Paleostress transition by fault-striation analysis in the northern and central Ryukyu arc, southwest Japan

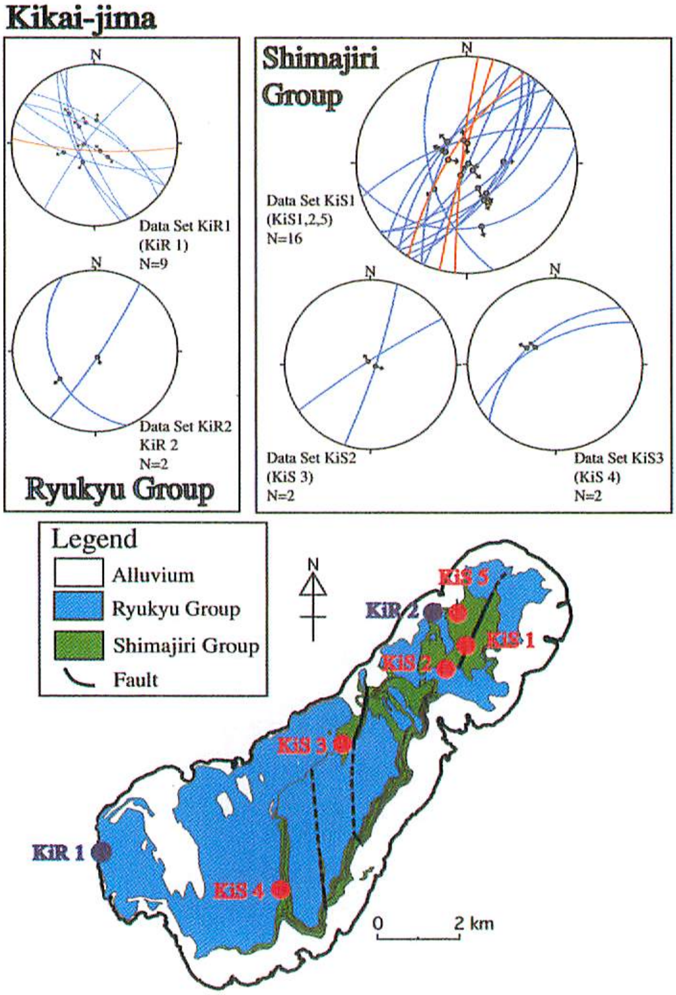

Fig.13. Fault-slip data collected in the Kikai-jima. Other explanations are same as in Fig.4.

formation belong to dip-slip normal fault. The strikes of these faults within these formations are NW-SE.

5. Result

Paleostress fields in the northern and central Ryukyu arc have been calculated using the Multi-inverse method (Yamaji, 2000) and Ginkgo method (Yamaji, 2003a). The multi-inverse method with k=5 is applied to most of the data sets. Several data sets are calculated by the Ginkgo method because the data sets include too few fault data to calculate by the Multi-inverse method. Figures 16 to 27 where clusters are labeled as A, B, C …, show the calculated stress states for every formations in surveyed islands. Though the strata of collected fault-slip data in the study area are gently tilted, tilting

