Miocene to Pleistocene stress field transitions, around the Miyako-jima Island, South Ryukyu, Japan

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Abstract

Three paleostress transitions are measured in Miyako-jima Island. NW-SE and NE-SW extensions are recorded in the Simajiri Group. Strike-slip type stress state where σ_1 directs to N-S and σ_3 directs to E-W, is recorded in the Ryukyu Group. Transition of paleostress is considered as follows. Before the sedimentation of the Shimajiri Group, NW-SE extension occurred in the Miyako-jima because the Miyako-jima was extended toward the Ryukyu Trench by the trench retreat during the subduction of the Philippine Sea plate. During the sedimentation of the Shimajiri Group, the arc-parallel stretching occurred in the Miyako-jima because the Okinawa Trough started to push the Miyako-jima toward the Ryukyu Trench. Then NE-SW extension occurred in the area. During the sedimentation of the Ryukyu Group, strike-slip type stress state occurred by the sinistral strike-slip movement along the central rift in the Okinawa Trough.

1. Introduction

In the area of plate convergence, oblique subdution is thought to induce various stress field within the edge of the overriding plate (Fuch, 1972; Beck, 1983; Jarrard, 1986; Yu et al., 1993). In the northwestern edge of the Philippine Sea (Fig. 1), Ryukyu arc-trench system is characterized by the subduction of the Philippine Sea plate beneath the Eurasia plate and by the crustal extension in the Okinawa Trough (Aiba and Sekiya, 1979; Lee et al., 1980; Kimura, 1985; Letouzey and Kimura, 1985, 1986; Sibuet et al., 1987). A small island Miyako-jima is located in the north of South Ryukyu. Many meso-scale faults are found in the island (Yazaki and Oyama, 1980). Many meso-scale faults are used to measure the direction of principal stress axes. Once the stress field is drawn, we could explain the tectonics around the island. Although the classical technique of stress analysis using conjugate faults was used in the last two decades, new inversion stress analysis technique (Angelier,

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1979, 1984) becomes the main method. Regarding to the Ryukyu Arc, Fabbri and Fournier (1999) have obtained NW-SE extension by the inversion method at Tanegashima Island in North Ryukyu. We think their study is insufficient to clear the paleostress field around the Ryukyu Island Arc.

The aim of the paper is to measure meso-scale faults in Miyako-jima and to clear the stress field around the island by the inversion method.

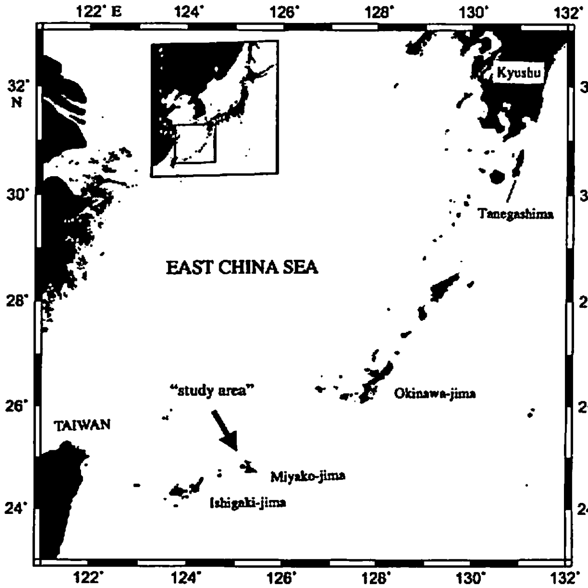

Fig. 1. Index map of the Miyako-jima.

2. Geological setting

Miyako-jima is the northernmost island of South Ryukyu, and lies about 250km southwest from Naha in Okinawa-jima and about 100km northeast from Ishigaki-jima (Fig. 1). The island shows a flat triangle with two equal sides (Fig. 2). The length of NW-SE side is about 30km. Several faults run along NW-SE and NNW-SSE in the island. Southwestern coast shows a steep scarp composed of the Ryukyu Group with a few meters to about 40 m in height.

Stratigraphy and structure

Geologic map and stratigraphy of the island are given in Fig. 2 and 3, respectively. The Shimajiri Group is the basement of the island, which consists of Miocene to lower Pleistocene strata, and is unconformably covered with the Ryukyu Group.

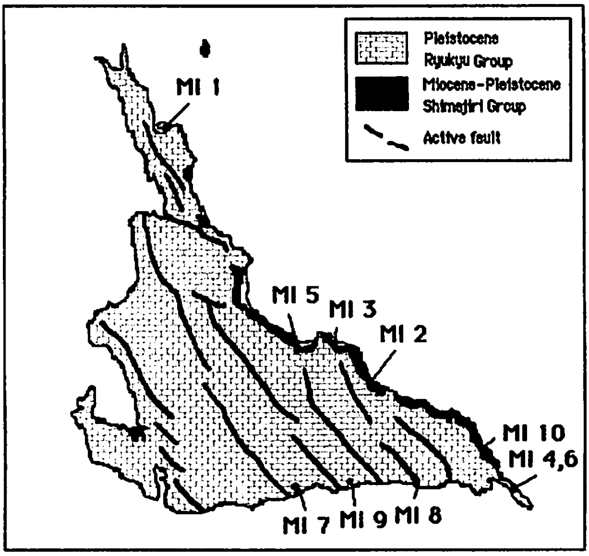

Fig. 2. Geological map of the Miyako-jima.

