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Extension in the southern Ryukyu arc (Japan): Link with oblique subduction and back arc rifting

Olivier Fabbri

Département de Géosciences, Université de Franche-Comté, Besançon, France

Marc Fournier

Département de Géotectonique, Université Pierre et Marie Curie, Paris

Abstract. Compilation of earthquake focal mechanisms, morphological analysis, and examination of mesofractures help to clarify the Cenozoic and recent stress history in the southern Ryukyu arc between the Ryukyu trench and the southern Okinawa Trough. (1) An older, pre-Miocene, intermediate-type stress field (vertical stress component $\sigma_V = \sigma_2$) is attested by conjugate strike-slip faults and shear joints in Eocene rocks of Ishigaki Island. The σ_1 axis trends N90°E to N110°E in present-day coordinates. (2) Normal faults and extensional joints in Mio-Pliocene strata of Iriomote and Yonaguni Islands and fault scarps in Pleistocene strata at Yonaguni allow us to reconstruct a Miocene to Pleistocene stress field of tensional type ($\sigma_V = \sigma_1$). The σ_3 axis trends about NW-SE. The effects of this stress field can be traced back in Eocene rocks of Ishigaki Island. (3) Evidence for the youngest, Holocene to present-day stress field comes from the analysis of the Harvard Moment Tensor Catalog (1976-1997) for shallow earthquakes, Quaternary fault scarps visible on the two islands of Miyako and Yonaguni, and extensional joints in Holocene rocks of Yonaguni. This stress field is tensional. Two directions of extension are inferred: a regional, arc-perpendicular (N-S) one and a local, arc-parallel (N60°E) one in the easternmost part of the area near Miyako. The record of Neogene to Quaternary tensional stress fields demonstrates that the extension in the Okinawa Trough can be traced until the arc region. Arc-oblique to arc-perpendicular stretching can be directly correlated with oceanward rifting in the back arc basin, while the arc-parallel stretching reflects the increase of the arc curvature. The predominance of extensional features, the absence of shortening or transcurrent deformation structures, and a weak interplate coupling do not support the forearc sliver model for the present-day southern Ryukyu arc.

1. Introduction

In a context of plate convergence, oblique subduction is thought to induce strike-slip tectonics within the edge of the overriding plate [*Fitch*, 1972; *Beck*, 1983; *Jarrard*, 1986; *Yu et al.*, 1993]. Depending on various parameters such as the angle of convergence (the angle between the normal to the trench and the direction of relative convergence), the angle of subduction (the dip of the Wadati-Benioff plane below the overriding plate edge), the degree of interplate coupling, or the thermal state of the overriding plate, oblique subduction can lead to the formation of so-called forearc slivers, which can be defined as microplates bounded by one or several transcurrent faults on the arc or continent side. Present-day examples of such tectonic settings include the Sumatra forearc between the Java trench and the Central Sumatra fault [*Fitch*, 1972], the SW Japan forearc between the Nankai Trough and the Median Tectonic Line [*Tsukuda*, 1992], the Kuril forearc region [*Kimura*, 1986], or the Aleutian forearc region [*Avé Lallemant*, 1996].

In the northwestern edge of the Philippine Sea (Figure 1), the Ryukyu arc-trench system is characterized by the subduction of the Philippine Sea plate beneath the Eurasia plate and by crustal extension at the back of the arc in the Okinawa Trough [*Aiba and Sekiya*, 1979; *Lee et al.*, 1980; *Kimura*, 1985; *Letouzey and Kimura*, 1985, 1986; *Sibuet et al.*, 1987]. Most recent estimates of the direction and rate of convergence between the Philippine Sea plate and the Eurasia plate as deduced from interplate earthquake slip vectors are N310°E and 7.4 cm/yr, respectively [*Seno et al.*, 1993]. Spatial geodesy gives the same direction of relative convergence and a slightly higher rate of convergence of 8.3 cm/yr between the Philippine Sea plate and south China [*Yu et al.*, 1995]. In the southwestern part of the arc, the angle of convergence increases westward from 15° to a maximum of about 50° immediately to the east of Taiwan. On the basis of onshore stress field analysis and interpretation of offshore single-channel seismic reflection profiles, *Kuramoto and Konishi* [1989] regarded the southern Ryukyu arc as being a forearc sliver separated from the Eurasia plate and moving westward because of the push of the obliquely subducting Philippine Sea plate.

In order to check the relative importance of extensional tectonics (vertical stress component σ_V equal to maximum principal stress component σ_1) versus strike-slip tectonics (σ_V equal to intermediate principal stress component σ_2), we carried out a fracture analysis on the four main islands of the southern Ryukyu arc, which are, from east to west, Miyako, Ishigaki, Iriomote, and Yonaguni (Figure 1). Fracture investigation was done at two scales: at the island scale, by interpretation of air photographs of Miyako and Yonaguni, and at the outcrop scale for all the islands. Analysis of outcrop-scale fractures in Cenozoic and Quaternary strata allows us to reconstruct local stress tensors and to infer the regional stress field history since the Eocene.

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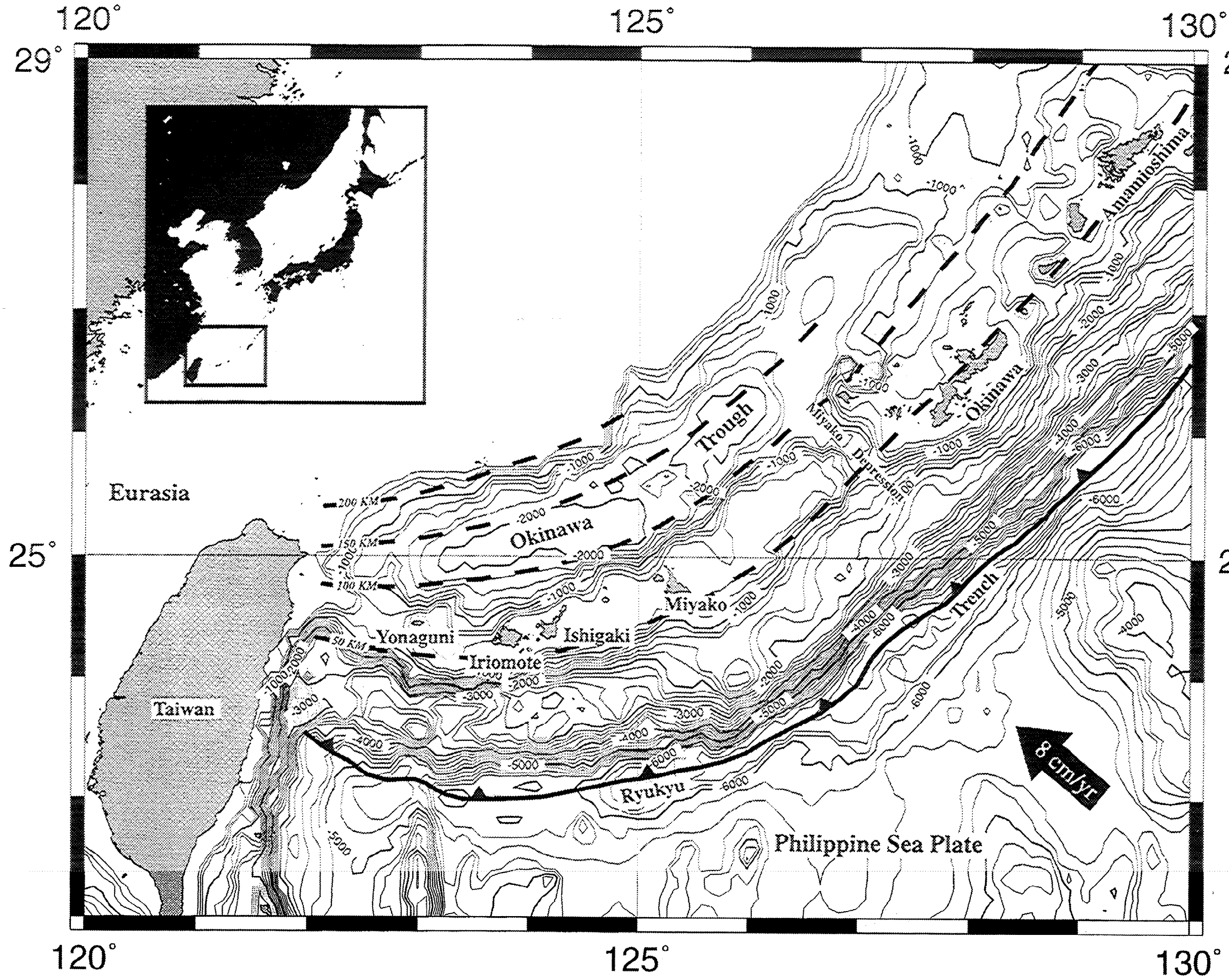