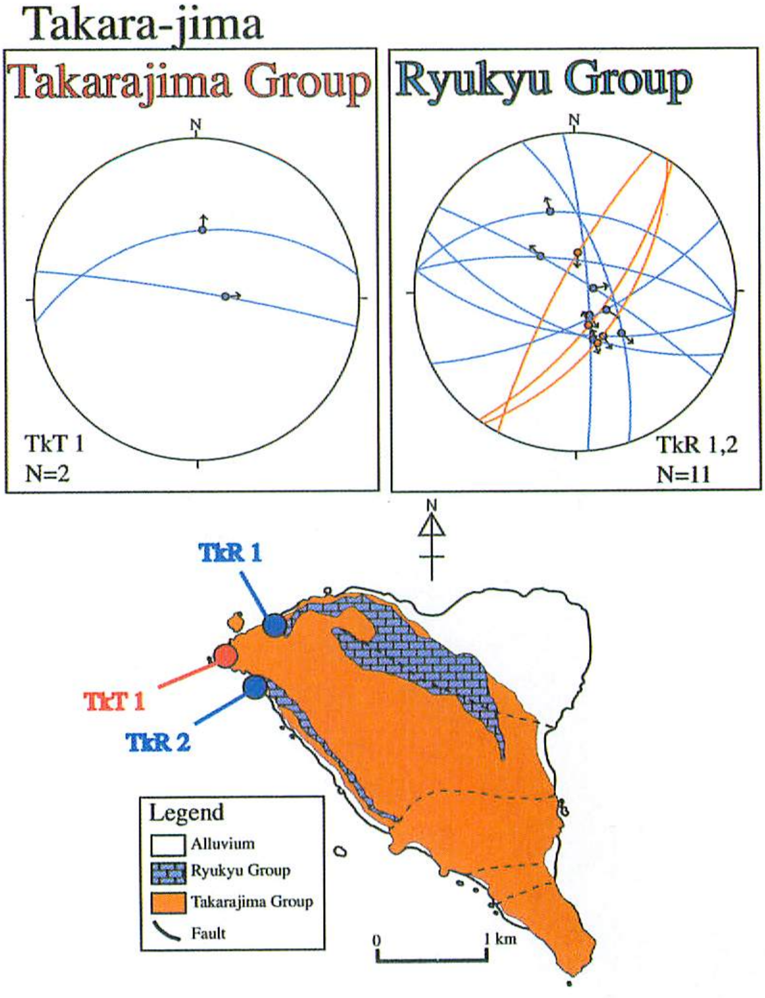

Fig.14. Fault-slip data collected in the Takara-jima. Other explanations are same as in Fig.4.

corrections are not performed for all the data. "Stress state" is sometimes described as "stress" hearafter.

5.1. Okinawa-jima

Results of fault-striation analysis in the Okinawa-jima are shown in Figs. 16-19. Calculated significant stresses from the Multi-inverse method are represented by the clusters of dot with bar symbols. The left side figures show the direction of σ_1 axis and the right side figures show the direction of σ_3 axis. The direction and length of the bar attached to the dot indicate the azimuth and plunge of the σ_1 axis of the stress state, respectively. Stress ratio is shown by color.

