	041-81	307-01	0.415	Sakurai	early Miocene
3B	210-07	329-75	118-13	0.226	Sakurai	early Miocene
4	202-86	046-03	316-02	0.839	Nagura	early Miocene
5	073-29	236-60	339-08	0.509	Yoshida	early Miocene
6	101-84	217-03	307-06	0.456	Yoshida	early Miocene
7	207-03	063-87	297-02	0.365	Sakurai	early Miocene
Noto						
2	342-63	208-19	112-18	0.480	Anamizu	early Miocene
3	036-06	141-69	304-20	0.188	Anamizu	early Miocene

Table 1. (continued)

Site	σ_1	σ_2	σ_3	Φ*	Formation	Age, Ma
5A	159-06	250-10	040-78	0.433	Anamizu	early Miocene
5B	007-19	156-68	273-11	0.192	Anamizu	early Miocene
6	039-72	211-18	302-03	0.607	Anamizu	early Miocene
7	207-02	298-34	114-56	0.114		middle Miocene
10	022-65	180-23	274-08	0.342	Anamizu	early Miocene
15	075-38	255-52	165-00	0.597		middle Miocene
18	206-05	114-23	309-66	0.160	Anamizu	early Miocene
Yatsuo						
1	206-05	106-63	298-26	0.297	Nirehara	early Miocene
2	155-76	056-02	325-14	0.846	Iwaine	early-middle Miocene
4	217-24	053-65	310-06	0.701	Iwaina	early-middle Miocene
6	167-71	071-02	340-19	0.290	Kurosedani	middle Miocene
Sakhalin						
TPF1	179-40	332-47	077-14	0.712	Bikov	Late Cretaceous
TPF3	252-09	360-62	158-26	0.551	Krasnoyarkov	Late Cretaceous
TPF5	268-39	102-50	004-07	0.657	Bikov	Late Cretaceous
TPF7	086-17	277-72	177-03	0.549	Bikov	Late Cretaceous
TPF8	230-15	139-04	036-75	0.078	Tchekhov	middle Miocene
TPF9	078-19	346-07	237-69	0.212	Gastello	early Miocene
TPF10	028-43	175-41	281-17	0.247	Kholmsk	early Miocene
TPF12	251-04	157-44	345-46	0.231	Tchekov	middle Miocene
Tonino1	055-12	324-03	222-78	0.492	Naiba	Cretaceous
Tonino2	034-03	123-01	237-86	0.342	Bikov	Late Cretaceous
Tonino3.1	191-01	329-78	281-06	0.738		Cretaceous
Tonino3.2	264-12	093-77	359-23	0.342		Cretaceous
Tonino4.1	316-16	056-10	172-70	0.592		Cretaceous
Tonino4.2	047-03	238-86	137-01	0.986		Cretaceous
Tonino5.1	200-12	313-62	104-24	0.282		Cretaceous
Tonino5.1	097-15	003-15	228-68	0.624		Cretaceous
Tonino6	173-46	034-36	287-21	0.713	Bikov	Late Cretaceous
WSak1	084-30	296-55	182-15	0.806	Kurasys	Late Miocene
ESak1	028-09	140-68	295-20	0.016		Jurassic

* $\Phi = (\sigma_2 - \sigma_3) / (\sigma_1 - \sigma_3)$.

Table 2. Mean Trend and K-Ar Age of Dike Swarms Plotted in Figure 9

No.	Locality	Mean Trend	Reference	Age, Ma	Reference
1	Shidara	N000°-20°E	1	14.9-16.5	4
2	Tango	N-S	2	14.1-15.5	4
3	Shionomisaki	N135°E	3	14	5
4	Ishizuchi (Shikoku)	E-W	3	14	5
5	Takaiwa (Shikoku)	N80°E	3	14	5

References: 1, *Kogi* [1983]; 2, *Kobayashi* [1979a]; 3, *Kobayashi* [1979b]; 4, *Tsunakawa et al.* [1983a]; 5, *Shibata and Nozawa* [1967].

will earlier episodes be recognized. We did not observe such changes for the early and middle Miocene stress field and believe that the measured stress field is likely to have prevailed throughout the opening of the Sea of Japan (24-11 Ma).