Figure 1. Geodynamic setting of the Ryukyu arc-trench system and associated back arc basin (Okinawa Trough). Isobaths of the Wadati-Benioff zone are after *Eguchi and Uyeda* [1983]. The solid arrow represents the direction of plate convergence after *Seno et al.* [1993].

2. Geological Outline of the Surveyed Islands

The onshore geology of the Ryukyu arc was synthetized by *Konishi* [1965] and *Kizaki* [1978, 1986]. In the following, we briefly describe the segment of the arc which is located to the southwest of the Miyako depression (Figures 1 and 2).

2.1. Geology

The substratum of the southern Ryukyu arc consists of a pre-Tertiary metamorphic basement and of Tertiary and Quaternary sedimentary and volcanic strata with minor intrusive rocks. The pre-Tertiary basement is exposed on the two islands of Ishigaki and Iriomote. It includes Triassic high-pressure schists and Jurassic epimetamorphic sedimentary rocks [*Kizaki*, 1986; *Faure et al.*, 1988]. Similar rocks are exposed in Taiwan as well as in SW Japan [*Faure et al.*, 1987; *Isozaki and Nishimura*, 1989].

The Tertiary cover [*Kizaki*, 1978; *Sakai et al.*, 1978; *Ujiie and Oki*, 1974] is composed of (1) Eocene platform limestones (Miyaragawa Formation) and volcanic tuffs and breccias (Nosoko Formation) distributed at Ishigaki and Iriomote, (2) lower to middle Miocene (approximate range of 20-15 Ma) alternations of deltaic sandstones and siltstones (Yaeyama Group) exposed at Iriomote and Yonaguni, and (3) Pliocene (6-2 Ma) marine sandstones and siltstones (Shimajiri Group) locally observable at Miyako. At Ishigaki, the basement rocks and the Nokoso Formation are intruded by a 21-Myr-old granite. Zircon fission track datings of the Nosoko Formation have yielded ages of 45 to 43 Ma [*Miki*, 1995].

The Quaternary deposits can be found to variable extents on all islands and consist of late Pleistocene reef limestones (Ryukyu Limestone) and Holocene alluvium, dune deposits, and raised reef limestone. At Yonaguni, Holocene "continental" silts, gravels, and sands (Urabu Beds) are present along depressed zones inside the island and represent syntectonic deposits coeval with normal fault activity [*Sakai et al.*, 1978].

2.2. Paleomagnetic Data

Paleomagnetic investigations have revealed a post-Eocene clockwise (CW) rotation of Ishigaki, Iriomote, and Miyako islands [*Miki et al.*, 1990; *Miki*, 1995]. CW deflections of

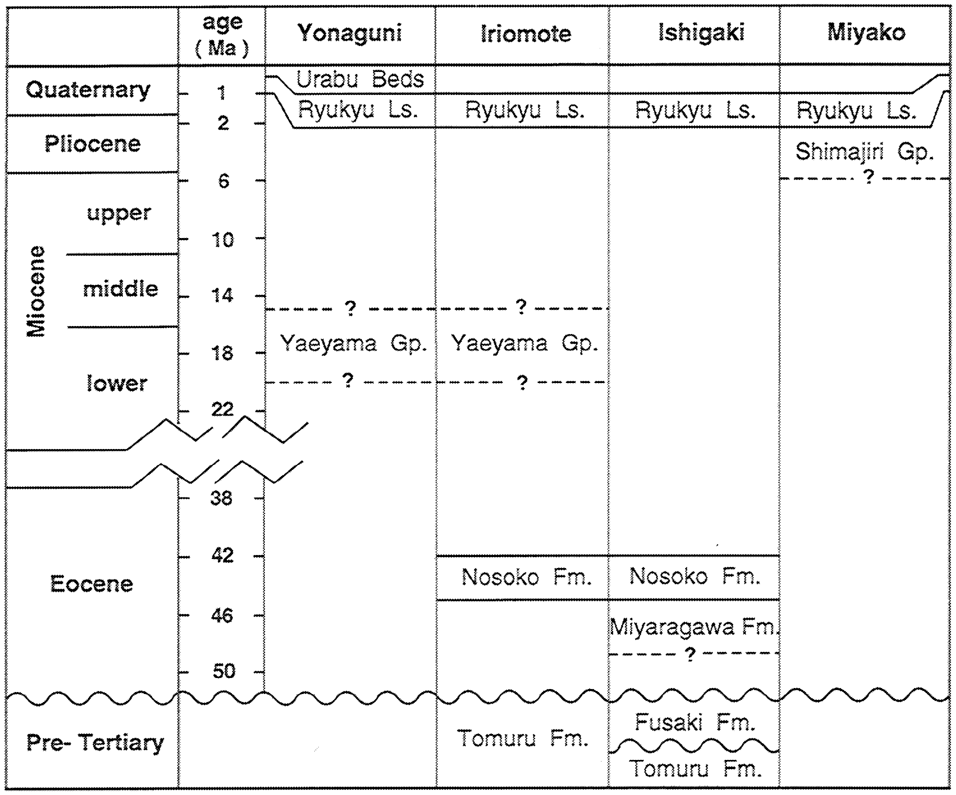

Figure 2. Stratigraphy of the southern Ryukyu islands (compiled after *Ujiie and Oki* [1974], *Sakai et al.* [1978], and *Kizaki* [1985, 1986]). Not mentioned is a 21 Ma granite crosscutting the Nosoko Formation at Ishigaki.

paleodeclinations are estimated between 19° [*Miki et al.*, 1990] and 25° (most plausible value [*Miki*, 1995]). The 25° rotation occurred after 10 Ma (age of the youngest rotated rocks) and before 6 Ma (approximate age of the oldest unaffected rocks) and was not accompanied by any significant N-S translation [*Miki*, 1995]. The absence of any pronounced bathymetric discontinuity between the islands allows us to consider that the southern Ryukyu arc has been forming a rigid block since the Neogene and thus rotated as a whole.