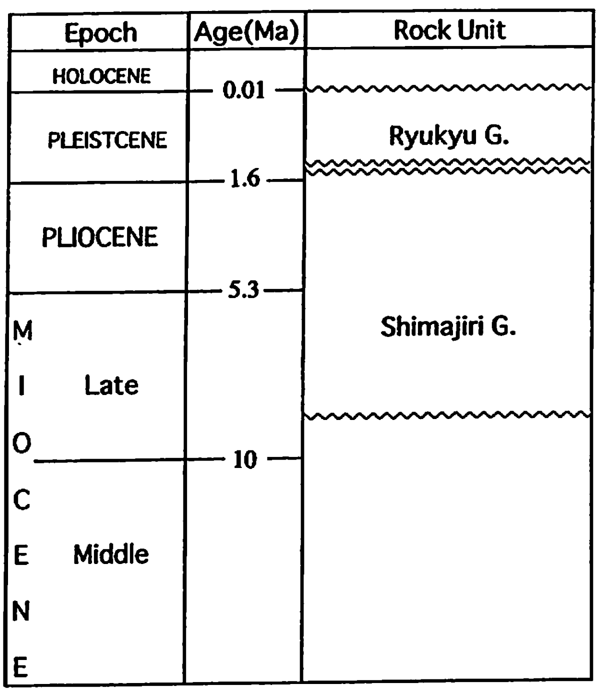

Fig. 3. Stratigraphy of the Miyako-jima.

2.1. *Shimajiri Group*

Base of the Shimajiri Group is exposed along the scarps of the eastern side of the island. It is difficult to observe the outcrop of the group in the southern side because of its steep scarps. The Shimajiri Group consists of mudstone and sandy mudstone, and shows soft to semiconsolidated state in one of the weathered outcrops. Outcrops show generally weathering in its upper part. Thick strata at several outcrops contain clay. In the alternation of sandy mudstone and mudstone, some sandy mudstone beds protruded by differential erosion. The Shimajiri Group shows the anticline whose fold axis directs to NE-SW and plunges to SW and whose wavelength is 4 to 6 km.

2.2. *Ryukyu Group (Ryukyu Limestone)*

The group covers extentively the island and its lithostratigraphic column is observed in the steep scarps of the southern coasts. The group consists of basal conglomerate, coral limestone, rudstone and floatstone from lower to upper, which shows transgressive facies from coarse size (deep) to fine (shallow).

The group shows anticline whose fold axis directs to NW-SE and which passes through the center of the island. Both limbs of the anticline dip 10 degrees. There are many faults whose offset is less than 30 m and whose strike is parallel to fold axes, and they show stair step shape. The anticline forms a low ridge hill of the island. The undulation of surface reflects the undulation of the basement of the island. Cuesta is characteristic to the Miyako-jima and is derived from the fault topography.

2.3. *Meso-scale faults in Miyako-jima*

Many meso-scale faults develop in the island and have a gap from few cm to 3 m. Most of them are normal faults, and reverse faults and strike-slip faults are a few. Many faults show NE-SW linear arrengement. One of the author could not reach to a few faults because weathering of outcrop progresses in both the Shimajiri and Ryukyu Group. Total 78 faults are measured along the southern and northeast coast.

3. Paleostress analysis

3.1. *Determination of paleosress derived from meso-scale faults*

Meso-scale faults means the one which can be observed in the scale of outcrop (Angelier, 1994). Meso-scale faults are frequently observed than macro-scale faults, and are easy to be measured amount and sense of displacement, and to be deduced their order of formation from "cut or be cut" relation. Meso-scale faults of this kind are used to measure the direction of principal stress axes. Relation of the regional stress field and geometric structure are discussed using the principal stress. If the principal stress axes show systematic trend, we consider to obtain the regional stress field with which tectonics around these are explained. The classic stress analysis method using conjugate faults was popular in Japan. It is found that the stress direction obtained by the classic method is correct only in a special case. If all faults are created in one tectonic period and are conjugate faults, plane strain state occurs in the perpendicular plane to σ_2 axis. Many faults are not always conjugated because the strain state is three-dimensional. Thus the classic method can not obtain correct stress field. The new methods which can treat with the three-dimensional stress are developed by Angelier (1979, 1984) and Marrett and Allmendinger (1990). The new method is called inversion method. The new methods are necessary to observe fault-slickenline and this is the different point from the classical one. In the inversion method, faults occur along the direction of shear stress (Wallace., 1951,

