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# Alternate senses of displacement along the Tsushima fault system during the Neogene based on fracture analyses near the western margin of the Japan Sea

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## Abstract

The western margin of the Japan Sea is characterized by the existence of a N20°E-trending transcurrent fault system in the Korea strait between Korea and Kyushu. This fault system, called here the Tsushima fault system, played a major role during the opening of the Japan Sea during the Tertiary. In order to understand its displacement history, we analysed the deformation recorded by Neogene rocks exposed on the Korea strait islands (Tsushima, Goto and Hirado islands).

A synthesis of published stratigraphical and structural data together with our field observations reveals that two tectonic events occurred in succession in the study area: an Early Miocene NW–SE-oriented extension (event I); and a Middle Miocene NW–SE-oriented shortening (event II). Two distinct families of fractures with contrasted stratigraphic occurrences have been recognized in the Neogene rocks exposed on the Korea strait islands and allow us to define and date the stress fields characterizing each tectonic event. Stress field I is of intermediate type (the vertical axis is either $\sigma_1$ or $\sigma_2$) with a N45°E $\sigma_{Hmax}$ and a N135°E $\sigma_{Hmin}$ and was active between 22 and 16 Ma. Stress field II is compressional (the vertical axis is $\sigma_3$) with a N135°E $\sigma_{Hmax}$ and a N45°E $\sigma_{Hmin}$ and was active between 15 and 10 Ma. The trends of stress field I principal axes imply that the displacement along the Tsushima fault system was dextral during the Early Miocene. Conversely, the trends of stress field II principal axes imply that the displacement along the same fault system was sinistral during the second half of the Middle Miocene.

The inferred displacement history agrees with: (1) a pull-apart model for the opening of the Japan Sea during the Early Miocene; and (2) transition from tensional to compressional stress fields in the Japanese arc and back-arc region at the end of the Middle Miocene.

## 1. Introduction

The Japan Sea (Fig. 1) is a marginal basin which was formed behind the Japanese arc in Oligo-Miocene times (e.g., Tamaki et al., 1992). Several models have been proposed to account for the mode of opening. A first category of model invokes a trenchward retreat of the arc rendered possible by simultaneous clockwise rotation of southwestern Japan and counterclockwise rotation of northeastern Japan as supported by geological and geophysical

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data (Otofuji et al., 1985, 1991, 1994; Otofuji and Matsuda, 1987; Celaya and McCabe, 1987; Faure and Lalevée, 1987; Moreau et al., 1987; Tosha and Hamano, 1988; Hayashida et al., 1991). A second category emphazises the role of regional-scale transcurrent faults along the eastern and western margins of the Japan Sea and inside the Japanese arc (Otsuki and Ehiro, 1978; Kimura and Tamaki, 1986; Lallemand and Jolivet, 1986). Such models oppose previous scenarios by calling for a pull-apart type opening. Recent syntheses have pointed out that both end-members are not mutually exclusive and that the trenchward differential migration of the arc was preceded or accompanied by a translation more or less parallel to the arc (Jolivet et al., 1989, 1990, 1991; Jolivet and Tamaki, 1992; Tamaki et al., 1992; Tatsumi et al., 1990).

The aim of this paper is to clarify the Neogene kinematics of one of the fault systems of the western margin of the Japan Sea, the Tsushima fault system (Tomita et al., 1975; Nagano et al., 1976; and references herein), located between southeastern Korea

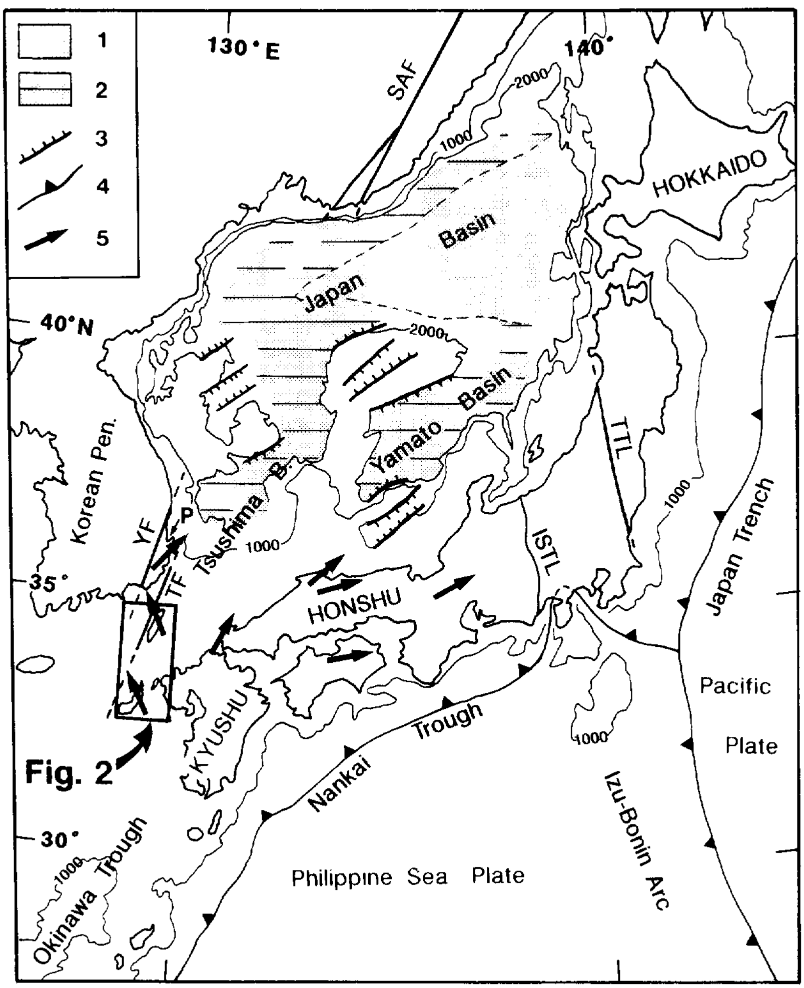


Fig. 1. Geodynamical setting of the Japan Sea back-arc basin [modified from Jolivet et al. (1991) and Tamaki et al. (1992)]. Insert is for the study area. Symbols: *1* = oceanic crust; *2* = thinned continental crust; *3* = major normal faults; *4* = subduction front; *5* = paleomagnetic declinations for southwestern Japan and southeastern Korea (compiled after various sources cited in the text). Abbreviations: *ISTL* = Itoigawa–Shizuoka Tectonic Line; *TTL* = Tanakura Tectonic Line; *SAF* = Shikote–Alin fault; *TF* = Tsushima fault; *YF* = Yangsan fault; *P* = Pohang basin.

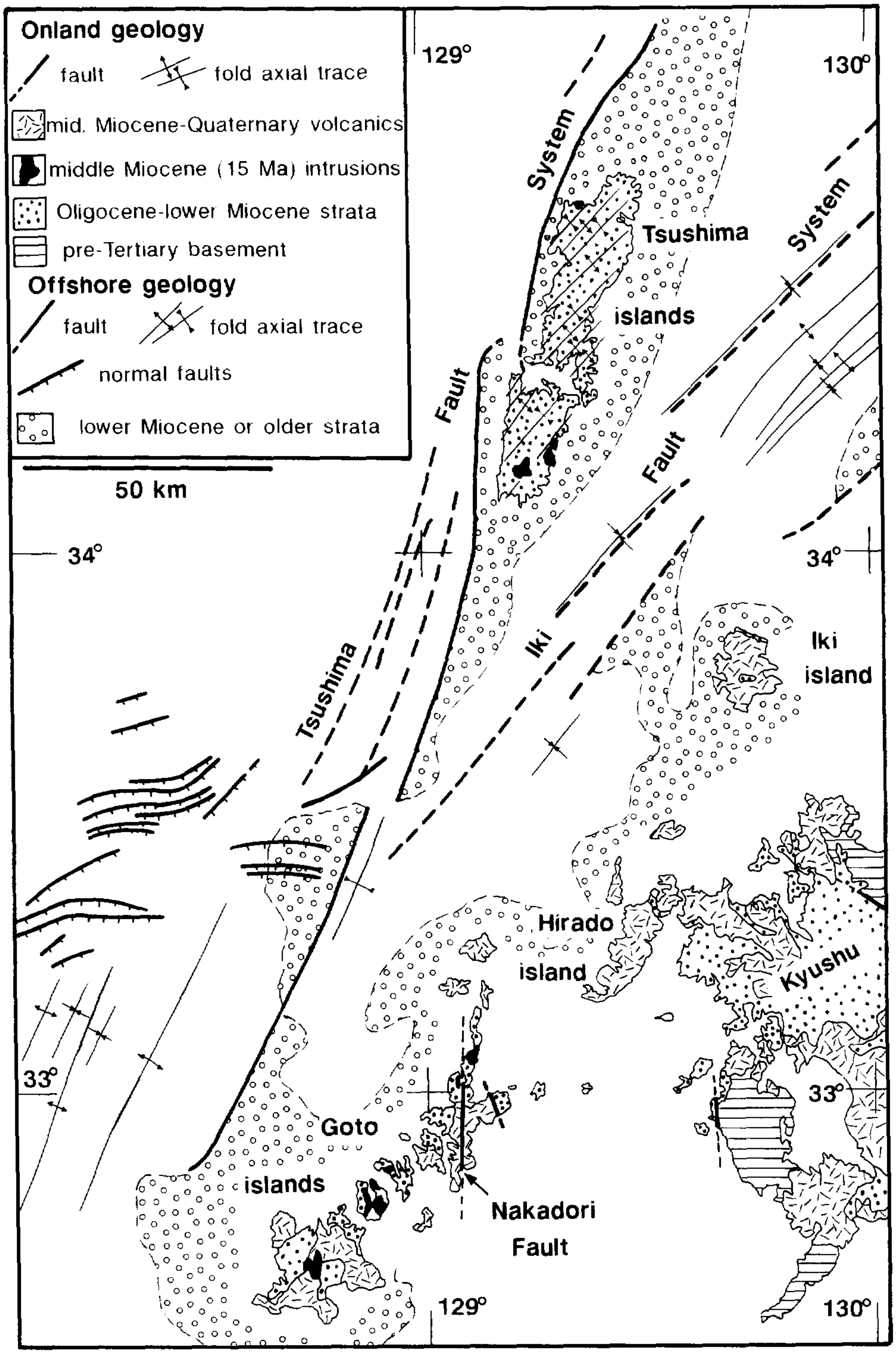


Fig. 2. Simplified geological map of the study area and surrounding sea floor. Offshore geology is simplified after Tomita et al. (1975). Normal faults to the west of the Tsushima fault system are after Itoh et al. (1992). Unpatterned sea floor is covered by undifferenciated Plio-Quaternary sediments.