3. Focal Mechanisms of Earthquakes in the Central and Southern Ryukyu Arc and Back Arc Region

The nature and distribution of the seismicity along the plate interface or within the subducting slab has been intensively studied [*Katsumata and Sykes*, 1969; *Shiono et al.*, 1980; *Eguchi and Uyeda*, 1983; *Kao and Chen*, 1991]. The Wadati-Benioff zone beneath the central and southern Ryukyu arc dips 40° to 50° and can be traced down to a depth of about 250 km. There is no report of a major shallow earthquake at the plate interface in the Ryukyu region [*Kao and Chen*, 1991], and the oceanic plate in the vicinity of the Ryukyu Trench is devoid of compressional outer rise earthquakes [*Christensen and Ruff*, 1988]. These two points indicate that the interplate coupling is weak.

In the following, we examine the focal mechanisms of shallow earthquakes (depth < 50 km) whose hypocenters are located within the Eurasia plate (Figure 3). The data base for this study is the Harvard Moment Tensor Catalog for the period 1976 to February 1997 [*Dziewonski et al.*, 1997, and references therein]. We also include event 3 (May 17, 1974) of *Kao and Chen* [1991] whose focal mechanism was derived from first arrivals. The focal depth of this event is 25 km, and its epicenter is located about 50 km northeast of the Miyako Island. Figure 3a shows that the focal mechanisms are of two types: normal fault type and strike-slip fault type. Tensional types predominate in the southwestern part of the area, between Ishigaki Island and Taiwan, whereas strike-slip types are more numerous in the northeastern part, northwest of the islands of Okinawa and Amamioshima. A closer examination of Figure 3a allows us to define four domains, each being characterized by similar trends and plunges of seismic axes (Figure 3b). The north and central Okinawa domains show subhorizontal tension (T) axes trending around N150°E. In the north Okinawa domain, strike-slip earthquakes prevail and are associated with a few extensional events: Compression (P) axes and null (N) axes tend to be either vertical (or nearly vertical) or horizontal (or nearly horizontal) and trending N60°E. Such a permutation is not observed in the central Okinawa domain where the P and N axes remain scattered along a great circle whose pole is close to the mean of the T axes. In the south Okinawa domain, T axes are more scattered but remain subhorizontal and tend to cluster around N10°E. Like in the central Okinawa domain, the P and N axes are scattered around a great circle whose pole can be equated to the mean T

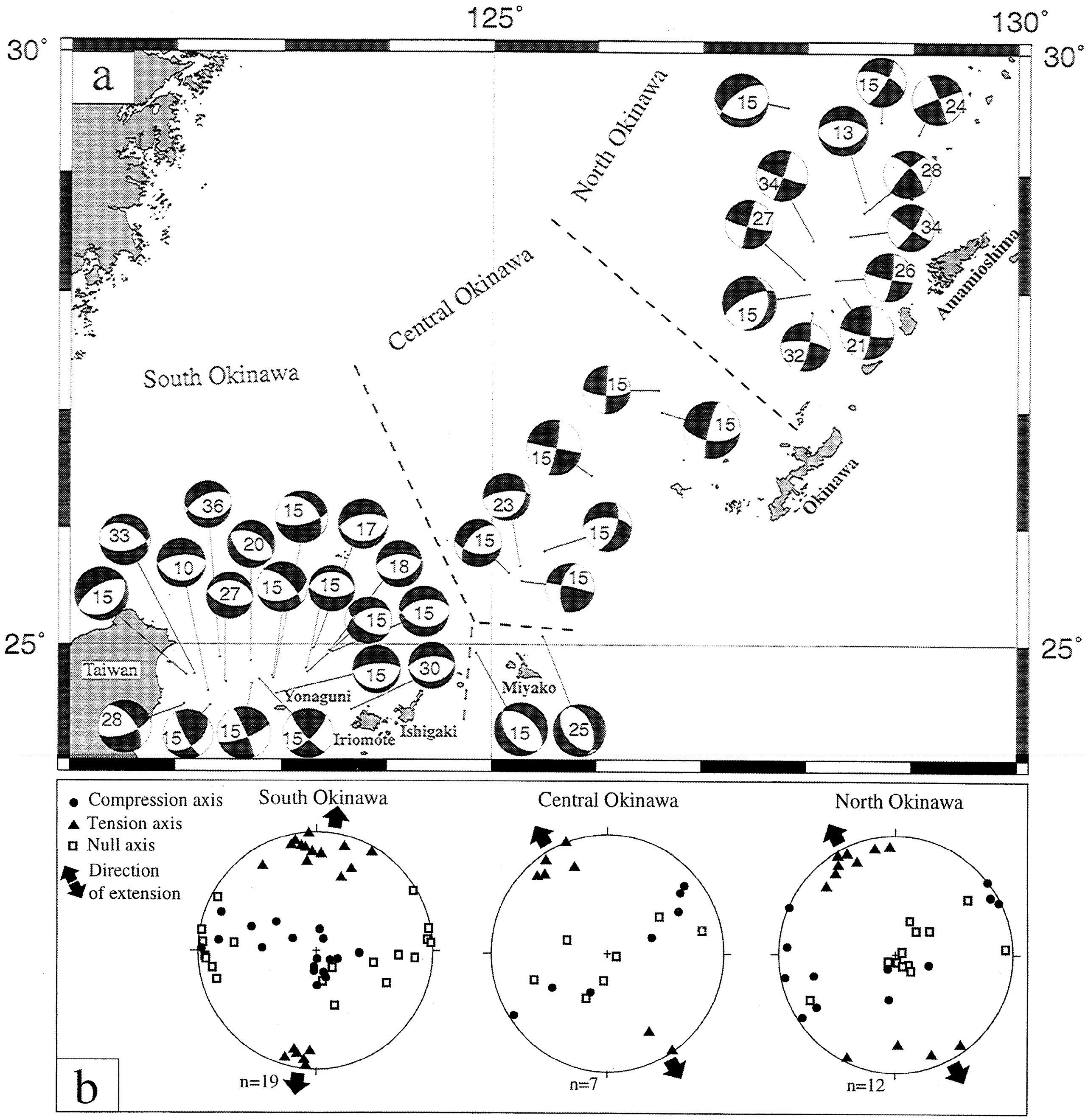

Figure 3. (a) Shallow seismicity (depth < 50 km) between 1976 and February 1997 in the Ryukyu arc-Okinawa Trough region. Focal mechanisms are from the Harvard Moment Tensor Catalog [*Dziewonski et al.*, 1997]. Also projected is the mechanism of the May 17, 1974, event immediately to the northeast of Miyako island (D=25 km, *Kao and Chen* [1991]). Numbers inside the circles are focal depths in kilometers. For each event, the diameter of the circle is proportional to the magnitude. Solid areas correspond to dihedra in tension. (b) Lower hemisphere equal-area projection of compression, tension, and null axes for events representated in Figure 3a, with the exception of the two events near Miyako Island.

axis. However, purely extensional events clearly prevail. The two events near Miyako Island are characterized by nodal planes striking N130°E to N150°E and by T axes trending N45°E to N60°E. They cannot be included in any of the three previously defined domains, but the trend of their T axes is the same as the direction of extension suggested by recent normal faults mapped on Miyako Island (see section 4.2).