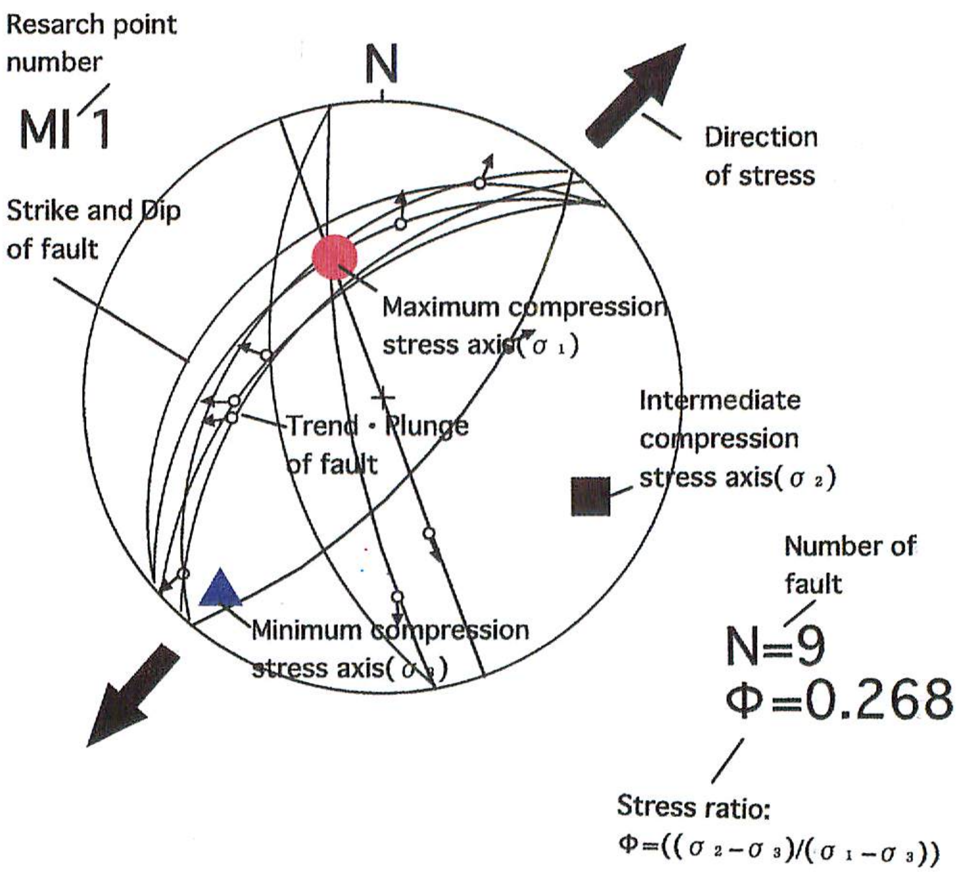

Fig. 4. Legend of paleostress analysis.

(a) Fault-slip data are projected to lower-hemisphere of equal-area net. N gives the number of slip vectors (slickenlines) measured at each site and used for computation. Small arrows on the fault planes indicate the sense of slip. Arrow head means that the sense of slip was determined with full confidence. The projection of the principal stress axes have the following symbols:circle (σ_1), square(σ_2), triangle (σ_3). The large divergent arrows outside the nets indicate the direction of extension and the large convergent arrows indicate the direction of compression.