In central Japan, paleostress field directions rotated during the Tanzawa and Izu collisions and are not consistent with those of the northern coast of SW Japan. Nevertheless, the MTL basin results show that the MTL has been a normal fault with likely a left-lateral strike-slip component in its eastern part during the opening of the Sea of Japan.

Comparison Between Dike Strike Statistics and Fault Slip Analysis Results

Neogene stress field trajectories in SW Japan were previously determined using dike strike statistics by *Kobayashi* [1979a, b], *Nakamura and Uyeda* [1980], *Tsunakawa* [1986], and *Yamamoto* [1991]. In this section, we discuss results of dike strike statistics and their compatibility with results of fault slip analysis.

Tsunakawa [1986] recognized five stages for the evolution of the stress field since the early Miocene: σ_{Hmax} trends E-W before 15 Ma, N-S from 15 to 12 Ma, E-W from 12 to 9 Ma, N-S from 9 to 1 Ma, and WNW-ESE since 1 Ma. Stage 3 is derived from two data points, one in the Tango Peninsula [*Tsunakawa*, 1986, site 23B] and one in NW Shikoku [*Tsunakawa*, 1986, site 30]. The first data point relies on one dike direction measurement (N120°E) only, which is not representative of the N-S mean direction of the Tango dike swarm [*Kobayashi*, 1979a]. The second data point corresponds to a dike swarm dated at 12.6 ± 0.6 Ma [*Tatsumi et al.*, 1980] and trending N50°E. We do not consider it reasonable to derive the stress field for the whole of SW Japan from this single datum. If stage 3 is not taken into account, stages 2 and 4 can be gathered in one stage as they are similar (N-S trending σ_{Hmax}), and a three-step evolution is obtained. Stage 2 started 15 m.y. ago and ended 1 m.y. ago. This evolution is similar to that proposed by *Yamamoto* [1991]. However, it does not take into account several E-W trending dike swarms radiometrically dated at 14 Ma in the area of Shikoku [*Shibata and Nozawa*, 1967; *Kobayashi,* 1979b; *Nakamura and Uyeda,* 1980; *Tohara*, 1978].

According to *Kobayashi* [1979b] and *Nakamura and Uyeda* [1980], σ_{Hmax} trended ENE-WSW during the Miocene in SW Japan north of the MTL and NNW-SSE (normal to the Nankai trough) south of the MTL. They used seven data points in SW Honshu (fault and dike orientations) to derive their stress trajectories north of the MTL [*Nakamura and Uyeda*, 1980, Figure 7]. Among them, two are of dubious value as they correspond to nondated normal faults south of the Shimane Peninsula and near the Shidara basin (in the latter basin the emplacement of a N-S trending dike swarm at 16.5-14.9 Ma is not compatible with the N160°E extension derived from the fault). Three other data points correspond to dike swarms older than 15 Ma in the Noto Peninsula (27-16 Ma [*Shibata et al.*, 1981]), SW Kanazawa (17-15 Ma [*Shibata et al.*, 1981]), and Yoka (20.2-19.5 Ma [*Tsukunawa et al.*, 1983a]). The last two dike swarms are not dated. The ENE-WSW direction of σ_{Hmax} north of the MTL proposed by *Nakamura and Uyeda* [1980] is therefore valid before 15 Ma, and it is in agreement with the stress field determined by *Tsunakawa* [1986] and *Yamamoto* [1991] before 15 Ma.

We have plotted in Figure 9 the mean direction of all dike swarms of SW Japan radiometrically dated from the middle Miocene (Table 2). We have arbitrarily retained only dike swarms with at least 10 dike direction measurements. Azimuths of dike swarms are scattered from N-S to N135°E. From this map, it appears that the E-W direction of σ_{Hmax} is well constrained in the area of Shikoku by several dike swarms dated about 15 Ma, which is consistent with fault analysis results. In central Japan, the Shidara dike swarm may have been rotated during the Tanzawa and Izu collisions. The direction of σ_{Hmax} also probably changes in the vicinity of the Nankai subduction zone, as proposed by *Nakamura and Uyeda* [1980]. Part of the scattering might also be explained by the fact that dikes may have been emplaced along preexisting fractures not necessarily parallel to σ_{Hmax} [e.g., Delaney et al., 1986]. To conclude, the number of dated dike swarms is not sufficient to derive stress field trajectories in SW Japan during the middle Miocene. Nevertheless, it is clear that σ_{Hmax} did not simply trend N-S in the whole SW Japan during middle Miocene. More information is needed to determine the precise stress field trajectories at that time.