The remarkable clustering of T axes as shown by Figure 3b demonstrates that extension in the crust underlying the central and southern Ryukyu arc and back arc region is basically radial, that is, normal to the local strike of the arc. The regional stress field changes progressively from mostly intermediate type (strike slip) to the north to mostly extensional in the southern part of the Okinawa Trough. The

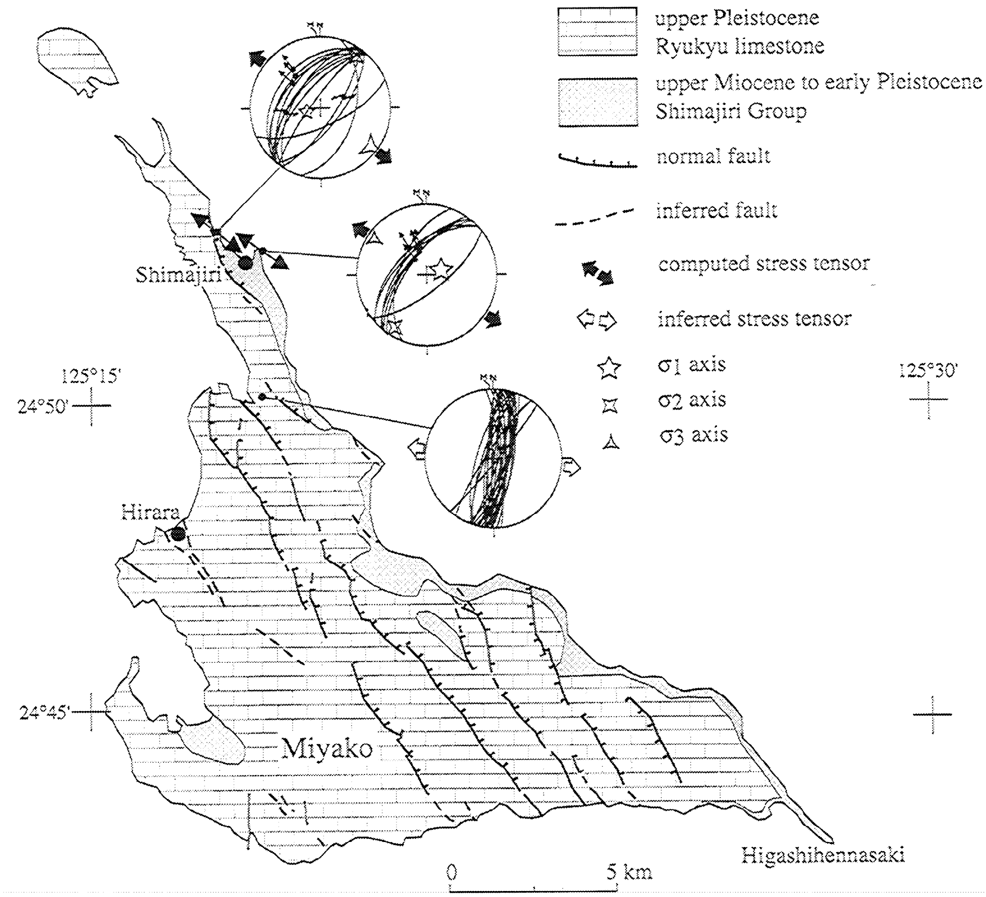

Figure 4. Regional fault patterns deduced from air photograph analysis and outcrop-scale fractures at Miyako (geology after *Kizaki* [1985]).

only exception to the radial extension is provided by two events near Miyako Island which indicate a local arc-parallel stretching. This reflects a crustal adjustment in response to the increasing curvature of the oceanward migrating arc.

4. Onland Deformation in the Southern Ryukyu Arc

4.1. Methodology

Recent faulting on the two islands of Miyako and Yonaguni was examined by the means of black and white air photographs of the Japan Geographical Survey at a scale of 1/20,000. Observed fault scarps are reported on the geological maps of the two islands.

For all investigated islands, joint and fault-slip data were gathered in the field. A fault-slip datum consists of a fault plane on which kinematic indicators (striations in most cases) give the direction and sense of slip. In the localities where fault-slip data are sufficiently numerous (at least four), we performed a computer-aided determination of the orientations of the three principal stress axes by using stress inversion methods and routines elaborated by *Angelier* [1984, 1990]. In the localities where fault-slip data are scarce or nonexistent, stress inversion is not possible, but the principal axes of deformation (extension axis X, intermediate axis Y, shortening axis Z) can be deduced from the arrangement of tectonic joints [*Hancock*, 1985; *Bergerat et al.*, 1992]. In order to allow a comparison between the stress axes deduced from fault-slip data inversion and the deformation axes deduced from joint geometry, we assume that the principal stress axes σ_1, σ_2, and σ_3 are parallel to the shortening, intermediate, and extension axes Z, Y, and X, respectively.

4.2. Miyako Island

Fault scarps of kilometric extent are well expressed in the topography of Miyako Island and reflect post-Pleistocene (post-Ryukyu Limestone deposition) displacements. They are found in the late Pleistocene Ryukyu Limestone where they trend uniformly about N150°E and face predominantly eastward (Figure 4). The height of the scarps ranges from a few meters to about 40 m. The lack of exposure along the scarps prevents obtaining direct information regarding the slip vector. Nevertheless, the general "horst-and-graben" morphology strongly suggests normal displacements along the fault planes. This is in agreement with borehole data which indicate normal offsets of the Ryukyu Limestone [*Yazaki and Oyama*, 1980].