and Kyushu (Figs. 1 and 2). Since this major system is not exposed onland, we use an indirect approach which consists in determining the (paleo) stress fields recorded in rocks exposed in the vicinity of the fault system. Indeed, knowledge of the stress fields can bring reliable indications constraining movement along regional faults (e.g., Hancock and Barka, 1981). Our analysis shows that the displacement along the Tsushima fault system was polyphase: during the Early Miocene, the regional stress field favored a right-lateral motion; and during the Middle Miocene, a different stress field was operant and induced a left-lateral displacement. Comparison with regional data shows that the Middle to Late Miocene change of stress field is not a local phenomenon but is recorded at the scale of the whole Japan Sea region. The displacement history of the Tsushima fault zone can be explained within the framework of the interactions between the Asia plate and the subducting oceanic plates (Pacific or Philippine Sea plates).

## 2. Geology of the study area

### *2.1. Geology of the surveyed islands*

Field work has been carried out on the Tsushima islands lying between Kyushu and southeastern Korea and on the Goto and Hirado islands to the west of Kyushu (Fig. 2). Stratigraphic attributions of the Cenozoic rocks exposed on these islands are summarized in Table 1.

Upper Oligocene–Lower Miocene strata are exposed widely on the Goto (Goto Group) and Tsushima (Taishu Group) islands and locally on Hirado island (Hirado Formation). They consist of marine sandstones and siltstones with tuffaceous intercalations (Tomita et al., 1975; Inoue, 1982; Kawahara et al., 1984; Sakai, 1993). At Goto and Tsushima, they are intruded by stocks and sills which fission track ages range from 16 to 12 Ma with a cluster at 15 Ma (Ishikawa and Tagami, 1991; Kano et al., 1991).

On the Goto islands, the Middle Miocene Nakadori Group unconformably covers the 15 Ma intrusions and the Lower Miocene Goto Group (Kawahara et al., 1984). It consists of poorly stratified marine tuffaceous sandstones, pebbly mudstones and breccias intercalated or overlain by marine to terrestrial andesitic lavas and tuffs. Syn-sedimentary disturbance such as slump folding or block sliding is locally common, especially in the vicinity of important faults (Fabbri, 1992). The Himosashi andesites exposed on the Hirado island are probably lateral equivalents of the Nakadori Group. Rare radiometric datings and comparison with underlying intrusive rocks or overlying basalts give a 13–10 Ma estimate

Table 1
Stratigraphic attributions of the sedimentary and volcanic rocks exposed in the study area (compiled after Kano et al., 1991; Mizuno et al., 1993; Sakai, 1993; Ibaraki, 1994). Wavy line is for unconformity

| Epoch | Age (Ma) | Tsushima islands | Goto islands | Hirado island | Off west Tsushima | SE Korea |
|---|---|---|---|---|---|---|
| Quaternary | 2 | | alkaline basalts | | D Group | |
| Pliocene | | | | | | Umockdong F. |
| Late Miocene | | | | alkaline basalts | ? | Yeonil Group |
| Middle Miocene | 10 | | Nakadori Group | Himosashi and. | K Group | |
| | | | | | ? | |
| Early Miocene | 20 | Taishu Group | Goto Group | Hirado ? Form. | N Group | Yangbuk Group |
| | | | ? | | ? | |
| Late Oligocene | 28 | ? | | | X Group | ? |

for the age of the Nakadori–Himosashi rocks (Matsui et al., 1989; Kano et al., 1991; Ishikawa and Tagami, 1991).

Upper Miocene alkaline basalts cover older rocks at Hirado. These basalts consist of lava flows and pyroclastics which radiometric ages are comprised between 10 and 6 Ma (Matsui et al., 1989; Kano et al., 1991). They are in turn covered by Plio-Quaternary alkaline basalts.

The Nakadori fault on the northern Goto islands (Fig. 2) is the largest fault exposed onland in the study area. This vertical fault is thought to be of strike-slip type because of horizontal slickensides on associated second-order faults (Fabbri, 1992). Whereas the stratified deposits of the Goto Group do not show any notable facies variations near the Nakadori fault, the chaotic facies of the Nakadori Group are found along the Nakadori fault and branching faults. We conclude that the Nakadori fault was significantly active during the Middle Miocene, concurrently with deposition of the Nakadori Group, but not during the deposition of the Lower Miocene Goto Group.

Northeast- to NNE-trending folds are pervasive at Tsushima; both the Lower Miocene Taishu Group and the 15 Ma hypabyssal sills are folded (Kitamura, 1962; Tomita et al., 1975; Shimada, 1977; Inoue, 1982).

### 2.2. Offshore geology of the Korea strait

In the Korea strait area, depth of the sea floor seldom exceeds 200 m. Seismic profiling has shown that the pre-Tertiary basement has subsided to depths ranging from about 500 to 2500 m or more below the sea floor and is unconformably covered by a succession which spans from the Late Oligocene to the Quaternary (Table 1; Minami, 1979; Inoue, 1982; Katsura, 1992).

The most conspicuous offshore structural features are a series of NNE-trending faults (Fig. 2; Tomita et al., 1975; Nagano et al., 1976; Honza et al., 1979). These faults, which constitute the Tsushima fault system, have rectilinear traces and can be followed to the west of the Goto and Tsushima islands. They are thought to be transcurrent faults similar to NNE-trending faults of southeastern Korea (Reedman and Um, 1975; Sillitoe, 1977; Otsuki and Ehiro, 1978; Inoue, 1982). Seismic reflection profiles across the Tsushima fault system at the latitude of the Tsushima islands have revealed the presence of reverse faults displacing Middle–Upper Miocene layers (Minami, 1979; Katsura, 1992). Still by means of seismic reflection, Itoh et al. (1992) have mapped a series of N45°E- to N75°E-trending normal faults affecting Lower Miocene and older strata to the west of the Tsushima fault system (Figs. 2 and 3a). These authors interpret the normal faults as being second-order tension fractures associated with the Tsushima fault system acting as a right-lateral strike-slip master fault (Fig. 3a). Lastly, the N30°E-trending Iki fault system runs between the Tsushima and Iki islands (Fig. 2; Inoue, 1982).

Folds are pervasive in the sedimentary substratum of the Korea strait (Fig. 2; Honza et al., 1979; Research Group for Active Tectonics in Kyushu, 1989). Their NE to NNE axial trends are similar to those of the folds exposed on land. According to Inoue (1982), the folds are transpressional structures reflecting a left-lateral strike-slip displacement along the Tsushima fault system and the Iki fault system (Fig. 3b). This motion is opposite to the right-lateral one proposed by Itoh et al. (1992). As will be discussed further below, these two interpretations are not contradictory but simply reflect different motions at different periods.

### 2.3. Cenozoic block rotations

Paleomagnetic studies onshore have shown that, unlike most of the Korean peninsula which has remained fixed relatively to Eurasia since the end of the Cretaceous (Otofuji et al., 1986), several clockwise (CW) rotations have affected Oligo-Miocene rocks of southeastern Korea (40°; Kikawa et al., 1994), western Honshu (up to 50°; Otofuji and Matsuda, 1987; Otofuji et al., 1991; Hayashida et al., 1991) and northernmost Kyushu (about 30°; Fig. 1; Ishikawa, 1990). According to Otofuji et al. (1991) and Hayashida et al. (1991), the CW rotation in western Honshu is dated at 16–14 Ma, although Jolivet et al. (1995) have proposed extending this range to 17–13 Ma. All authors agree with the establishment of a link between the CW rotation of southwestern Japan and the opening of the Japan Sea.