Mechanism of Deformation of SW Japan During the Sea of Japan Opening

We have seen that the stress and strain field during the opening of the Sea of Japan is in agreement with a model of opening in an extensional transfer zone between two N-S dextral strike-slip zones. Experiments of analogue modeling of the opening performed by *Jolivet et al.* [1991] showed that this model is compatible with clockwise rotations in SW Japan. However, kinematic reconstructions of the opening of the Sea of Japan realized by closing the main basins of the Sea of Japan [*Jolivet et al.*, 1991] showed that the opening accounts for 20° to 30° of clockwise rotation in SW Japan, while paleomagnetic rotations range from 40° to 50° [*Otofuji et al.*, 1991; *Hayashida et al.*, 1991]. The model of opening of the Japan Basin proposed by *Tamaki et al.* [1992], with initiation of the accretion in the eastern part of the basin and westward propagation, also results in clockwise rotation of SW Japan by about 20° to 30°. Rotation of 10° to 30° is not accounted for by these models. Moreover, the age of the rotations is is not in agreement with the timing of opening of the Sea of Japan determined by drillings. In the next sections, we discuss this problem of diachronism and the relations between strain field and rotations in Japan.

Apparent Diachronism Between Rotations in SW Japan and Accretion in the Japan Basin

Otofuji et al. [1991] and *Hayashida et al.* [1991] constrained the age of the paleomagnetic rotations in SW Japan between 16 and 14 Ma. *Tamaki et al.* [1992] constrained the age of opening of the Sea of Japan between 32 and 10 Ma and the age of accretion in the Japan Basin between 24 and 17 Ma from radiometric datings of oceanic basalts and micropaleontologic dating of sediments. According to these results, there is a diachronism between rotation and accretion. If correct, SW Japan did not rotate as a single block, because such a rotation would necessarily be linked with the opening of a large back arc basin, and rotations of small blocks have to be considered. Nevertheless, following *Jolivet et al.* [1995], who discussed the constrains on the ages of rotation and accretion, we consider that there is most probably an overlap in time between the accretion and the rotations.

Sense of Rotation With Respect to Strain Field

In contrast with what has long been written, paleomagnetic rotations are not clockwise in SW Japan and counterclockwise in NE Japan: the sense of rotation is directly linked with the strain field. In a first approach, rotations are clockwise in the Neogene deformation zones (Sakhalin [*Takeuchi et al.*, 1992], the Hokkaido central zone [*Kodama et al.*, 1993], the Tanakura Tectonic Line [*Otofuji et al.*, 1985b], and the Yangsan and Dongnae faults in SE Korea [*Kim et al.*, 1986; *Kikawa et al.*, 1994]) and counterclockwise in nondeformed blocks in NE Japan [*Otofuji et al.*, 1985b, 1994; *Tosha and Hamano*, 1988]. It is not surprising that clockwise rotations are systematically measured in Neogene deformation zones since they all accommodated right-lateral strike-slip motions [*Koshiya*, 1986; *Jolivet and Huchon*, 1989; *Fabbri and Charvet*, 1994; *Fournier et al.*, 1994]. The counterclockwise rotations measured in middle Miocene rocks in the Tsushima strait (Figure 1) [*Ishikawa et al.*, 1989; *Ishikawa and Tagami*, 1991] are because of the late Miocene deformation which reworked the right-lateral strike-slip faults as left-lateral faults [*Fabbri and Charvet*, 1994].

As discussed before, SW Japan has likely been rotated 20° to 30° clockwise as a single block during the opening of the Sea of Japan mainly due to asymmetric accretion with westward propagation in the Japan Basin, but 10° to 30° of rotation remains to be found. In the following section, we present structural data from the Shimane Peninsula suggesting that the remaining rotation might be found in the internal deformation of SW Japan.