Outcrop-scale faults in the Shimajiri Group (two localities

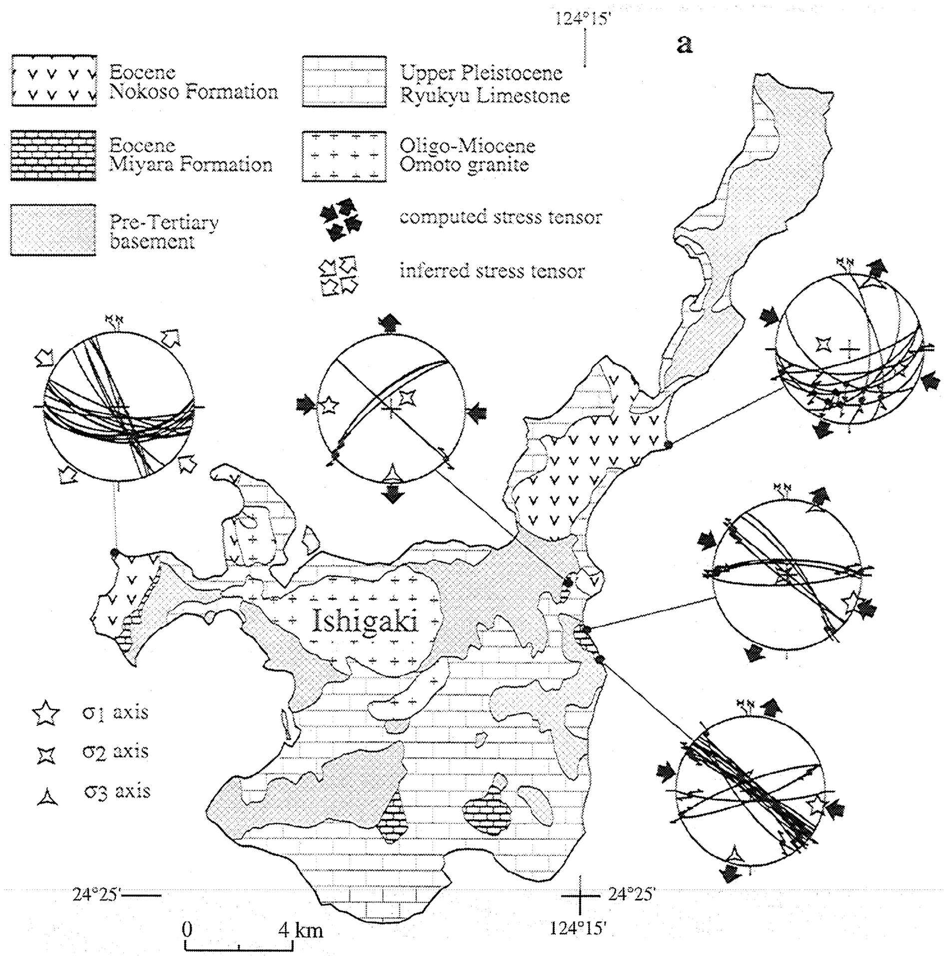

Figure 5. Outcrop-scale fractures at Ishigaki (geology after *Kizaki* [1985]): (a) fractures pertaining to intermediate-type stress field and (b) fractures pertaining to tensional stress field.

in Figure 4) strike about N45°E and dip preferentially to the northwest. Striation-bearing planes consist of normal faults. Computed stress tensors give $\sigma_V = \sigma_1$ and $\sigma_{H\min} = \sigma_3$ along N130°E. Fractures in the Ryukyu Limestone could be examined at only one site (Figure 4). They consist of extensional joints striking N0° to N30°E, with an average strike about N5°E. The inferred direction of extension, N95°E, is at odds with the N60°E post-Ryukyu Limestone extension inferred from the trend of fault scarps. The N60°E direction is likely more representative of the post-Ryukyu Limestone extension at Miyako than the N95°E one is, given the local character of this latter trend and the absence of any slip indicator on the concerned fractures.

4.3. Ishigaki Island

Fractures at Ishigaki were observed in the Eocene Miyara and Nokoso Formations and fall into two types: strike-slip faults and shear joints relevant to an intermediate-type stress field (Figure 5a) and normal faults and extensional joints pertaining to a tensional stress field (Figure 5b).

4.3.1. Intermediate-type stress field. Fractures associated with an intermediate-type stress field could be found in five localities: three sites in limestones of the Miyaragawa Formation and two sites in tuffs of the Nokoso Formation (Figure 5a). The three sites located in the Miyaragawa Formation display conjugate sets of strike-slip faults. Inversion gives $\sigma_v = \sigma_2$ and $\sigma_{H\max} = \sigma_1$ trending N90°E to N110°E. One of the Nokoso sites presents a mixing of strike-slip and normal faults, which inversion gives $\sigma_v = \sigma_2$ and $\sigma_{H\max} = \sigma_1$ along N110°E. The remaining site exhibits only joints which we interpret as being shear joints compatible with an horizontal σ_1 axis directed along N130°E.

4.3.2. Tensional stress field. Fractures relevant to a tensional stress field could be found in four sites: three sites in the Miyaragawa Formation and one site in the Nokoso Formation (Figure 5b). Computed or inferred tensors are characterized by $\sigma_V = \sigma_1$ and $\sigma_{H\min} = \sigma_3$ trending between N130°E and N160°E.

4.4. Iriomote Island

The fractures observed at Iriomote are restricted to extensional joints in two localities in the Yaeyama Group (Figure 6). The joints strike N50°E to N110°E, and the inferred extension axes trend N150°E to N170°E.

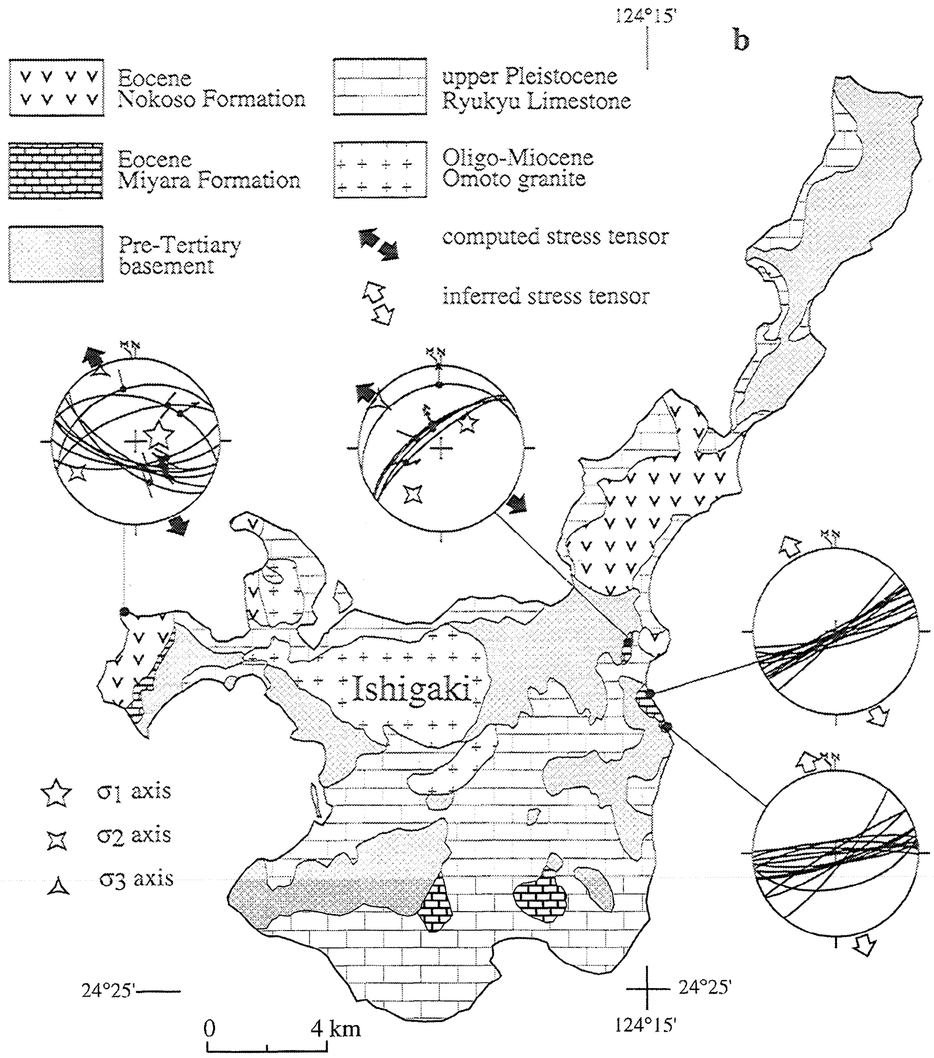

Figure 5. (continued)