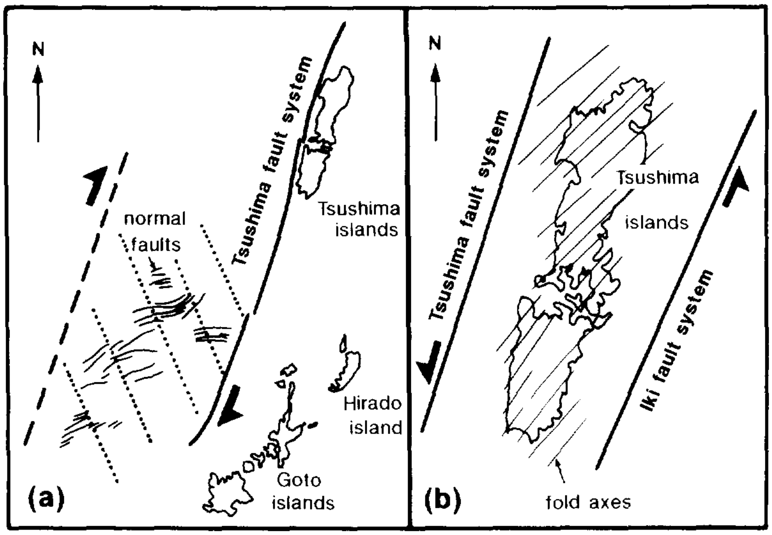


Fig. 3. Opposite senses of displacement proposed for the Tsushima fault system. (a) N70°E-trending normal faults are interpreted as second-order tension fractures associated with the right-lateral Tsushima fault system (after Itoh et al., 1992). Dotted lines are for average trend of $\sigma_{Hmin}$ axis. The second-order faults are restricted to Lower Miocene strata so the right-lateral displacement can be inferred to pre-date the Middle Miocene. (b) NNE- to NE-trending folds are transpressive structures linked with the left-lateral Tsushima fault system and Iki fault system during the Late Miocene (after Inoue, 1982).

In contrast to the above-described CW rotations, counterclockwise (CCW) rotations of about 30° are recorded by Upper Oligocene–Lower Miocene rocks of the Taishu and Goto groups at Tsushima and Goto (Fig. 1; Ishikawa et al., 1989; Ishikawa and Tagami, 1991). Since the 15 Ma intrusions at Tsushima have recorded the CCW rotation (Ito et al., 1980; Ishikawa et al., 1989) but not the Middle Miocene Nakadori Group at Goto (Ishikawa and Tagami, 1991), an estimation of the age of the CCW rotation is 14 or 13 Ma. According to Ishikawa and Tagami (1991), the CCW deflections were caused by block rotations in a sinistral transpressive fault zone encompassing the Tsushima strait area.

### 2.4. Conclusion: identification of two tectonic events

As underlined by Inoue (1982), Ishikawa and Tagami (1991), Sakai (1993) and others, the reverse faults and folds recognized both onland and offshore indicate an approximately NW–SE-directed shortening and affecting Middle Miocene and older rocks. Probably coeval with this deformational event was the uplift accompanying the sedimentation of the Middle Miocene K Group, before the deposition of the unconformable uppermost Miocene D Group (Table 1; Inoue, 1982). On the Goto islands, chaotic horizons belonging to the Nakadori Group and distributed in the vicinity of the Nakadori fault testify of a tectonic activity of this fault during the late Middle Miocene (13–12 to 10 Ma).

Tectonic activity during the Early Miocene is less obvious and is testified only by offshore normal faults affecting Lower Miocene strata but being sealed by Middle–Upper Miocene layers (Minami, 1979; Itoh et al., 1992). Mapping of these faults by Itoh et al. (1992) indicate a NW–SE-directed extension (Fig. 3a).

The late shortening event will be called event II while the early extensional event will be called event I. In the following, we try to determine the characteristics of the stress fields associated with the two events by analysing the fractures in Neogene rocks of the Korea strait islands.

## 3. Fracture analysis

### 3.1. Method

Our basic approach is to determine, from fracture systems observed on single outcrops (Figs. 4–10), the orientations of the three principal stress axes ($\sigma_1 > \sigma_2 > \sigma_3$) or their horizontal projections ($\sigma_{Hmax}$ and $\sigma_{Hmin}$) by using the principles and methods proposed by numerous authors, notably Angelier (1979), Hancock (1985) and Engelder (1989). In favorable sites where enough striated fault planes are exposed (Figs. 4–7 and 9), determination of the orientation of the three principal stress axes was done by using computerized inversion methods (Angelier, 1984). In other sites (Figs. 8 and 9), only

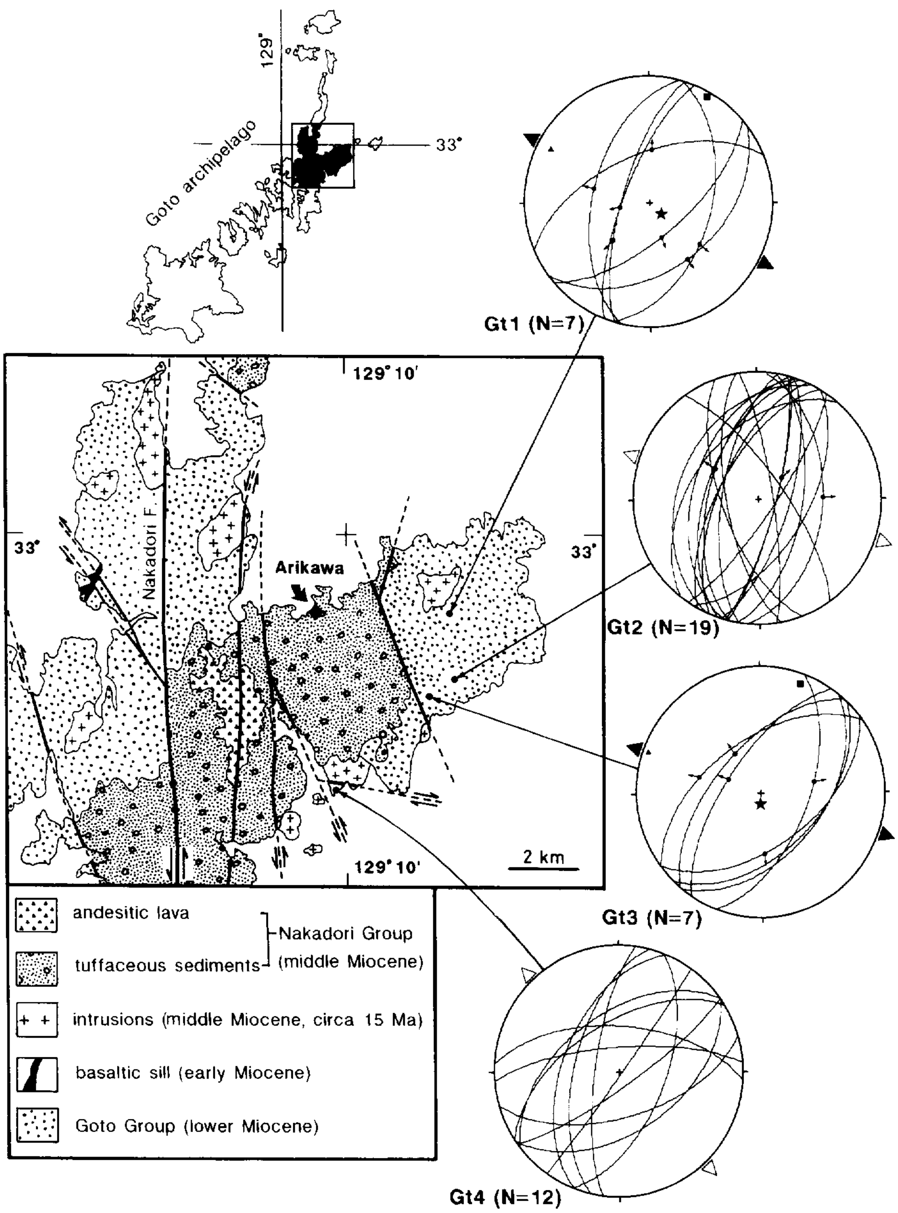


Fig. 4. Type I fault-slip data in the Lower Miocene Goto Group exposed in the Arikawa district, northern Goto islands (lower hemisphere equal-area projections). Geology partly after Kawahara et al. (1984). Divergent arrow heads represent stretching directions. Filled arrows are for directions deduced from computed principal stress axes, open arrows are for directions inferred from the geometry of the fracture system. When determined, the principal stress axes $\sigma_1$ (★), $\sigma_2$ (■) and $\sigma_3$ (triangle) are also projected.

approximate orientations of the principal stress axes were evaluated by using widespread tectonic joints.

Relying on simple conjugate or pseudo-conjugate fault systems, we could define two elementary stress fields corresponding to two discrete deformational events labelled I and II. Complex fault systems which obviously cannot be accounted for by a single stress field were found at two sites located on the Tsushima islands (sites 3 and 6, Figs. 5 and 7): most of the observed faults at these sites could be geometrically sorted into two subsets, each subset being explained by one of the two single fields previously