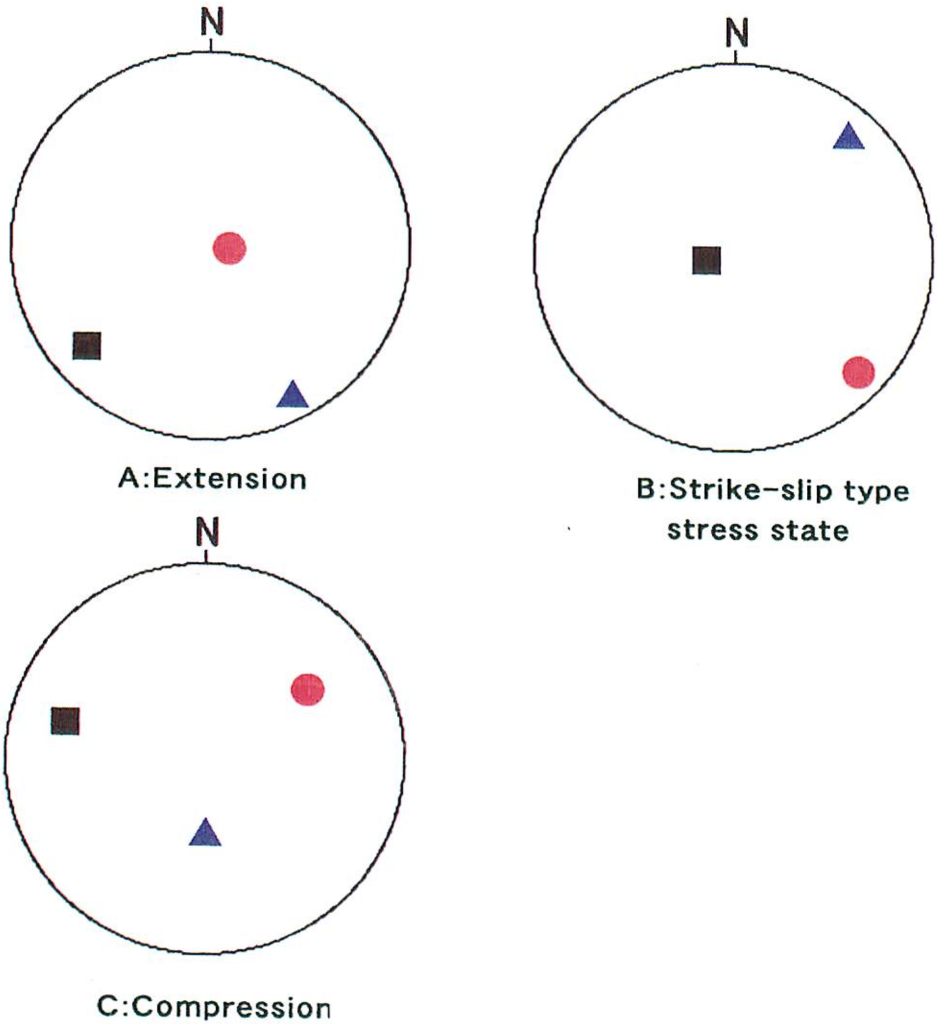

Fig. 4. (b) A, B, C show stress patterns. A ($\sigma_v \fallingdotseq \sigma_1$):extension (extensional type stress state). B ($\sigma_v \fallingdotseq \sigma_2$):strike-slip type stress state. C ($\sigma_v \fallingdotseq \sigma_3$):compression (compressional type stress state).

Bott., 1959). If we can measure slickenline on a fault plane, we knows the true sense of displacement of fault. For example, the fault which seems like a normal fault or a reverse fault is really an oblique fault or a strike-slip fault by measuring slikenline.

3.2. Method

Strike and dip of 78 faults (39 faults in the Shimajiri Group, 39 faults in the Ryukyu Group), and trend and plunge of slickenlines on the fault plane are measured along the southern and northeastern coast of Miyako-jima. Orientation of three principal stress axes are determined by using the freeware program of stress inversion method "TectonicVB" which is developed by H.Ortner.

3.3. Result

Figure 4 explains how the result of paleostress analysis is drawn on a Schmidt net. Great circles are the fault planes which show the strike and dip of faults and arrows are the trend and plunge of slikenlines. N is the number of faults in the measured points. Stress ratio Φ is described as $\Phi = (\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$ and shows the values between 0 and 1. Φ means whether σ_2 is near to σ_1 or σ_2 is near to σ_3. If Φ is equal to 0, then the stress state is axial symmetric ($\sigma_1 \geqq \sigma_2 = \sigma_3$). If Φ is equal to 1, stress is the other axial symmetric ($\sigma_1 = \sigma_2 \geqq \sigma_3$). If Φ shows intermediate value ($0 < \Phi < 1$), it shows three axial stress. Symbols ●, ■, ▲ in the circles show principal stress axes; ● shows maximum compressive stress axis (σ_1), ■ shows intermediate compressive stress axis (σ_2) and ▲ shows minimum compressive stress axis (σ_3). If ●(σ_1) shows near the center, we call this stress state as extension. Otherwise ■(σ_2) shows near the center, the stress state is called as strike-slip type stress state. While ▲(σ_3) shows near the center, stress state is compression. The black arrows outside the circles indicate the directions of paleostress.

3.3.1. Stress field of the Shimajiri Group

Total 39 faults of 5 sites are measured (MI 1~MI 5) in the Shimajiri Group. 4 sites of them corresponds to extension ($\sigma_v \fallingdotseq \sigma_1$). Directions of extension (σ_3) are NE-SW and NW-SE. We exclude stress state in MI 2 which is compression ($\sigma_v \fallingdotseq \sigma_3$), because the state is considered a local stress state. Stress state in MI 3 and MI 5 is NW-SE extension where Φ values are from 0.387 to 0.784. Stress state in MI 1 and MI 4 is NE-SW extension where Φ values move from 0.268 to 0.481 (Fig. 5, table 1).

3.3.2. Stress field of the Ryukyu Group

Total 39 faults of 5 sites are measured (MI 6~MI 10) in the Ryukyu Group. Stress state of MI 9 is NE-SW extension ($\sigma_v \fallingdotseq \sigma_1$; $\Phi = 0.014$) which is also observed in MI 1 and MI 4 of the Shimajiri Group. Stress state of 4 sites except for MI 9 is strike-slip type. Stress state in MI 7 and MI 8, is strike-slip type stress state where σ_1 directs to NNW-SSE. State of MI 6 and MI 10 is strike-slip type stress state where σ_1 directs to NNE-SSW. For the sake of simplicity, these two strike-slip type stress states are reduced to one strike-slip type stress state where σ_1 directs to N-S and σ_3 directs to E-W. Φ values range from 0.513 to 0.712 (Fig. 6, table 1).