Deformation Contemporaneous With Paleomagnetic Rotations in the Shimane Peninsula

Figure 10 shows an outcrop in the Kuri-Kawai formation, at the western extremity of the Shimane Peninsula (in Nakayama) and a stereo diagram of the observed fractures. This outcrop corresponds to site 8B in Figure 4. A system of conjugate strike-slip faults is observed, with right-lateral faults trending N150°E to N10°E and left-lateral faults with a normal component trending N50°E. The left-lateral faults are regularly spaced every 2 m (Figure 10a) and the offset along these faults is of the order of decimeters. The right-lateral faults are spaced every 20 cm and accommodate centimeter-scale offsets (Figures 10a and 10b). The right-lateral faults bound blocks 20 cm wide and 2 m long which are expected to have been rotated between the left-lateral faults.

The same fault geometry can be observed at the decimeter scale as illustrated in Figure 10c. Small blocks about 1 cm wide and 10 cm long and bounded by right-lateral faults with minor offsets are observed between left-lateral faults with horizontal offset of about 1 cm. The same geometry might also be observed at the meter scale since right-lateral faults with large offset have been observed regularly spaced every 10 m.

This deformation is characteristic of the early and middle Miocene Kuri-Kawai formation and has never been observed in the late Miocene Omori formation. It is contemporaneous with the rotations measured by paleomagnetism which occured after the deposition of the Kuri-Kawai formation and before the deposition of the Omori formation [*Otofuji et al.*, 1991]. A link between the rotations and the deformation with small blocks is then strongly suggested. These observations show that SW Japan was strained during the rotations and did not behave as a rigid block.

At larger scale, *Kanaori* [1990] proposed a model of deformation for SW Japan involving about 10 blocks rotating about vertical axes north of the MTL. The geometry of these blocks is well constrained in central Japan [Kanaori et al., 1992] but is less obvious in western Honshu. We estimate that our field observations in the Shimane Peninsula support this type of deformation model. We propose that SW Japan has been sheared between the two right-lateral strike-slip zones which bound the Sea of Japan and that the shear caused the rotation of blocks in SW Japan. The 10° to 30° of rotation missing in the kinematic reconstructions would be found in the internal deformation of SW Japan. In this interpretation, the MTL is a fault which rotates in a right-lateral shear zone and accommodates the clockwise rotation of SW Japan. Its normal motion with a left-lateral component is compatible with this interpretation.

Conclusion: Opening of the Sea of Japan

The data described in this paper and those previously obtained in Sakhalin, Hokkaido, and NE Honshu provide a significant data set at the scale of the Sea of Japan which support the model of pull-apart opening with rotations. This model is depicted in Figure 11 after *Jolivet et al.* [1995]. The Sea of Japan opened as a pull-apart basin during the Oligo-Miocene between two dextral strike-slip zones. Crustal thinning and extension prevailed at the initial stage. Seafloor spreading was initiated at 24 Ma along the eastern strike-slip margin [*Tamaki et al.*, 1992]. The spreading center propagated westward resulting in the clockwise rotation of SW Japan of 20° to 30°. The Median Tectonic Line rotated with SW Japan accommodated by normal faulting with a left-lateral component. The remaining 10° to 30° of rotation may be because of right-lateral shearing of SW Japan between the strike-slip zones which boarder the Sea of Japan. The shear is taken up by the internal deformation of SW Japan with rotations of blocks.