4.5. Yonaguni Island

As clearly seen on air photographs, the morphology of the Yonaguni Island is characterized by a series of blocks limited by fault scarps. The originally horizontal topographical surface of the tabular Ryukyu Limestone is tilted a few degrees toward the south. Faults scarps can be followed in the Ryukyu Limestone but often constitute the contact between the limestone and the Yaeyama Group. They are a few meters to about 50 m and face mainly north or northwest (Figure 7). Two groups of faults can be distinguished: faults trending about N60°E (from N60°E to N75°E) and faults trending approximately E-W (from N80°E to N120°E). E-W faults bound half grabens or grabens filled with Holocene sands, silts, and gravels (Urabu Beds), indicating concurrent normal faulting, block tilting, subsidence, and deposition [*Sakai et al.*, 1978]. Such an association between fault activity and sedimentation is less frequent for the N60°E faults. Northeast of Kubura, a N60°E trending fault abuts against an E-W trending fault, suggesting anteriority of N60°E faults. These observations allow us to conclude to the succession of two stages of extension: an older, N150°E extension at the origin of the N60°E faulting in the Ryukyu Limestone and Yaeyama Group and a younger, N-S extension responsible for the E-W faulting and southward tilting of the Ryukyu Limestone. This last stage of extension was coeval with the deposition of the Holocene Urabu Beds and likely reactivated older N60°E faults.

Outcrop-scale data were collected in the Miocene Yaeyama Group (seven sites) and in the Holocene raised reef limestone (two sites located near Hikawa along the southern coast, Figure 7). In the Yaeyama Group, fractures are predominantly joints or faults with rare slip indicators. Stress tensor inversion could be done only for two sites and gives $\sigma_V = \sigma_1$ and $\sigma_{H\min} = \sigma_3$ along N130°E to N140°E. For the other sites, the inferred stress tensors are quite similar: $\sigma_V = \sigma_1$ and $\sigma_{H\min} = \sigma_3$ along N130°E to N145°E.

Extensional joints in the Holocene raised reef limestone strike N70°E to N100°E and suggest a N170°E to N5°E extension. This N-S extension departs from the NW-SE extension recorded in the Yaeyama Group and confirms the

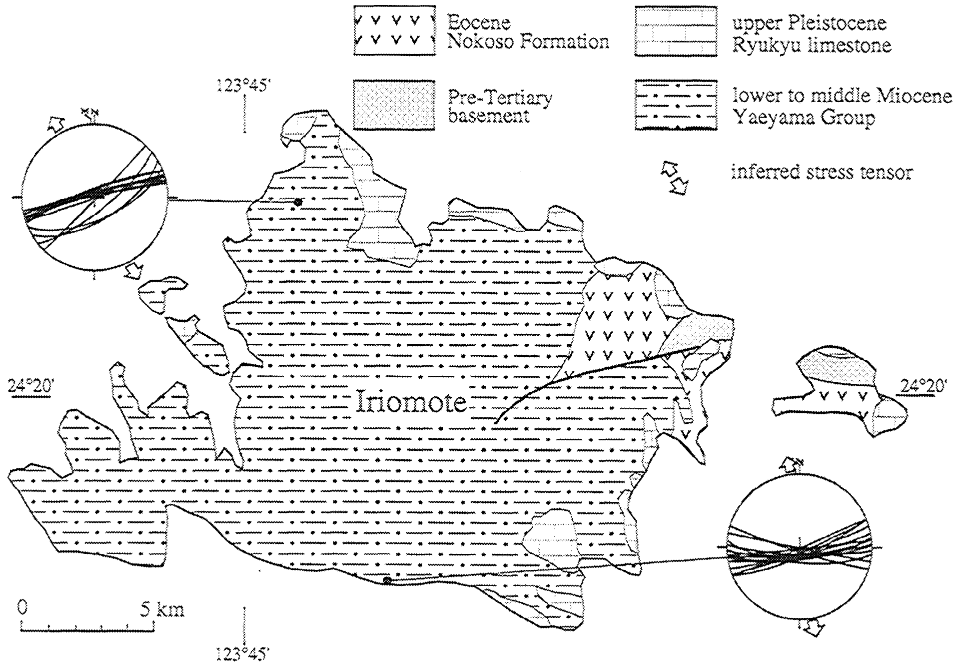

Figure 6. Outcrop-scale extensional joints at Iriomote (geology after *Kizaki* [1985]).

existence of two stages of extension, at least at Yonaguni: a NW-SE extension recorded in Miocene to Pleistocene strata and a N-S Holocene extension.

4.6. Synthesis of On-Land Deformation

4.6.1. Pre-Miocene Intermediate-Type Stress Field (Figure 8a). Fractures in the Eocene Miyara and Nosoko Formations allow us to reconstruct an intermediate-type stress field ($\sigma_V = \sigma_2$, Figure 5a), which cannot be traced in younger strata. The σ_1 axis trends N90°E to N110°E. After correction of the late Miocene CW rotation of 25° [*Miki*, 1995], these trends occur between N65°E and N85°E (Figure 8a).

4.6.2. Miocene to Quaternary Tensional Stress Fields (Figure 8b and 8c). Tensional stress fields are recorded on the four surveyed islands (Figures 4, 5b, 6, and 7). Relevant structures include normal faults and extensional joints. In the six localities (two for each island except Iriomote) where fault-slip data are sufficient to allow computation, stress inversion gives a subvertical σ_1 axis and a σ_3 axis trending N130°E to N150°E in pre-Holocene formations. The remaining fourteen sites exhibit mainly joints with some normal or oblique-slip faults. Such fracture systems do not allow stress computation; they, nevertheless, suggest extension axes trending about N135°E to N150°E in pre-Holocene strata in the three southernmost islands (Figure 8b). At Miyako, a N60°E extension is deduced from fault scarps in the late Pleistocene Ryukyu Limestone. At Yonaguni, extensional joints in the Holocene raised reef limestone indicate a N170°E to N185°E extension (Figure 8c).