3.3.3. Summary of stress field

Directions of extension (σ_3), NW-SE and NE-SW, are apparently recorded in the Shimajiri Group. Strike-slip type stress state where σ_1 directs to N-S and σ_3 directs to E-W, is recorded in the Ryukyu Group (Fig. 6).

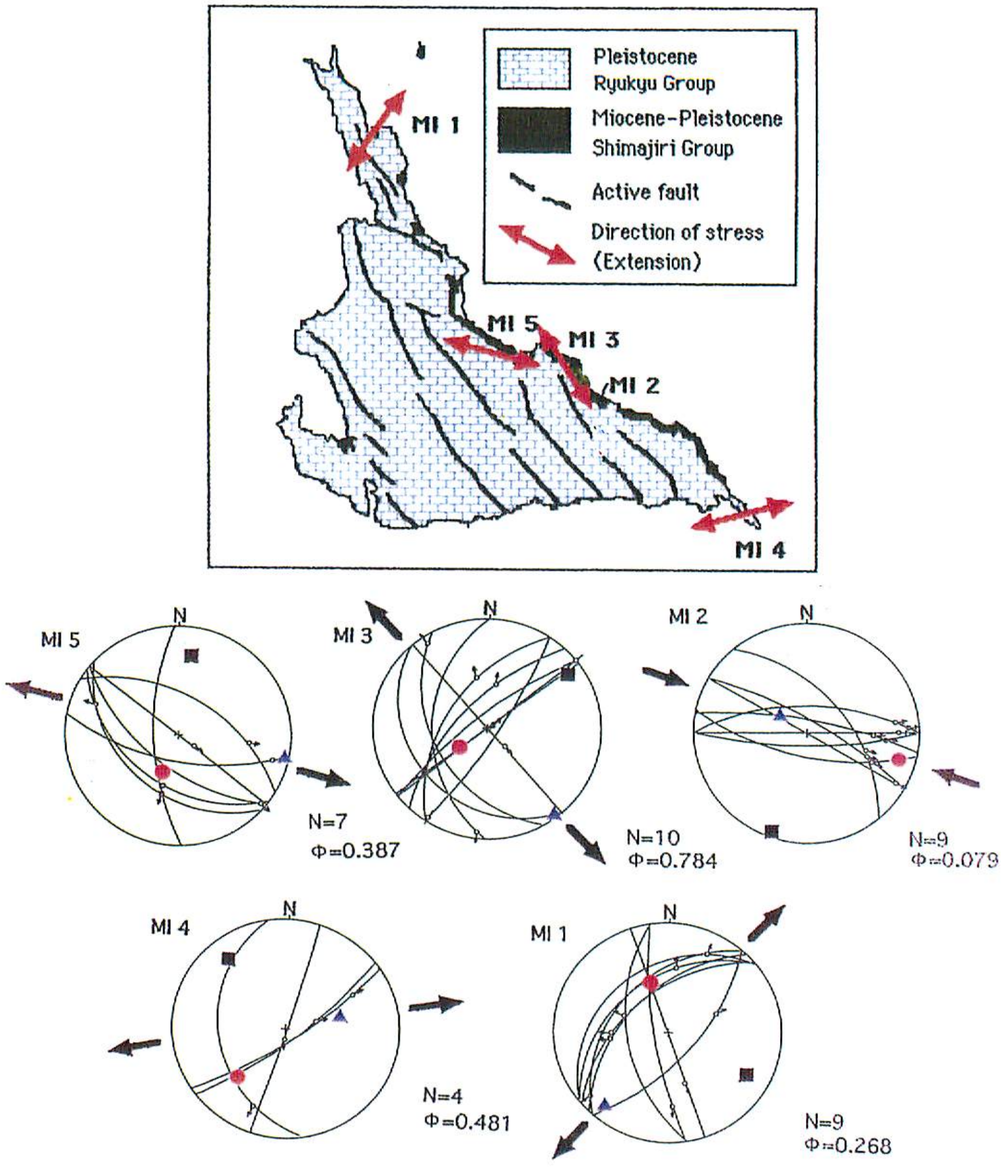

Fig. 5. Fault-slip data collected in the Shimajiri Group and attitudes of principal stress axes deduced from direct inversion method. Symbols are as Fig.4

Teble 1. Trend and plunge of principal stress axes and Φ computed from fault-slip data (striation and sense).
N is the number of fault-slip data used for computation at each site. Φ is the ratio $(\sigma_2-\sigma_3)/(\sigma_1-\sigma_3)$.