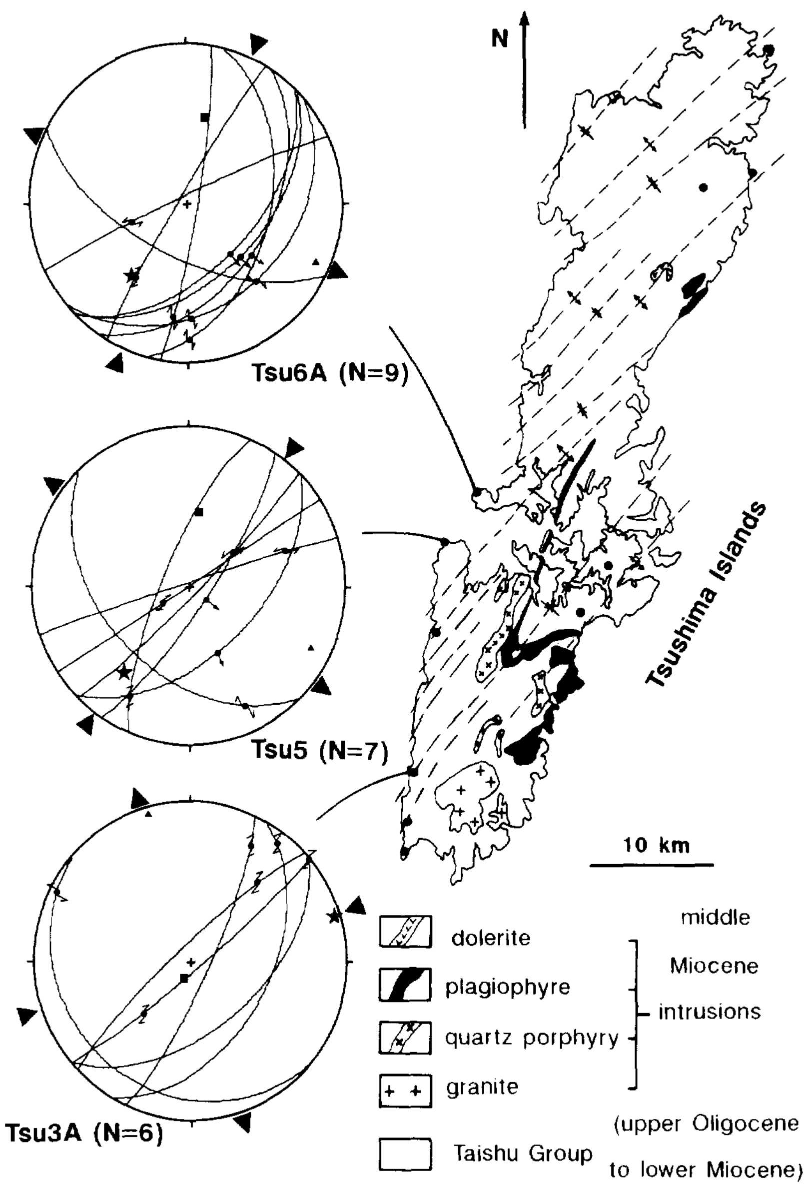


Fig. 5. Type I fault-slip data in the Upper Oligocene–Lower Miocene Taishu Group, Tsushima islands (explanations are the same as for Fig. 4; convergent arrow heads represent shortening directions). Geology simplified after Tomita et al. (1975).

identified. At other sites, the observed fault-slip data could be explained by a single stress field, showing that the systems are monophase.

### 3.2. Tensional to intermediate stress field associated with deformational event I

Evidence for a NW–SE-directed extensional deformation comes from the Lower Miocene Goto Group (Goto islands; Fig. 4, all sites), which exhibits conjugate sets of normal faults striking N45°E on average. Fault planes are rarely striated, so the orientation of the stress axes cannot be determined but an approximate NW–SE direction of extension is given by the overall geometry of the fault systems (Fig. 4, sites Gt2 and Gt4). When the stress axes can be computed (Fig. 4, sites Gt1 and Gt3), $\sigma_1$ is vertical, $\sigma_2$ about N45°E and $\sigma_3$ about N135°E. One should note that the senses of displacement along the macrofaults drawn on the geological map of Fig. 4, which are the presently observable ones, are relevant to the late deformational event II. Opposite senses of displacement should be expected at the time of formation of the NE–SW-trending normal faults.

Evidence for an intermediate stress field associating a NE–SW-directed compression and a NW–SE-directed tension can be found in the Upper Oligocene–Lower Miocene Taishu Group (Tsushima islands; Fig. 5, sites Tsu3, Tsu5 and Tsu6), and also in the Lower Miocene Hirado Formation, Hirado island. Faults in the Hirado Formation are too much scattered to allow a determination of the stress axes.

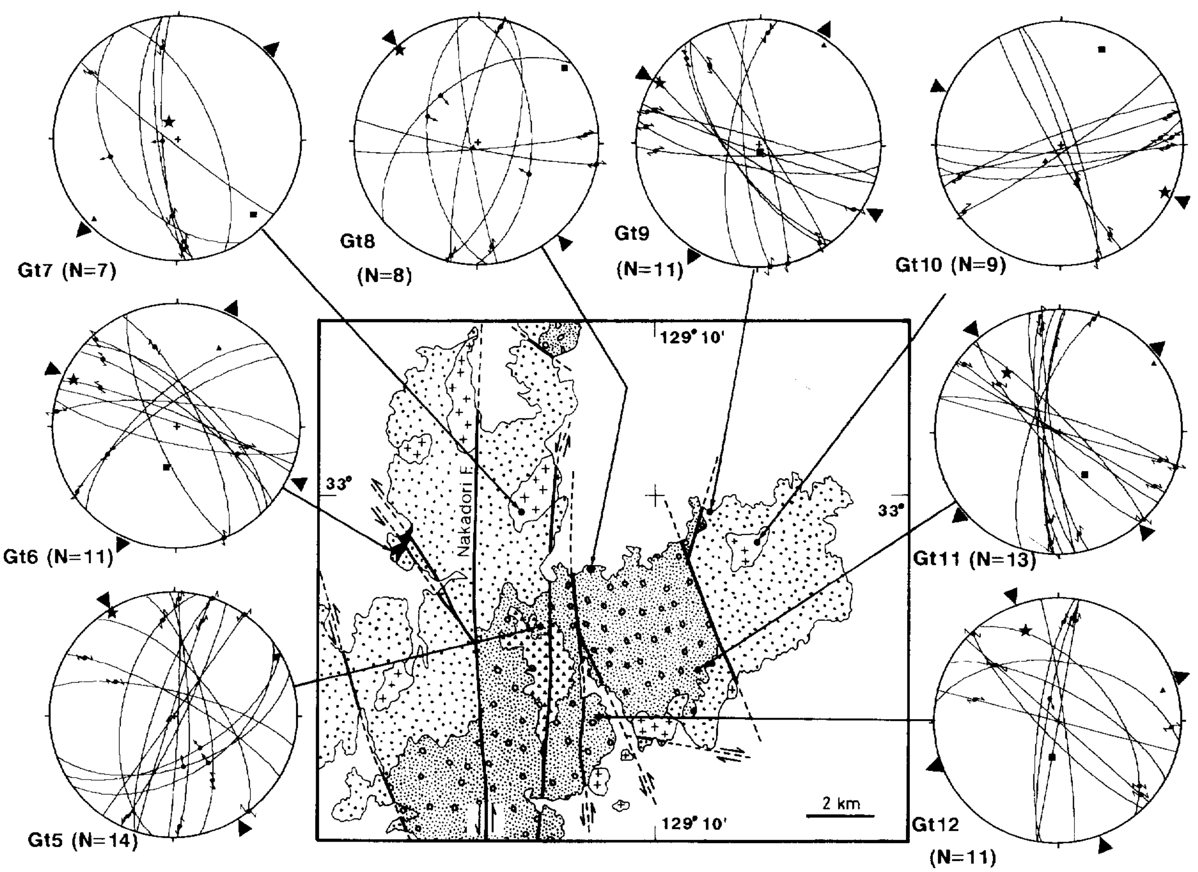


Fig. 6. Type II fault-slip data in the Neogene rocks exposed in the Arikawa district, northern Goto islands (same location as for Fig. 4; explanations are the same as for Figs. 4 and 5). Data are from sandstones of the Goto Group (site Gt9), from a Lower Miocene basaltic sill (site Gt6), from Middle Miocene granite (site Gt7) and gabbro (site Gt10), from tuffs and breccias of the Nakadori Group (sites Gt5, Gt8, Gt11 and Gt12).

Normal faults indicate a NW–SE-directed extension and rare strike-slip faults suggest a NE–SW-directed shortening. Inversion of Tsu3A, Tsu5 and Tsu6A data sets of Tsushima gives a stress field of intermediate type (the plunge of $\sigma_2$ is steeper than 45°). For these three sites, $\sigma_{Hmax}$ trends about N45°E and $\sigma_{Hmin}$ about N135°E. This stress field is compatible with that determined in the Goto Group. Both are relevant to the same tectonic event I.