One question remains: what is the significance of counterclockwise rotations measured in NE Japan outside the Neogene deformation zones? *Fournier* [1994] proposed a model for the deformation of NE Asia derived

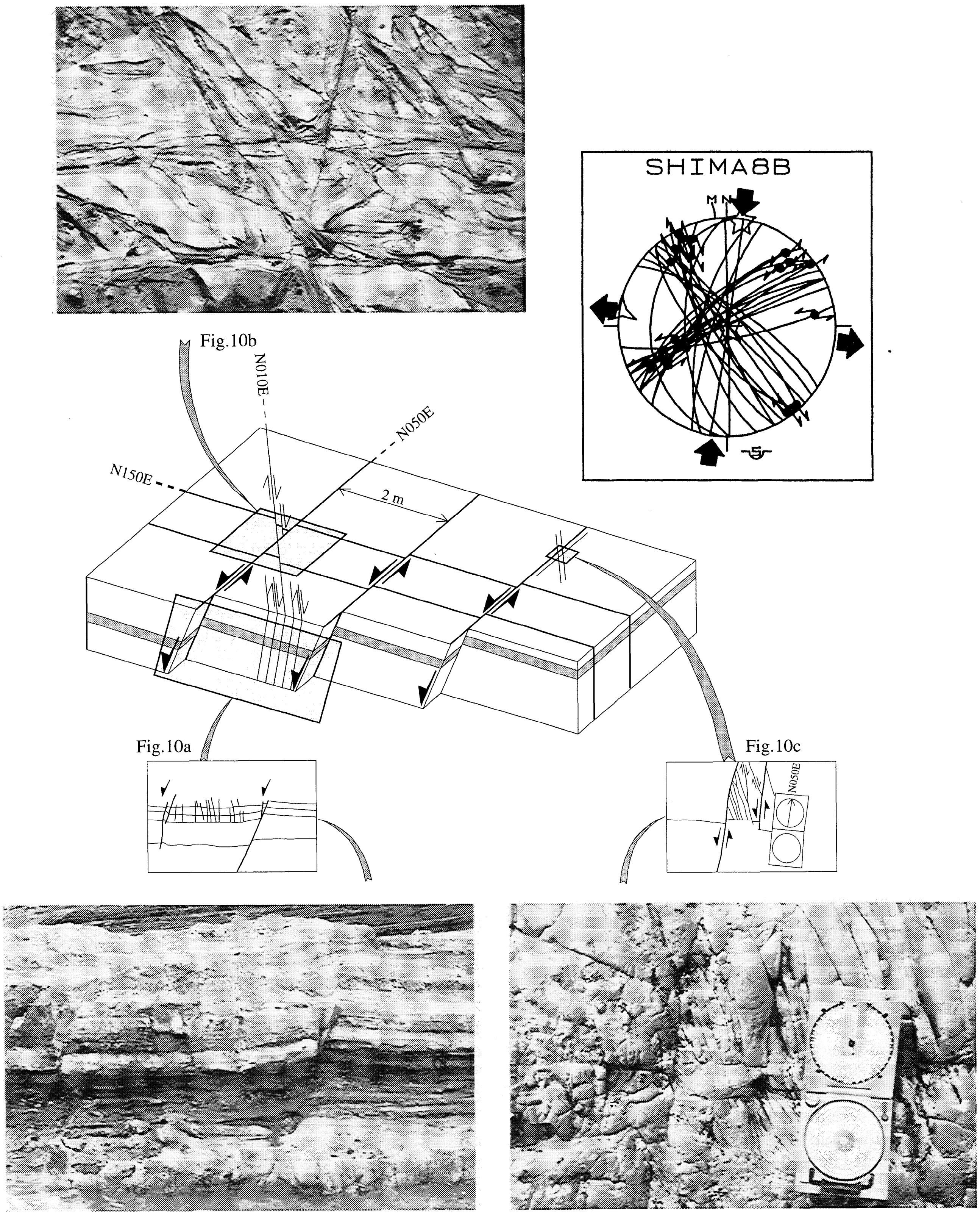

Figure 10. Detail of an outcrop in the early-middle Miocene Kuri-Kawai formation, Shimane Peninsula. (a) Right-lateral faults spaced every 20 cm between left-lateral faults with a normal component spaced every 2 m. (b) Conjugate strike-slip faults in the horizontal plane. (c) Small blocks bounded by right-lateral faults spaced every centimeter between left-lateral faults spaced every 10 cm.