Site	N	Rock Unit	σ_1 T(°)-P(°)	σ_2 T(°)-P(°)	σ_3 T(°)-P(°)	Φ
MI 1	9	Shimajiri G.	339-51	121-32	224-18	0.268
MI 2	9	Shimajiri G.	104-21	197-7.0	305-67	0.079
MI 3	10	Shimajiri G.	241-72	54-17	144-2.0	0.784
MI 4	4	Shimajiri G.	224-38	325-13	71-47	0.481
MI 5	7	Shimajiri G.	260-67	4.0-26	102-4.0	0.387
MI 6	8	Ryukyu G.	8.0-14	227-71	101-11	0.552
MI 7	12	Ryukyu G.	174-14	326-74	82-7.0	0.513
MI 8	8	Ryukyu G.	351-23	222-55	92-23	0.640
MI 9	5	Ryukyu G.	134-67	306-22	37-2.0	0.014
MI 10	6	Ryukyu G.	4.0-26	246-43	115-35	0.712

Since we want more clear stress field transition, we need in the future the detailed measurements in Miyako-jama and obtain more data of paleostress analysis in South Ryukyu (Ishigaki-jima, Yonaguni-jima and others).

4. Discussion

In Miyako-jima, these are two extensional stresses (σ_3), one is directs to NW-SE, and the other to NE-SW in the Shimajiri Group. There is also a strike-slip type stress state where σ_1 directs to N-S, and σ_3 directs to E-W in the Ryukyu Group. Figure 7 shows the relation of these three paleostresses where red arrows are the results of paleostress direction. We consider the stress field transition as follows without direct evidence of the order of fault formation.

NE-SW extensions are found in both the Shimajiri Group and the Ryukyu Group, though NW-SE extensions are found only in the Shimajiri Group. Thus, we consider that NE-SW extension occurred later than NW-SE extension. Because strike-slip type stress state obtained from the Ryukyu Group are not found in the Shimajiri Group, strike-slip type stress state are found later than NE-SW extension stress state.

Thus, we consider that the order of stress transition is NW-SE extension, NE-SW extension and strike-slip type stress state from older to newer.

4.1. NW-SE extension in the Shimajiri Group

Before the sedimentation of the Shimajiri Group, the Philippine Sea plate subduct

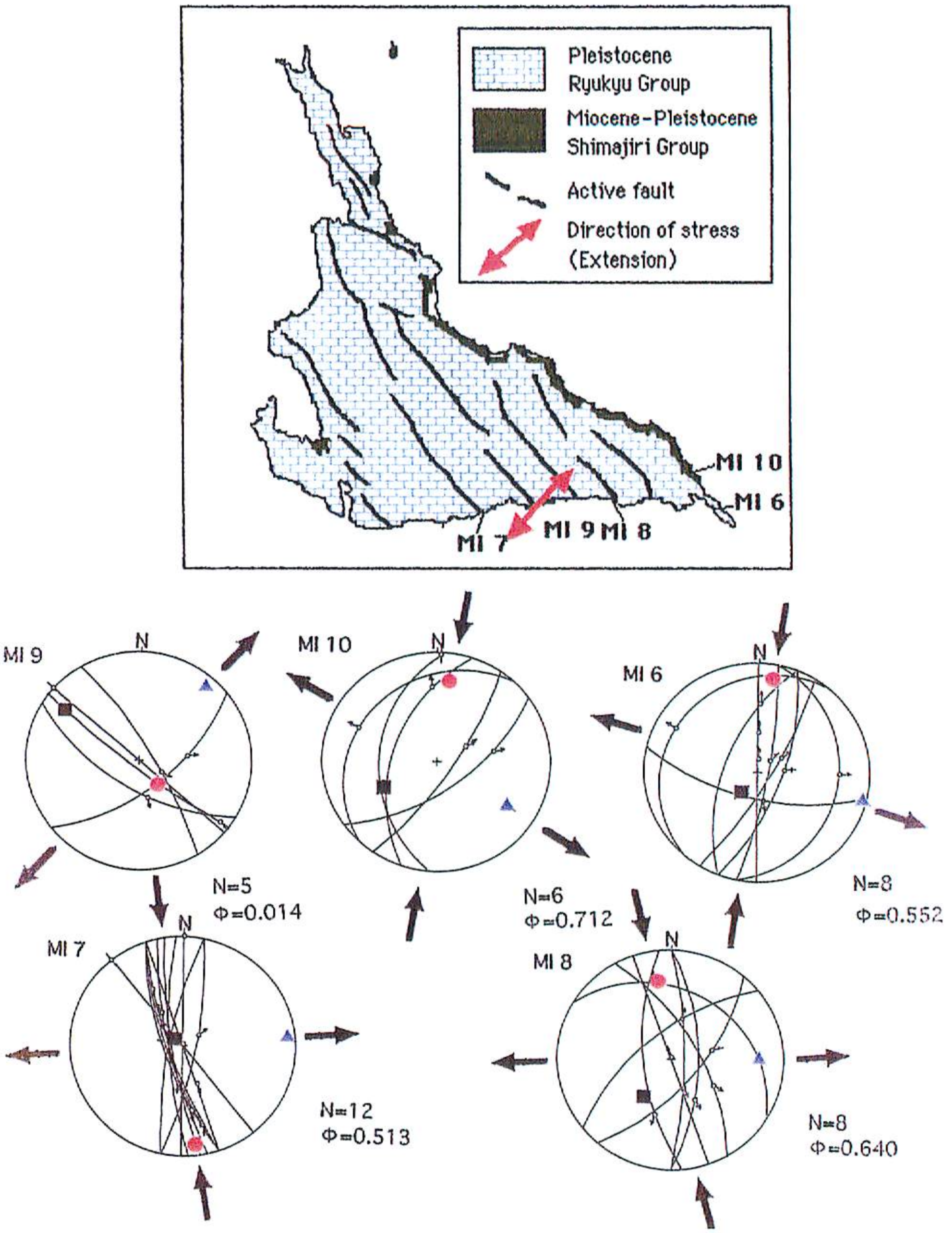

Fig. 6. Fault-slip date collected in the Ryukyu Group and attitudes of principal stress axes deduced from direct inversion method. Symbols are as Fig.4.