N30°E- to N70°E-oriented (strongest concentra-

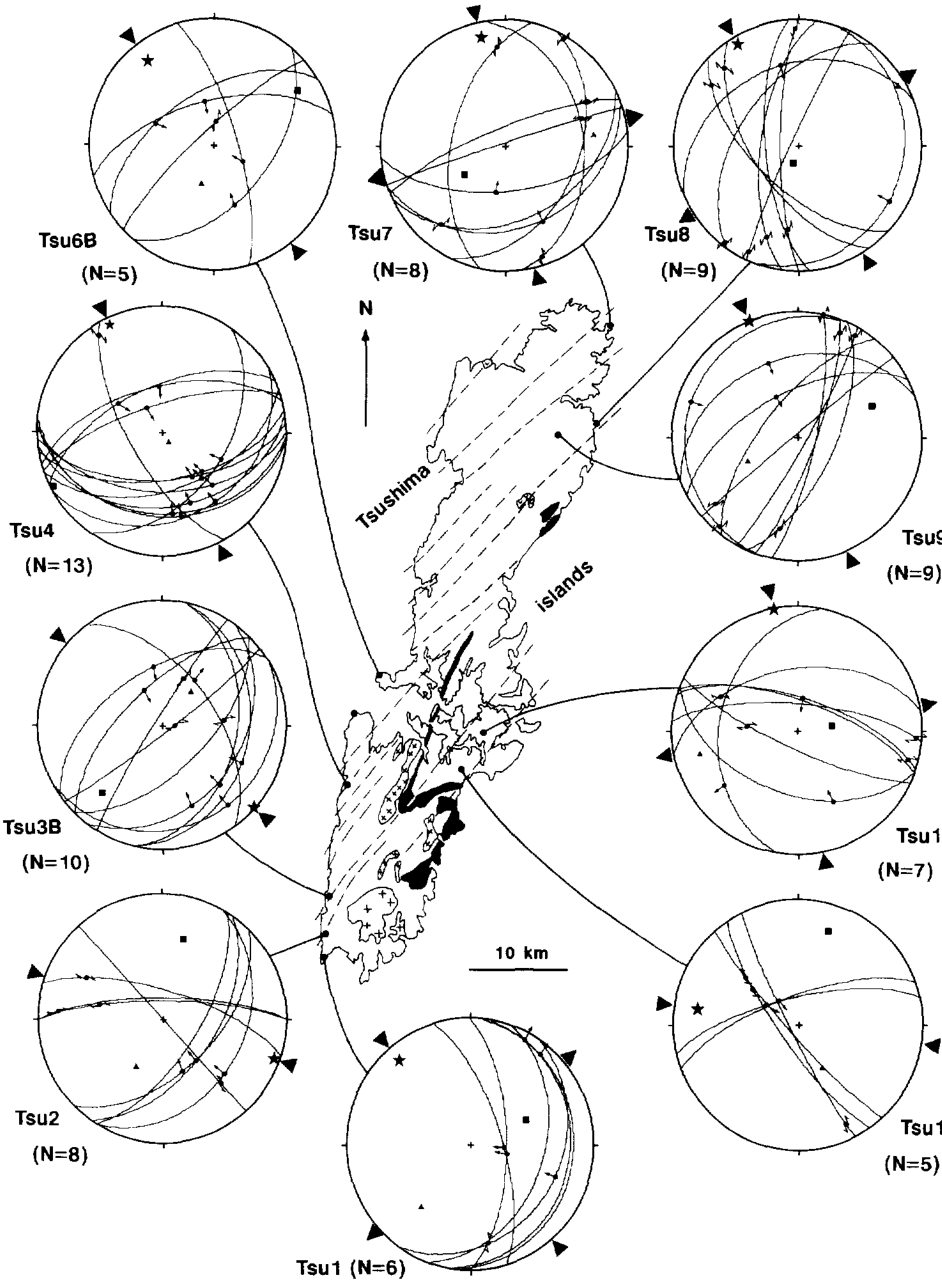


Fig. 7. Type II fault-slip data in the Upper Oligocene–Lower Miocene Taishu Group, Tsushima islands (explanations are the same as for Figs. 4 and 5).

tion at N40°E) vertical or steeply dipping tectonic joints are present in the sandstones of the Goto and Taishu groups (Kitamura, 1962; Fabbri, 1992). These joints are of two kinds. A first group consists of plurimetric regular fractures perpendicular to the stratification plane. Since they form single sets parallel to NE–SW-trending type I normal faults, they can be interpreted as extensional joints (Hancock, 1985). On some outcrops, N135°E-oriented joints abut against N45°E-oriented joints (Fig. 10a), suggesting that the N135°E-oriented joints could be older. However, this type of relationship is rare and does not allow to establish with certainty a relative chronology between the two joint sets.

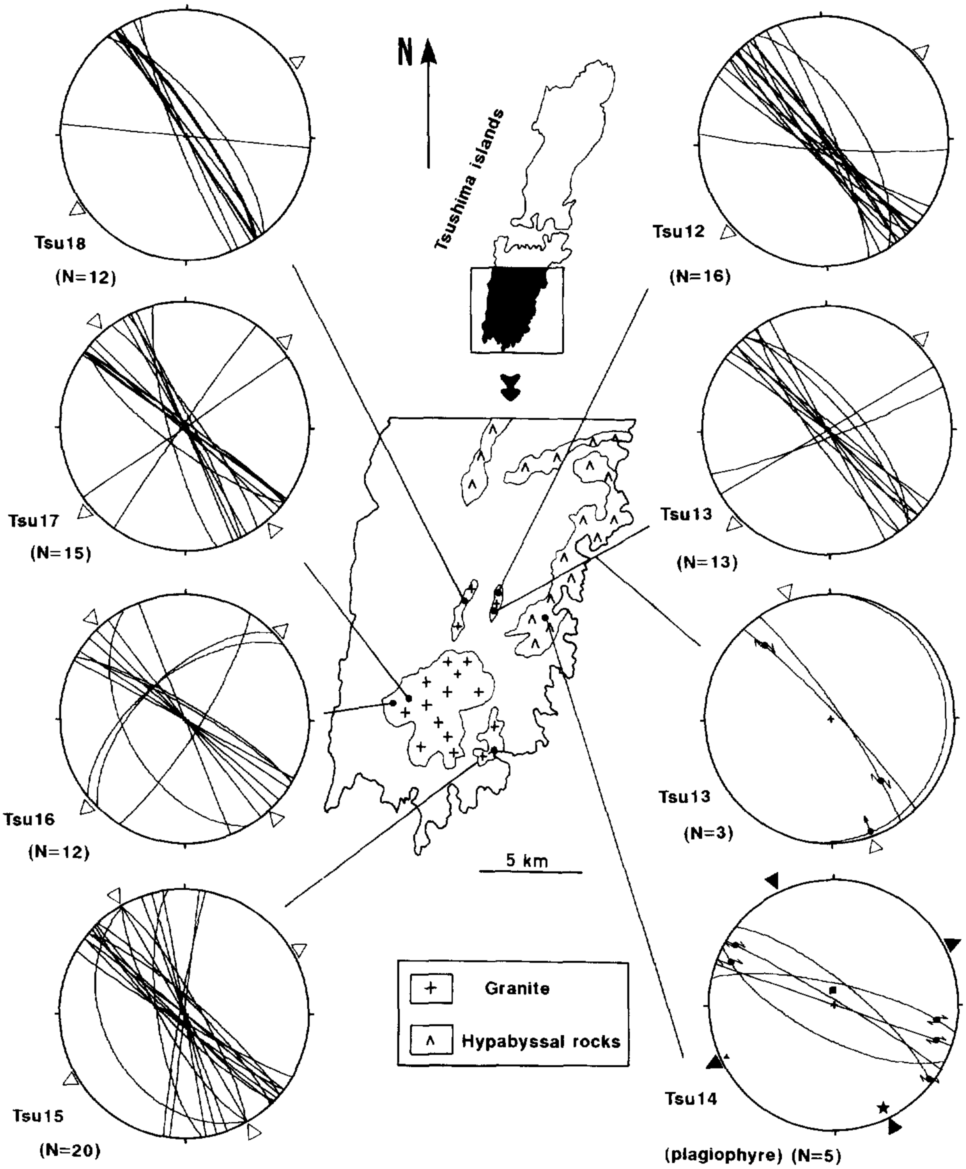


Fig. 8. Type II fault-slip and joint data in the Middle Miocene intrusions, southern Tsushima islands (explanations are the same as on Figs. 4 and 5). Data include fault-slip data (sites Tsu13 and Tsu14) and tectonic joint data (sites Tsu12, Tsu13 and Tsu15–18).

N30°E- to N70°E-trending subvertical tension gashes can be observed in the Taishu Group. In the favorable cases where it is preserved, the direction of growth of the filling mineral (mainly quartz or calcite) is normal to the fracture mean plane, allowing a determination of the orientation of the $\sigma_i$ axes. Type I tension gashes are characterized by $\sigma_1$ horizontal along N45°E and $\sigma_3$ horizontal along N135°E. An example of such a case is depicted in Fig. 11b.

### *3.3. Compressional stress field associated with deformational event II*

In the study area, several localities exhibit fault systems which indicate a NW–SE-directed shortening (Fabbri, 1992; Fabbri and Charvet, 1994). Most simple systems are Gt10 or Tsu11 (conjugate strike-slip faults, Figs. 6 and 7) and Tsu4 (conjugate reverse faults, Fig. 7). Inversion of fault slip data from these localities gives a $\sigma_{Hmax}$ about N135°E and a $\sigma_{Hmin}$ about N45°E. In other localities, the conjugate geometry is less obvious because of a scattering of fault plane attitudes and slip lineation pitches (Fig. 6, Figs. 7 and 9). Despite the scattering, inversion of fault slip data gives a $\sigma_{Hmax}$ about N135°E ($\pm$35°) and a $\sigma_{Hmin}$ about N45°E ($\pm$35°) with an exception at Hirado where faults in andesite (Fig. 9, site Hir1) give a $\sigma_{Hmax}$ about N85°E. This trend is closer to the average trend of type I $\sigma_{Hmax}$ (N45°E) than to N135°E, but we think that the fault pattern of site Hir is not relevant to stress field I. Indeed, as will be discussed in the next section, stress field I was no more active when the andesites were deposited. But it remains questionable whether Hir1 fault slip data