This allows us to distinguish at least two tectonic stages: a pre-Holocene stage characterized by a N135°E to N150°E extension for all islands and a Holocene stage for which the direction of extension trends roughly N-S (arc perpendicular) for the southernmost island of Yonaguni. The arc-parallel (N60°E) extension at Miyako is not tightly dated. It is recorded in the Pleistocene Ryukyu Limestone and is similar to the present-day stress field near Miyako as suggested by focal mechanisms (see section 3 and Figure 3). A Holocene age is probable.

5. Extension Axes Deduced From Offshore Investigations

Interpretation of SeaBeam maps and single-channel seismic reflection profiles allowed *Sibuet et al.* [1995] to recognize the succession of three extensional stages which are in the southern Okinawa Trough: (1) a middle to late Miocene extensional event responsible for the formation of N55°E trending normal faults; (2) a late Pliocene to late Pleistocene extension at the origin of N80°E trending normal faults; and (3) a Holocene to Recent extension characterized by N90°E trending normal faults. The total amount of horizontal extension in the southern Okinawa Trough is estimated to about 88 km, of which 85%, 9%, and 6% would have been accommodated by normal faulting during events 1, 2, and 3, respectively. If taken perpendicular to the average trend of the normal faults, the direction of extension for each event shows a clockwise rotation through time from N145°E (event 1) to N170°E (event 2) and to N180°E (event 3). This succession of extensional events recalls the succession deduced from the on-land fracture investigation (Figures 8b and 8c). Event 1 can be identified to the NW-SE extension recorded in the Miocene to Pliocene deposits, while event 3 likely corresponds to the N170°E to N180°E extension recorded in the Holocene raised reef limestone. Event 2 cannot be traced on land with enough

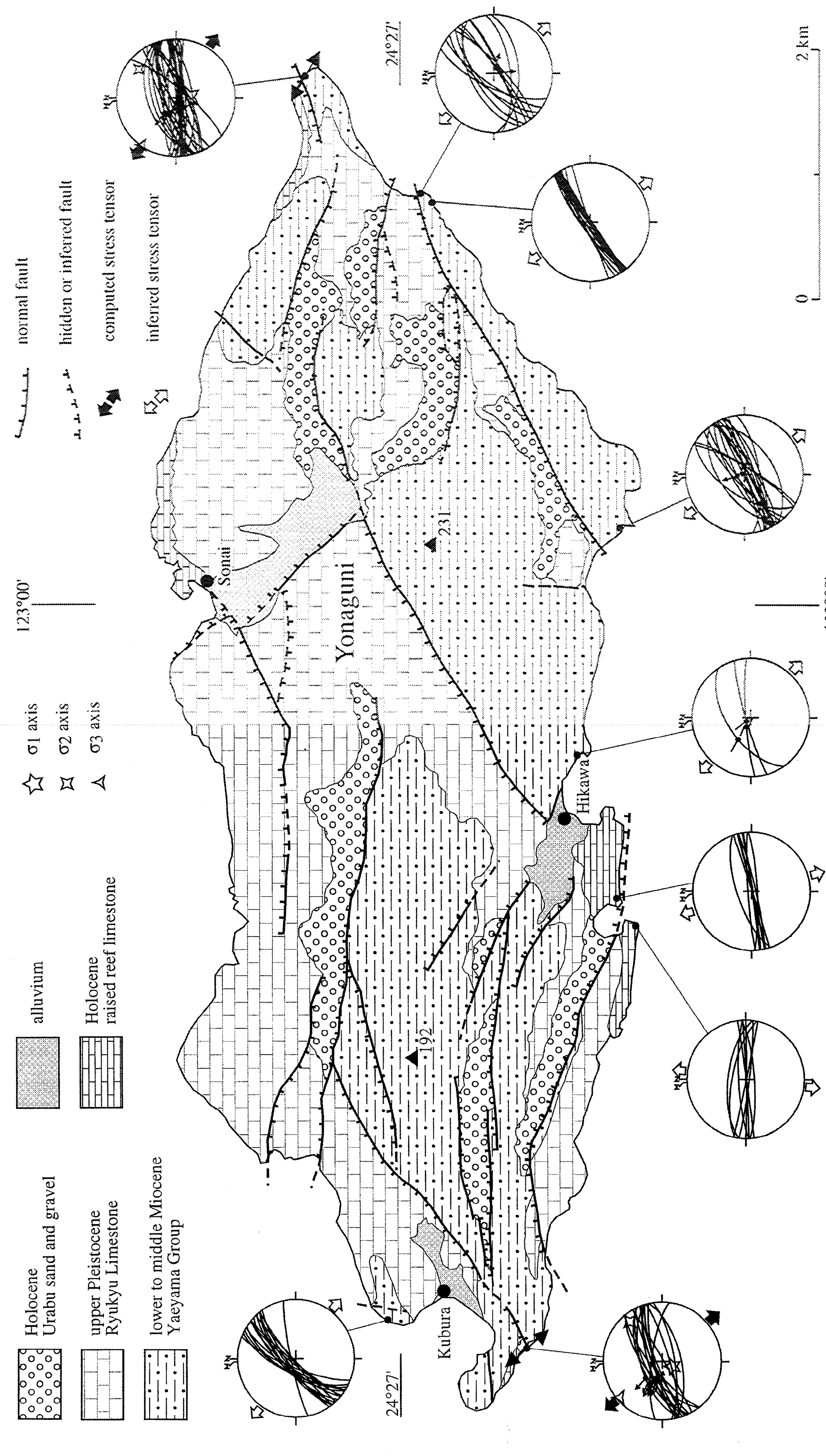

Figure 7. Regional fault patterns deduced from air photograph analysis and outcrop-scale fractures at Yonaguni (geology after *Sakai et al.* [1978]).