beneath the Eurasia plate to NW at speeds of 9～10cm／yr (Seno et al., 1993) to produce "trench retreat" (Hu.J.C et al., 1996), which is the cause of the NW-SE extension stress state in MI 3 and MI 5.

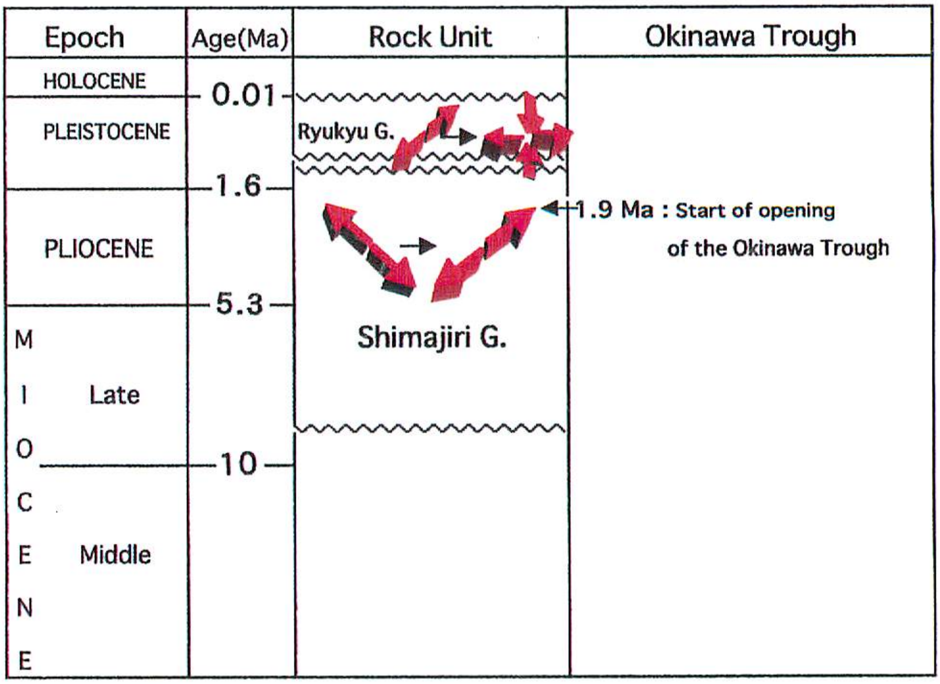

Fig. 7 . Paleostress transition in the Miyako-jima.

4.2. NE-SW extension in the Shimajiri Group

NE-SW extension is apparently recorded in MI 1 and MI 4 because NE-SW extension occurred by the effect of the expansion of the Okinawa Trough. The Okinawa Trough which is expanding in present, runs parallel to the western Ryukyu Arc in the East China Sea, and is considered the back-arc basin or the early shape of the back-arc basin of the Ryukyu Arc.

The area around Miyako-jima was pushed to the Ryukyu Trench by the expanding of the Okinawa Trough. As this area migrates oceanwards, its initial length increases and arc-parallel stretching (Fabbri,O., 2000) follows in response to this increase. Thus NE-SW extension occurred in the area around Miyako-jima. NE-SW extension is also observed in the middle Miocene Kukinaga Group of Tanegashima island 500 km northeast from the Miyako-jima island. Present expanding of the Okinawa Trough started before 1.9 Ma (Letouzey,J and Kimura,M., 1986) and from before 1.9 Ma, the area around Miyako-jima was pushed slowly to the Ryukyu Trench which extends parallel to the Ryukyu Arc.

4.3. Strike-slip type stress state in the Ryukyu Group

NE-SW extension is recorded at MI 9 in the Ryukyu Group. This shows that NE-SW extension observed in the Shimajiri Group continues during the sedimentation of the Ryukyu Group.