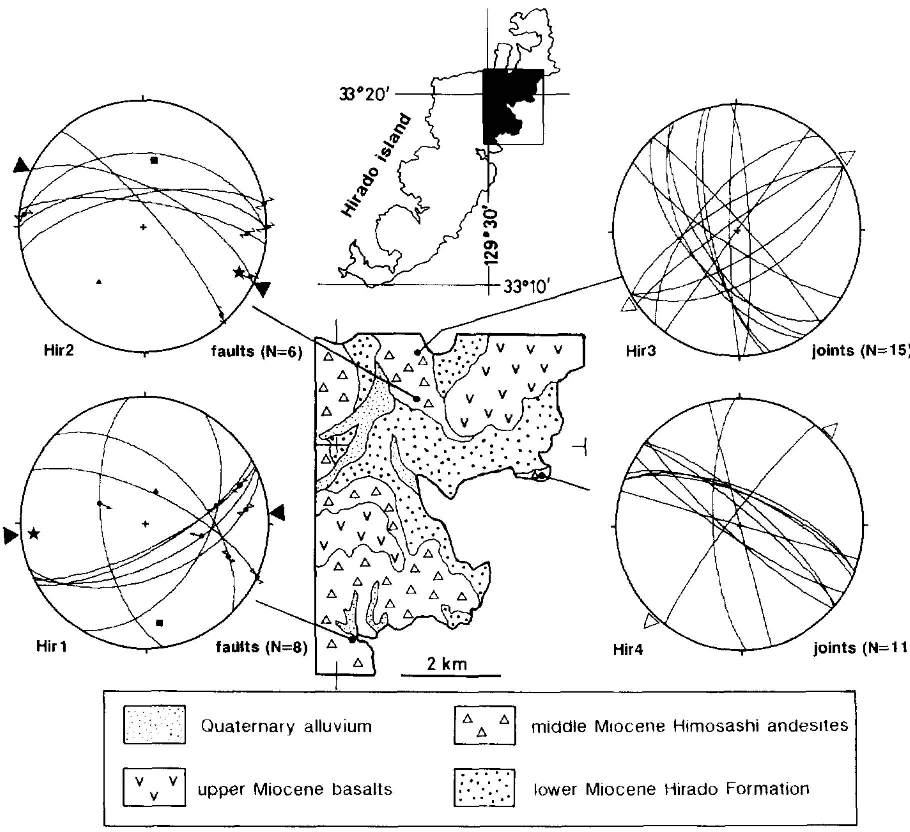


Fig. 9. Type II fault-slip and joint data in the upper Middle Miocene Himosashi andesites, Hirado island (explanations are the same as on Fig. 4 and Fig. 5). Data include fault-slip data (sites Hir1 and Hir2) and tectonic joint data (sites Hir3 and Hir4). Geology simplified after Matsui et al. (1989).

pertain to stress field II or to a more recent (Quaternary?) E–W-directed compressional stress field locally documented in northern Kyushu (Tsukuda, 1992; Fabbri, unpubl. data).

Except for site Gt7 where $\sigma_{Hmax}$ is $\sigma_2$, $\sigma_{Hmax}$ is always $\sigma_1$. Depending on the sites, there is a permutation between $\sigma_2$ and $\sigma_3$ axes: in localities where strike-slip faults predominate, $\sigma_{Hmax}$ is $\sigma_3$ and $\sigma_2$ is vertical (intermediate stress field) whereas in localities where reverse faults predominate, $\sigma_{Hmin}$ is $\sigma_2$ and $\sigma_3$ is vertical (compressional stress field).

As previously noted by early workers (Kitamura, 1962; Shimada, 1977), the widespread occurrence of NW–SE-oriented tectonic joints and tension gashes in the Taishu Group agree well with a NW–SE-directed compression. Fabbri (1992) showed that the same fractures were pervasive in the Goto and Nakadori groups and in the 15 Ma intrusions of the Goto islands. During the present study, we could observe abundant NW–SE-oriented tectonic joints in the 15 Ma intrusions at Tsushima (Fig. 8, all sites) and in the Himosashi andesites at Hirado (Fig. 9, sites Hir3 and Hir4).

Type II tectonic joints forming single or conjugate systems (Fig. 10a and c). Single joints strike N135°E on average. Conjugate systems consist of two subsets, one trending about N100–N120°E, the other about N150–170°E (Kitamura, 1962; Fabbri, 1992). The two subsets enclose an acute dihedral angle which bisector trends about N135°E. The value of the dihedral angle is between 30 and 60°. This moderate value suggests that type II joints are hybrid or shear joints (Hancock, 1985). Shear is further testified by: (1) the parallelism between type II conjugate joints and type II conjugate strike-slip faults (e.g., sandstones of site Gt11 at Goto); (2) the presence of secondary pinnate fractures branching on the main joint plane (sandstone or quartz porphyry at Goto); and (3) passage from joint to an array of en échelon microcracks (granite at Tsushima, sites Tsu12 and 13). The conjugate geometry and a hybrid or shear nature show that the type II joints were formed under a stress field characterized by a $\sigma_{Hmax}$ about N135°E and a $\sigma_{Hmin}$ about N45°E.

Type II tension gashes are common in the Taishu, Goto and Nakadori groups (Shimada, 1977; Fabbri, 1992). They strike N135°E and can form en échelon systems (Fig. 10d). When it is preserved, the direc-

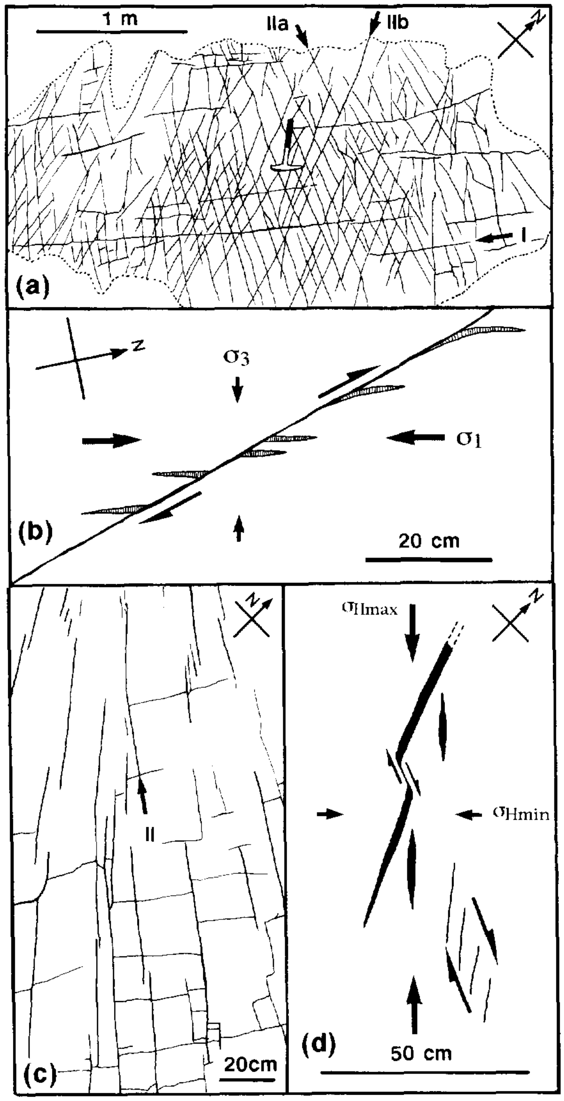


Fig. 10. Representative examples of joint and tension gash patterns in Neogene rocks of the study area. (a) Type II conjugate joints (*IIa* and *IIb*) abutting against older type *I* joints (thin-bedded sandstone, Goto Group, Goto islands). (b) Type I fault and associated en échelon tension gashes; the tension gashes are perpendicular to the slip lineations borne by the host fault plane, showing that the fault and the veins formed concurrently; the calcite fibers give the direction of $\sigma_3$ (massive mudstone, Taishu Group, Tsushima islands). (c) Perspective view of type *II* single joints with intervening perpendicular secondary tensile joints (thick-bedded sandstone, Goto Group, Goto islands). (d) Association of type II oblique pull-apart quartz vein, tension gashes and en échelon joints (massive mudstone, Taishu Group, Tsushima islands).

tion of growth of the filling minerals, which equates the direction of $\sigma_3$, is subhorizontal and trends about N135°E.

### 3.4. Age of the stress fields

Occurrence of type I faults is restricted to the Upper Oligocene–Lower Miocene Goto and Taishu groups and the Hirado Formation. Type I faults could not be found in the 15 Ma intrusions or younger rocks. The same can be said of type I joints and tension gashes. In faulted sandstones of the Goto Group, a syn-sedimentary activity of type I normal faults is supported by bed thickness variations across fault planes and by the presence of hydroplastic slickensides on some planes. Hydroplastic slicken-