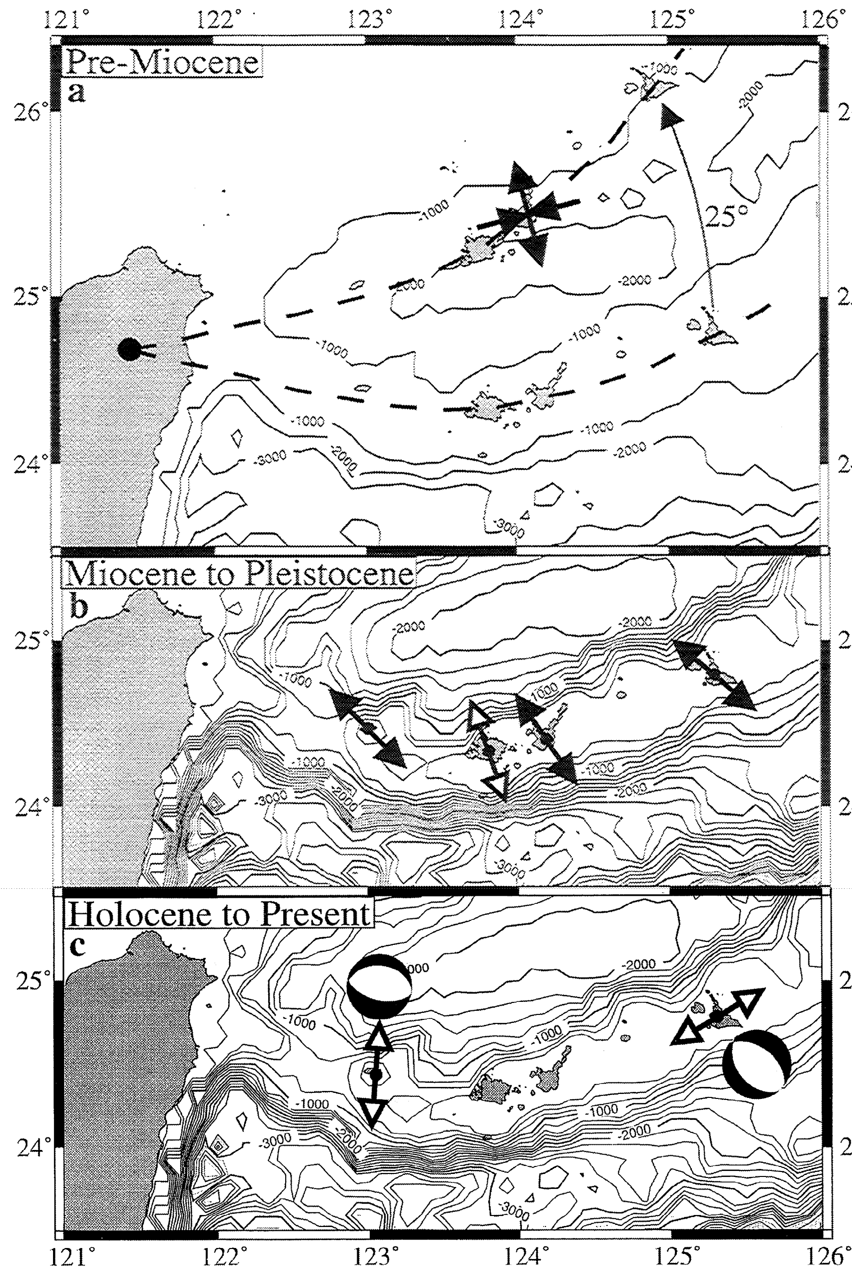

Figure 8. Trends of σ_1 and σ_3 axes computed (solid arrows) or inferred (open arrows) from fracture analysis. Also plotted are two focal mechanisms representative of the local shallow seismicity. Pre-Miocene trends have been corrected by taking into account the paleomagnetic results of *Miki* [1995] with a rotation pole located in northern Taiwan (solid dot).

confidence because of the lack of fault-slip data in the Pleistocene Ryukyu Limestone.

6. Discussion

6.1. Is the Southern Ryukyu Arc a Forearc Sliver?

We did not find any outcrop-scale structure indicative of strike-slip or shortening deformation in Miocene or younger strata in the surveyed islands. All fractures consist of either normal faults or extensional joints. At a broader scale, the morphological patterns observable on air photographs of Miyako and Yonaguni do not suggest anything but normal faulting. In particular, no en échelon structure (fault, graben, or fold) can be detected on land. In other words, our analysis shows that strike-slip tectonics have not been active in the southern Ryukyu arc since the Miocene, that is to say, since crustal thinning has been underway in the southern Okinawa Trough.

This leads us to question the validity of the forearc sliver model proposed by *Kuramoto and Konishi* [1989] for the southern Ryukyu arc. Indeed, a forearc sliver is mechanically decoupled from the back arc region through the means of one or several strike-slip faults, and the stress field is expected to be of intermediate type. In the present case, no strike-slip fault of regional importance could be recognized or inferred onshore (this study) [see also *Kizaki*, 1985]. Available SeaBeam mapping and seismic profiling have not revealed any transcurrent discontinuity offshore between the southern Ryukyu arc and the southern Okinawa Trough [*Sibuet et al.*, 1987, 1995]. In our opinion, the arc-parallel extension evidenced at Miyako (regional faults and focal mechanisms of two earthquakes) does not reflect the separation of the southwestward migrating southern Ryukyu arc but rather represents a local response to the increasing curvature of the whole arc accompanying the still active back arc extension. Strike-slip tectonics, if any, should be looked for oceanward of the southern Ryukyu arc where they would affect a quite limited part of the plate. Recently obtained offshore seismic profiles suggest the existence of a trench-parallel dextral strike-slip fault cutting the top of the accretionary wedge [*Lallemand et al.*, 1997].

Another condition which can favor the formation of a forearc sliver lies in a strong interplate coupling [e.g., *Jarrard*, 1986]. This condition is not met in the case of the southern Ryukyu arc. Indeed, the absence of major shallow earthquakes at the plate interface in the Ryukyu region attests to a weak interplate coupling [*Kao and Chen*, 1991].

6.2. Pre-Neogene Strike-Slip Tectonics in the Southern Ryukyu Arc

The record of an intermediate-type ($\sigma_V = \sigma_2$) stress field in Eocene rocks at Ishigaki indicates that strike-slip tectonics were active there during or after the Eocene and before the Miocene. In present geographical coordinates, the σ_1 axis trends N90°E to N110°E (Figure 5a); in pre-Miocene coordinates, this trends becomes N65°E to N85°E.

For the period ranging from 45 or 43 Ma (minimum age of deposition of the Nosoko Formation) to 20 Ma (approximate age of beginning of deposition of the Yaeyama Group), the paleogeographic reconstitutions [e.g., *Seno and Maruyama*, 1984; *Engebretson et al.*, 1985; *Jolivet et al.*, 1989; *Hall*, 1996] agree on the subduction in the study area of an oceanic plate beneath the Eurasia plate. However, two parametres remain poorly constrained: (1) the direction of relative convergence and (2) the age and nature of the crust (purely oceanic or laid out by plateaus) of the descending lithosphere. Only the knowledge of these two crucial data will allow us to discuss further the significance of the pre-Miocene intermediate-type stress field.

7. Conclusion

Fracture analysis in the southern Ryukyu arc brings a coherent picture of the stress history since the Eocene. A pre-Miocene intermediate-type stress field is recorded in Eocene rocks of Ishigaki Island. Neogene to Quaternary strata recorded only tensional stress fields. The determined or inferred directions of extension, taken parallel to σ_{Hmin}, are either perpendicular to the local trend of the arc or parallel to it. The first case shows that back arc rifting also affects the arc itself; arc-parallel extension is likely a response to the increasing curvature accompanying back arc rifting.

Our study does not support the results obtained by *Kuramoto and Konishi* [1989]. We have not recognized any onshore structure which could suggest strike-slip or reverse-slip deformation in the Neogene or Quaternary strata of the southern Ryukyu arc, whatever the scale. In the study area, morphological evidence as well as fault-slip data indicate nothing but normal faulting. The forearc sliver model may not be appropriate for the southern Ryukyu arc which seems to be still a part of the Eurasia plate.

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O. Fabbri, Département de Géosciences, UFR Sciences et Techniques, Université de Franche-Comté, La Bouloie, 25030 Besançon Cedex, France. (olivier.fabbri@univ-fcomte.fr)

M. Fournier, Département de Géotectonique, Université Pierre et Marie Curie, Case 129, 4 place Jussieu, 75252 Paris Cedex 05, France. (fournier@lgs.jussieu.fr)

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