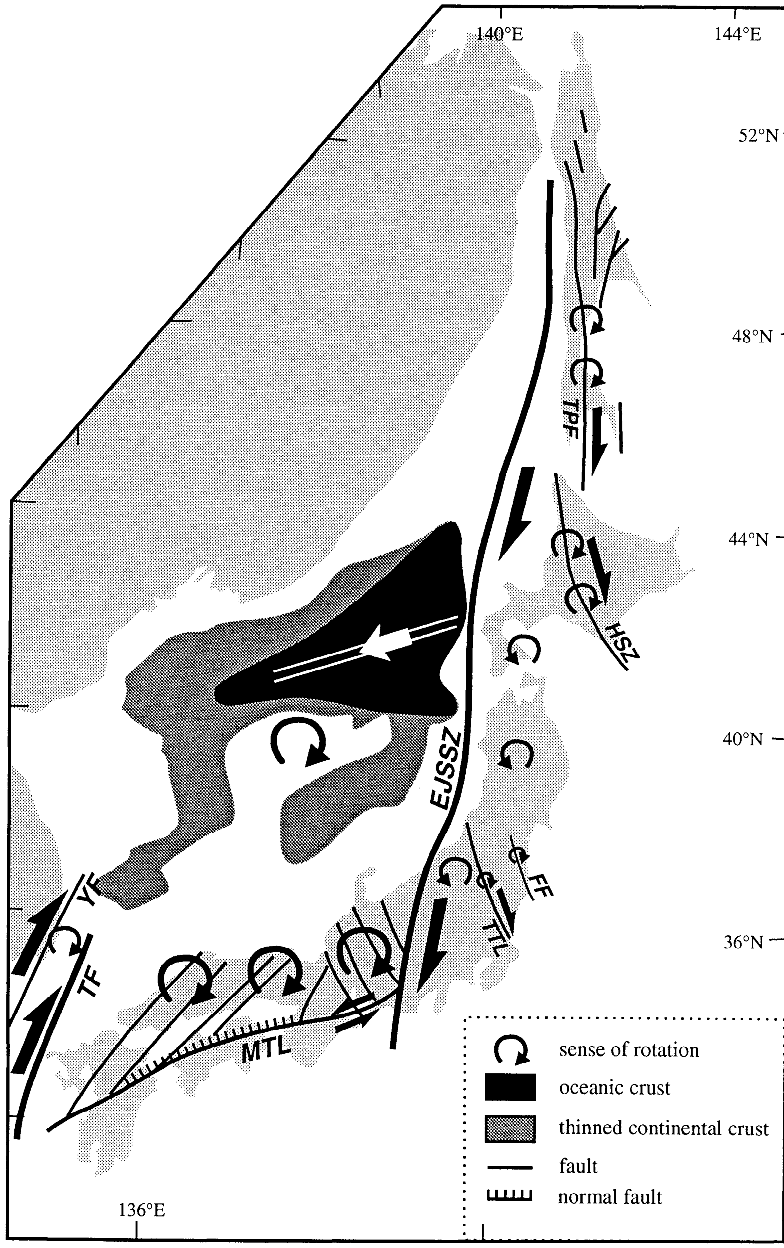

Figure 11. Model of opening of the Japan Sea [*Jolivet et al.*, 1994]. EJSSZ is the east Japan Sea shear zone, FF is the Futaba fault, HSZ is the Hokkaido shear zone, TF is the Tsushima fault, TPF is the Tym-Poronaysk fault, TTL is the Tanakura Tectonic Line, and YF is the Yangsan fault.

from the model of *Jolivet et al.* [1990] and based on analogue experiments of indentation. In this model, the northward motion of India is partly taken up by a large left-lateral shear zone running NE from the Pamir, which accommodates the eastward motion of China relative to Siberia. This shear zone widens to the northeast between the Qinling Shan and the Stanovoy ranges and encompasses continental blocks, like the Ordos block, bounded by right-lateral faults or fault zones, the right-lateral strike-slip zones which bound the Sea of Japan, the Tan-Lu fault, and the right-lateral en echelon grabens of Shansi in northern China. These right-lateral faults accommodate counterclocwise rotation of the continental blocks in the left-lateral shear zone. In the Sea of Japan area, the Neogene right-lateral deformation would accommodate the counterclockwise rotation of rigid blocks like NE Japan. More data from NE Asia is needed to further substantiate this hypothesis.

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