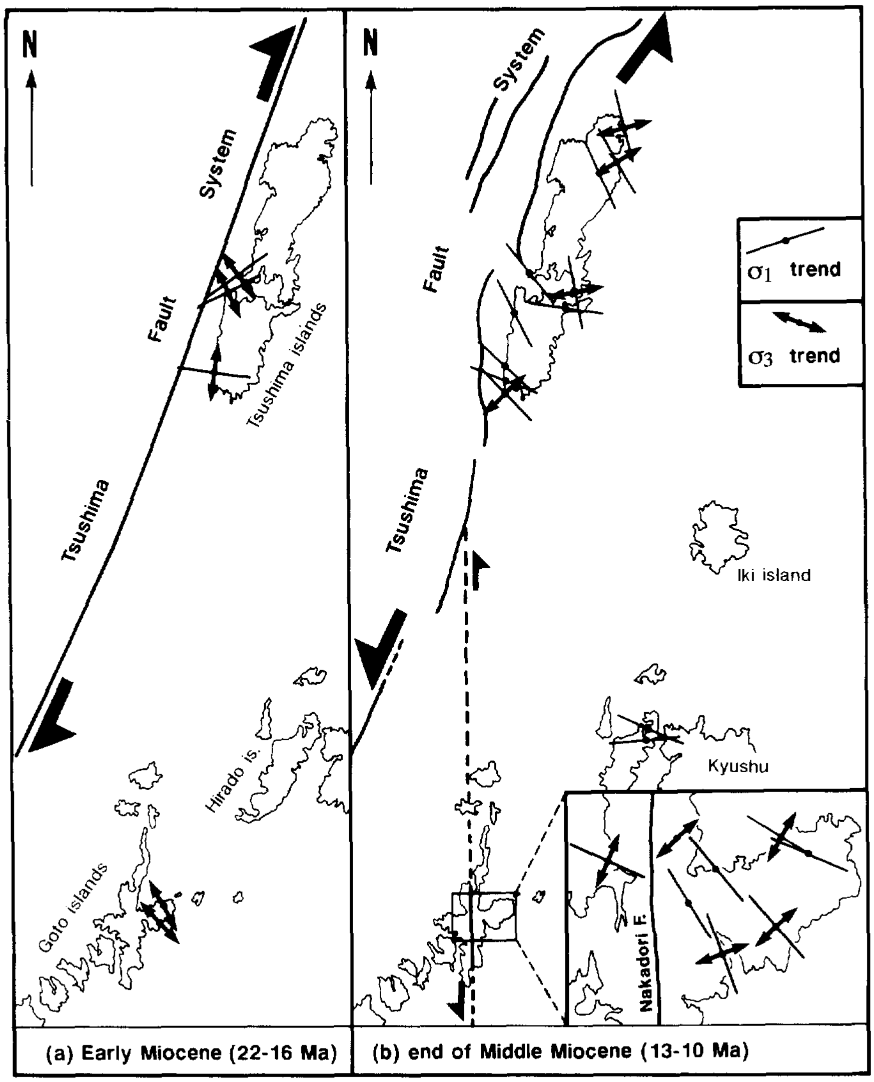


Fig. 11. Summary of the results of the paleostress analysis in the Korea strait and inferred senses of displacement along the Tsushima fault system (compare with Fig. 3). (a) Stress field during the Early Miocene (22–16 Ma; event I). Orientations of stress field I principal axes are rotated clockwisely of 30° in order to correct the counterclockwise rotation of the Tsushima and Goto islands (Ishikawa et al., 1989; Ishikawa and Tagami, 1991). Trend of the Tsushima fault system is not modified. The expected sense of displacement is right-lateral. (b) Stress field at the end of the Middle Miocene (15–10 Ma; event II). Orientations of stress field II principal axes are projected without modification because type II stress field is supposed to have been active during or after the clockwise rotation.

sides are diagnostic of slip before complete lithification of the sediments (Petit and Laville, 1987). Type I fractures thus formed during or after deposition of the Goto Group (22–16 Ma, Table 1) but before 15 Ma. We conclude that tectonic event I occurred between 22 and 16 Ma. The lower limit is not tightly constrained and could be older.

Type II fractures are common not only in the Taishu and Goto groups but also in the 15 Ma intrusive rocks and in the Middle Miocene Nakadori Group. In the Goto area, type II strike-slip faults have been found in granite and gabbro (Fig. 6, sites Gt7 and Gt10, respectively) and in the overlying Nakadori Group (Fig. 6, sites Gt5, Gt8, Gt11 and Gt12). At Tsushima, the few faults observed in the Middle Miocene intrusions are compatible with type II stress field (Fig. 8, sites Tsu 13 and 14). In the same rocks, type II joints are widespread (Fig. 8). Some joints striking northeast to east are tensile fractures liking type II joints and should not be mistaken for type I joints. At Hirado, four sites in the Himosashi andesites display type II faults and joints (Fig. 9), though one site (Hir1) may not be relevant to stress field II, but to a later, possibly Quaternary, E–W-directed compressional stress field detected to the east of the study area, on northern Kyushu. Type II fractures cannot be observed in the Upper Miocene (10 or 9 Ma to 6 Ma) basalts widely exposed at Hirado. An upper limit for the age of type II fractures is 10 Ma. The lower limit cannot be established with certainty but is not older than 15 Ma. Type II fractures were formed during tectonic event II, between 15 and 10 Ma.

### *3.5. Conclusion: kinematic implications*

Fracture analysis allows us to define the stress fields associated with the two tectonic events which occurred in the study area during the Neogene.

Tectonic event I is characterized by stress field I ($\sigma_{Hmax}$ about N45°E and $\sigma_{Hmin}$ about N135°E). Deformation regime is extensional ($\sigma_1$ vertical, Goto) or transcurrent ($\sigma_2$ vertical, Tsushima). Reconstructed directions of stress field I $\sigma_1$ and $\sigma_3$ are projected in Fig. 11a, with a 30° CW rotation in order to cancel the effects of the post-15 Ma CCW rotation reported at Goto and Tsushima (Ishikawa et al., 1989; Ishikawa and Tagami, 1991). The orientations of the principal axes of stress field I imply a mixed normal and right-lateral displacement along the Tsushima fault system (Fig. 11a).

Tectonic event II is characterized by stress field II ($\sigma_{Hmax}$ about N135°E and $\sigma_{Hmin}$ about N45°E). Stress regime is compressional ($\sigma_3$ vertical, Tsushima) or intermediate ($\sigma_2$ vertical or steep, Tsushima, Goto and Hirado). Reconstructed directions of stress field II $\sigma_{Hmax}$ and $\sigma_{Hmin}$ are projected in Fig. 11b. Since stress field II acted concurrently or later than the CCW rotation, no correction is made. The orientations of the principal axes of stress field II imply a mixed reverse and left-lateral displacement along the Tsushima fault system (Fig. 11b). Regional NE–SW-oriented folding of Middle Miocene or older rocks at Tsushima and locally at Goto is compatible with this displacement. We also suppose that the Nakadori fault of the northern Goto islands formed during event II as a second-order Riedel-type fault branching on the Tsushima fault system. Lastly, the post-15 Ma CCW rotations detected at Goto and Tsushima (Ishikawa et al., 1989; Ishikawa and Tagami, 1991) were likely caused by local block rotations along the sinistral Tsushima fault system during event II. Since the 13–10 Ma Nakadori Group has not recorded the CCW deflections, the block rotations were mostly completed at 13 Ma.

In order to check whether the two tectonic events I and II are significant at the regional scale, we examine in the following the results of tectonic investigations from a wide area encompassing southeastern Korea, the southern margin of the Japan Sea and southwestern Honshu.

## 4. Comparison with regional data from the southern Japan Sea area

### *4.1. Southeastern Korea*

In southeastern Korea, Paleogene rocks are reduced to isolated outcrops of rhyolitic tuffs dated at 46–42 Ma (Middle Eocene; Chang et al., 1990). Upper Oligocene–Miocene rocks are distributed in the Pohang basin and consist of two series (Table 1;

Reedman and Um, 1975; Lee and Pouclet, 1988; Ingle, 1992). The lower one (Yangbuk Group) ranges in age from 30 or 25 Ma to 17 Ma (Late Oligocene–Early Miocene). The upper series (Yeonil Group) unconformably covers the lower one and was deposited between 17 or 16 Ma and 6 Ma (Middle–Late Miocene; Ingle, 1992). The lower series has recorded a regional extensional deformation characterized by block faulting and tilting along N20°E to N45°E-trending faults (Reedman and Um, 1975; Lee and Pouclet, 1988). The deformation occurred coevally with sedimentation and predates the deposition of the undeformed Yeonil series. From an analysis of fault-slip data in the Yangbuk Group and older rocks in the Pohang area, Hwang et al. (1991) and Hwang (1992) have identified a stress field characterized by subhorizontal $\sigma_1$ and $\sigma_3$ axes trending about N45°E and N135°E, respectively. This stress field is consistent with the NW–SE-oriented extensional deformation at Pohang. It is also compatible with right-lateral motion along the Yangsan fault between 42 and 15 Ma as deduced by Chang et al. (1990) from geological mapping: Eocene tuffs are dextrally displaced by the Yangsan fault but strata of the Yeonil Group are not faulted. The tectonic event recorded in the Yangbuk Group and older rocks can be correlated to event I of the study area; both took place during the Early Miocene and are characterized by similar stress fields: N45°E $\sigma_{Hmax}$ and N135°E $\sigma_{Hmin}$. Furthermore, the CW block rotations detected in the Yangbuk Group (Kikawa et al., 1994) could well result from right-lateral strike-slip motion of the Yangsan fault system possibly before deposition of the Yeonil series.

In the Pohang basin, an uplift eventually resulting in an emersion of the top of the Yeonil Group took place during the Late Miocene, before the deposition of Pliocene deposits. It suggests the existence of a compressive event between 11 and 6 Ma (Ingle, 1992), which could be the same as event II in the study area.

A similar tectonic history including (1) a Late Oligocene to Early Miocene stage of extensional shear with dextral strike-slip movement and (2) a late Middle Miocene to Quaternary shortening phase has been reconstructed in an offshore basin located to the north of the Pohang basin (Yoon and Chough, 1995).

### *4.2. The southern margins of the Tsushima and Yamato basins*

Chough and Barg (1987) provide paleobathymetric estimations of a > 4000-m-thick Neogene section drilled in the southwestern end of the Tsushima basin. The section has recorded an abrupt change from bathyal to neritic depths between 11 and 9 Ma (base of the Upper Miocene). Subsidence analysis shows that the shallowing, which eventually led to the creation of a Late Miocene regional unconformity, resulted from a tectonic uplift (Chough and Barg, 1987). The Late Miocene unconformity has also been recognized in the study area at the base of the Upper Miocene–Pliocene D group (Table 1; Minami, 1979; Honza et al., 1979; Inoue, 1982).