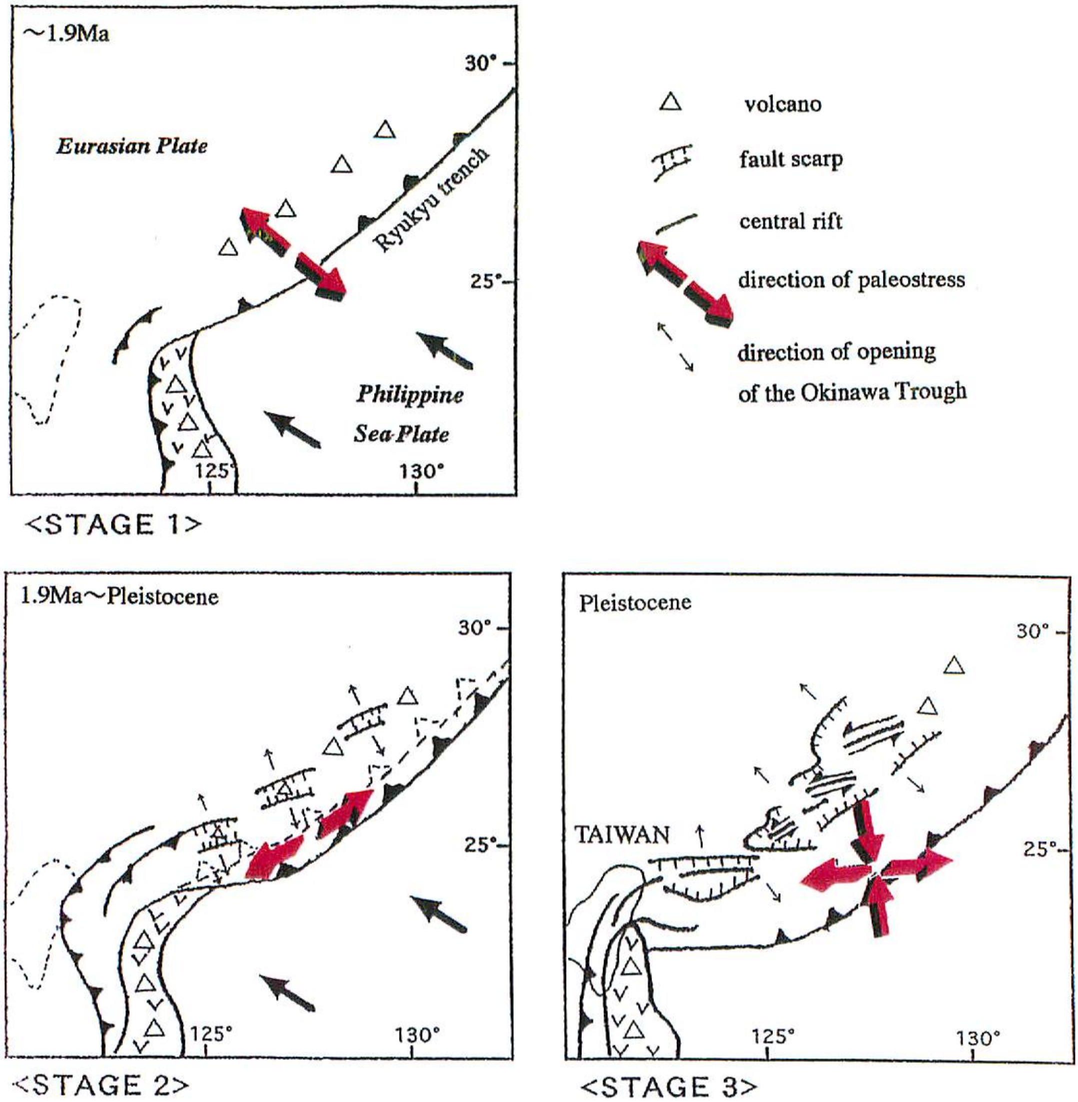

Fig. 8. Schematic diagram to show the tectonic evolution around Miyako-jima with paleostress transition.

In the Ryukyu Group, we find strike-slip type stress state where σ_1 direct to N-S, and σ_3 directs to E-W. We think that the sense of the strike-slip stress state is sinistral from the direction of slickenline on meso-scale fault planes. We infer that the sinistral strike-slip type stress state occurred by the oblique subduction of the Philippine Sea plate at Pleistocene (sedimentation period of the Ryukyu Group). On the contrary, it is found that such oblique subduction do not occur from the result of GPS observation (Kotake, 1998). There is active fault called "central rift" in the Okinawa Trough. If the sinistral strike-slip faults occur in the central rift, strike-slip type stress state occurs around the Miyako-jima. Thus the strike-slip type stress state is caused by the sinistral movement of the central rift.

5. Conclusion

Results of the paleostress analysis in the Miyako-jima are concluded as follows (Fig. 8). Before the sedimentation of the Shimajiri Group, NW-SE extension occurred in the study area because the Miyako-jima and the area around the island on the Eurasia plate was extended toward the Ryukyu Trench (southeast) by the trench retreat during the subduction of the Philippine Sea plate (stage 1). During the sedimentation of the Shimajiri Group (1.9 Ma), the arc-parallel stretching occurred in the area around Miyako-jima because the Okinawa Trough started to push the area to the Ryukyu Trench toward (southeast). Therefore NE-SW extension occurred in this area (stage 2). During the sedimentation of Ryukyu Group, strike-slip type stress state where σ_1 directs to N-S and σ_3 directs to E-W, occurred by the sinistral strike-slip movement of the central rift (stage 3).

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