Along the southern margin of the Yamato basin, seismic sections display widespread folds and reverse faults in the pre-uppermost Miocene or pre-Pliocene strata (Tanaka and Ogusa, 1981; Iwazaki, 1992; Yamamoto, 1993). Deformed strata are covered by undeformed Pliocene deposits. Yamamoto (1993) suggested that the shortening deformation originated from a compressive stress field active during the Late Miocene and characterized by a NNW–SSE- to N–S-oriented $\sigma_{Hmax}$ axis.

### *4.3. Japan Sea coast of western Honshu*

From observations along the northern coast of western Honshu (San-in coast), Fournier et al. (1995) showed that the Lower–Middle Miocene rocks have recorded a regionally consistent stress field characterized by a N45°E $\sigma_{Hmax}$ ($\sigma_1$ or $\sigma_2$ depending on the sites) and a N135°E $\sigma_{Hmin}$ ($\sigma_3$ for all sites). According to Fournier et al. (1995), this stress field was active from 23 to 12 Ma (Early to Middle Miocene) while, in the study area, stress field I was active from 22 to 16 Ma (Early Miocene). Despite this discrepancy which may originate from unsufficiently accurate stratigraphic datings, we think that both stress fields correspond to the same tectonic event I.

In the same area, a broadly N–S-oriented compression is suggested by E–W-trending folds and reverse faults in Lower and Middle Miocene formations (e.g. Kano et al., 1994) and also by the presence of N–S to NNW–SSE-trending Late Miocene dykes in the same formations (Kobayashi, 1979; Yamamoto, 1991). Fournier et al. (1995) have determined the orientations of the stress axes: $\sigma_1$ is horizontal and trends north to northwest, the vertical axis being either $\sigma_2$ or $\sigma_3$. The deformation is estimated to date from the Late Miocene, which slightly post-dates tectonic event II.

### *4.4. Conclusion: regional consistency of events I and II*

The stress fields recorded in Lower to Middle Miocene (23 or 22 to 16 or 12 Ma) rocks of southeastern Korea (Hwang, 1992) or along the southern coast of the Japan Sea (Fournier et al., 1995) are characterized by a N45°E $\sigma_{Hmax}$ and N135°E $\sigma_{Hmin}$. A similar stress field has also been detected on northeastern Honshu and Hokkaido (Otsuki, 1990a; Jolivet and Huchon, 1989; Jolivet et al., 1991; Fournier et al., 1994) and offshore in Lower–Middle Miocene strata drilled in the Japan Basin (ODP Leg 128, hole 794D; Charvet et al., 1992). There is no doubt that stress field I is the expression in the study area of a regional stress field active in and around the Japan Sea during Early to Middle Miocene times.

The effects of Middle to Late Miocene compressional events can be traced along the southern margins of the Tsushima and Yamato basins, along the northern coast of western Honshu and possibly in the Pohang basin and adjacent basins of southeastern Korea. When determined from fracture analysis, the $\sigma_{Hmax}$ axis is N–S to NW–SE trending (western Honshu; Fournier et al., 1995), which is similar to the $\sigma_{Hmax}$ axis of the study area. Despite dating uncertainties, we tentatively correlate these events with event II of the study area.

## 5. Discussion

### *5.1. Origin and significance of deformational event I*

Kimura and Tamaki (1986), Lallemand and Jolivet (1986) and Jolivet et al. (1990 and subsequent papers) proposed that the Japan Sea opened as a broad pull-apart zone between two major dextral strike-slip shear zones located along the western and eastern margins of the basin. A pull-apart opening schematically mixes two components: an extensional one and a strike-slip one. In the case of the Japan Sea, the extensional component was probably induced by the trench roll-back phenomenon associated with the subduction process (Uyeda and Kanamori, 1979). The dextral strike-slip component was caused by a N45°E $\sigma_{Hmax}$ acting obliquely on N0° to N20°E faults bordering the eastern Asian margin. The origin of the N45°E $\sigma_{Hmax}$ could be found in the Himalayan collision between 45 and 15 Ma (Kimura and Tamaki, 1986; Jolivet et al., 1990). Indeed, small-scale analogous experiments reproducing the indentation of Asia by India predict such a stress field in the area corresponding to the Japan Sea (Jolivet et al., 1990, Jolivet et al., 1991; Fournier, 1995). The data from the Korea strait are in agreement with the pull-apart model and the Himalayan collision appears as a viable cause for stress field I.

Reconstructions by Jolivet et al. (1991) and Jolivet and Tamaki (1992) give a 150–200 km estimate for the amount of dextral displacement along the Yangsan–Tsushima fault systems between the Late Oligocene and the Middle Miocene. Chang et al. (1990) documented a 35 km dextral offset of 42 Ma rhyolitic tuffs along the Yangsan fault. The offset was achieved at 15 Ma, the age of unfaulted sedimentary rocks covering the fault. Regarding the Tsushima fault system, the submarine geology in the vicinity of the fault zone is not known enough to allow an estimate of the offset, which would remain minimum anyway, given the superimposed sinistral displacement.

### *5.2. Origin and significance of deformational event II*

The regional extent of the effects of the Middle to Late Miocene compression implies that the cause of this event is not local but regional. A possible explanation lies in a radical change of stress state along the Asia (Amuria)–Pacific plate boundary towards the end of the Miocene, as advocated by several authors (Sugi et al., 1983; Jolivet and Huchon, 1989; Otsuki, 1990a; Jolivet et al., 1991, Jolivet et al., 1995; Sato and Amano, 1991; Ingle, 1992; Yamamoto, 1993; Fournier et al., 1994). From the Late Oligocene to the Middle Miocene (30 or 25 Ma to 12 Ma; Ingle, 1992), the subduction-type plate boundary was extensional, allowing back-arc rifting and spreading. The boundary progressively became compressive between 12 and 10 Ma and is still under such conditions (Fukao and Furumoto, 1975; Nakamura, 1983; Tamaki and Honza, 1985). Why did the stress state along the plate boundary radically change about 12–10 Ma is still a matter of debate. The causes which have been called upon include: (1) arrival in the subduction zone of the young and thick oceanic crust of the Philippine Sea Plate and associated ridges, but the timing of this arrival is still disputed; depending on the geodynamical reconstructions, estimates vary from 40 to 12 Ma (Seno and Maruyama, 1984; Charvet and Fabbri, 1987; Jolivet et al., 1989; Hibbard and Karig, 1990; Otsuki, 1990b); (2) collision of the Kuril arc with Hokkaido (Kimura and Tamaki, 1985); and (3) change in the dip angle of the subducting plate (Chough and Barg, 1987). The results from our study cannot help to resolve this problem. We shall only retain that the Middle to Late Miocene compressive stress field, recorded in a wide region, has arisen from a change of stress state along the Asian–Pacific plate boundary.

In the study area, the compressive stress field II is considered to be responsible for a reactivation of the Tsushima fault system as a sinistral-reverse fault sometime between 15 and 10 Ma. To the east of the Tsushima strait, Smith and Yamauchi (1994) pointed out the existence of extensional subbasins and grabens arranged en échelon along the southern rim of the Yamato basin. According to these authors, the grabens are oblique to the trend of southwestern Japan and can be interpreted as the remnants of a right-stepping en échelon array. Such a geometry indicates a pre-15 Ma sinistral displacement of southwestern Japan relative to Asia and suggests that sinistral motion in the southern rim of the Yamato basin may have begun earlier than in the Tsushima strait area.

## 6. Conclusion

Synthesis of the published geological data combined with our field observations leads to the recognition of two tectonic events which affected the Korea strait during the Neogene. Event I consists of a NW–SE-directed extension and occurred during the Early Miocene (approximate dating 22–16 Ma). Event II consists of a NW–SE-directed shortening and occurred during the Middle Miocene (approximate dating 15–10 Ma). Analysis of the fractures in the Tertiary rocks exposed on the Korea strait islands shows that each event is characterized by a distinct set of faults and tectonic joints, and further allows a reconstruction of the paleostress fields. Determination of the directions of the maximum and minimum horizontal stress axes put constraints on the kinematics of the Tsushima fault system. First, a right-lateral displacement during the Early Miocene (event I) is supported by a NE-trending $\sigma_{Hmax}$ (stress field I, Fig. 11a); it is in agreement with the development of offshore normal faults interpretable as tension fractures in a transtensional context (Fig. 3a; Itoh et al., 1992). Second, a left-lateral motion during the second half of Middle Miocene (event II) agrees with a NW-trending $\sigma_{Hmax}$ (stress field II, Fig. 11b); it is compatible with the en échelon folding (Fig. 3b; Inoue, 1982; Research Group for Active Tectonics in Kyushu, 1989) and with reverse faulting (Minami, 1979; Katsura, 1992). CCW deflections detected at Goto and Tsushima (Ishikawa et al., 1989; Ishikawa and Tagami, 1991) can also be explained by block rotations within a left-lateral transpressional system.

The pull-apart model requires a right-lateral motion along the eastern and western margins of the Japan Sea during the opening. The Early Miocene right-lateral motion along the eastern margin is well established (e.g. Jolivet et al., 1991). Regarding the Yangsan fault system, offset geological markers bring direct evidence for a dextral displacement between 42 and 15 Ma (Chang et al., 1990). Though relying on indirect arguments, the present analysis supports an Early Miocene dextral motion along the Tsushima fault system and further shows that the later sinistral motion clearly post-dates the opening of the Japan Sea since it is dated at the end of Middle Miocene.

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