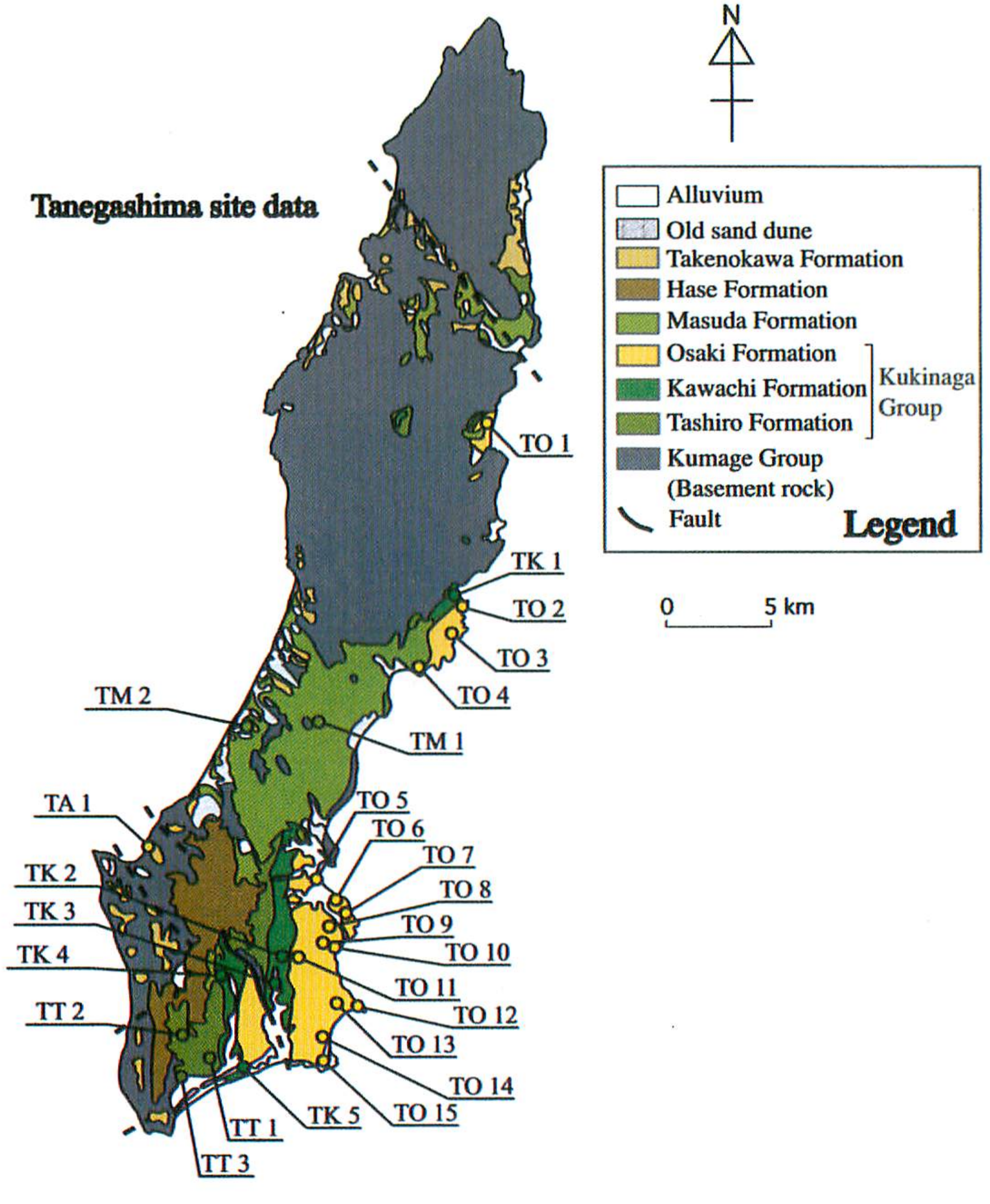

Fig.15. Fault-slip data collected in the Tanegashima. Other explanations are same as in Fig.4.

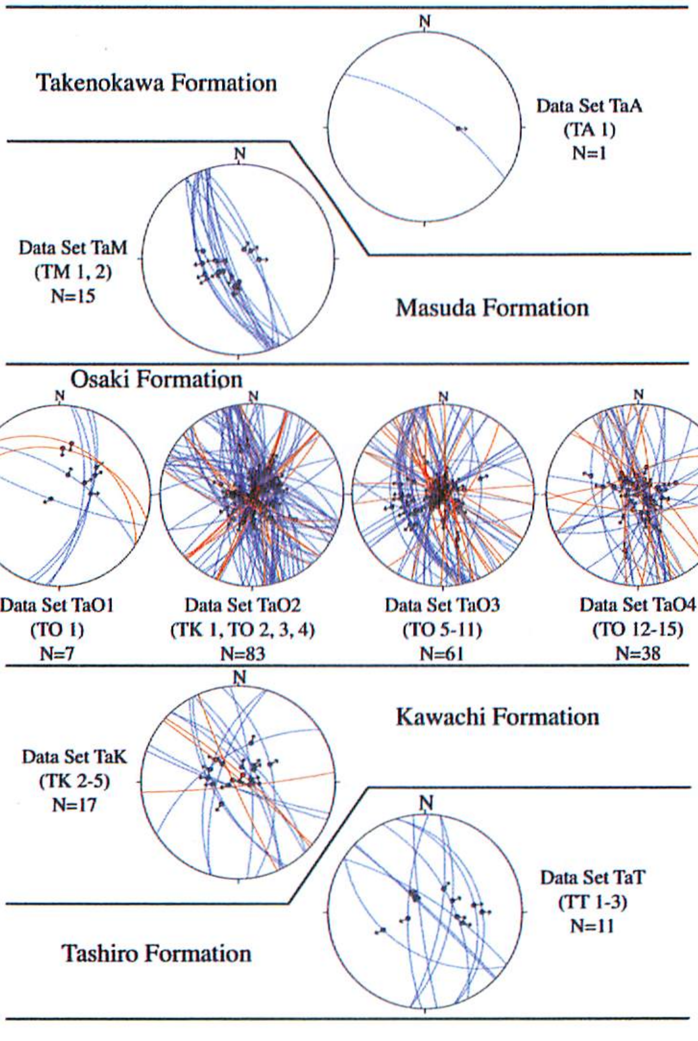

Fig.15. continued.

5.1.1. Tomigusuku formation

The stresses A, B and C are identified in the Tomigusuku formation by the Multi-inverse method and Ginkgo method. The stress A has vertical σ_1-axis and the σ_3-axis directs to N30° E. Its stress ratio is 0.1-0.4. The stress B is represented by the clusters of greenish symbols, which represent a triaxial stress with vertical σ_1-axis and E-W trending σ_3-axis. The stress C is represented by the clusters of yellow and light green symbols, which represent triaxial stress with NNE-SSW to NE-SW trending and 30° plunging σ_1-axis and NNE-SSW to NE-SW trending and 60° plunging σ_3-axis. We have judged that the stresses A and B belong to normal faulting regime, and the stress C is reverse faulting regime based on the Anderson's (1951) fault classification.

5.1.2. Yonabaru formation

The clusters A, B, C, D and E are obtained from the Yonabaru formation. The stress A is of normal faulting regime with the stress ratio around 0.5 and the σ_3-axis is oriented in NW-SE. The stress B is of normal faulting regime with its σ_3-axis in NE-SW. The stress ratio is 0.1-0.3. The stress C is represented by the clusters of violet symbols, which represents axial compression with vertical σ_1-axis and with σ_3-axis scattering on a great-circle girdle. The stress D is of normal faulting regime with its σ_3-axis in E-W whose stress ratio is 0.1-0.3. The stress E is represented by the clusters of orange symbols, which represent triaxial stress with NW-SE trending and 20° plunging σ_1-axis and NW-SE trending and 75° plunging σ_3-axis. The stress E is of reverse faulting regime with NW-SE compression.

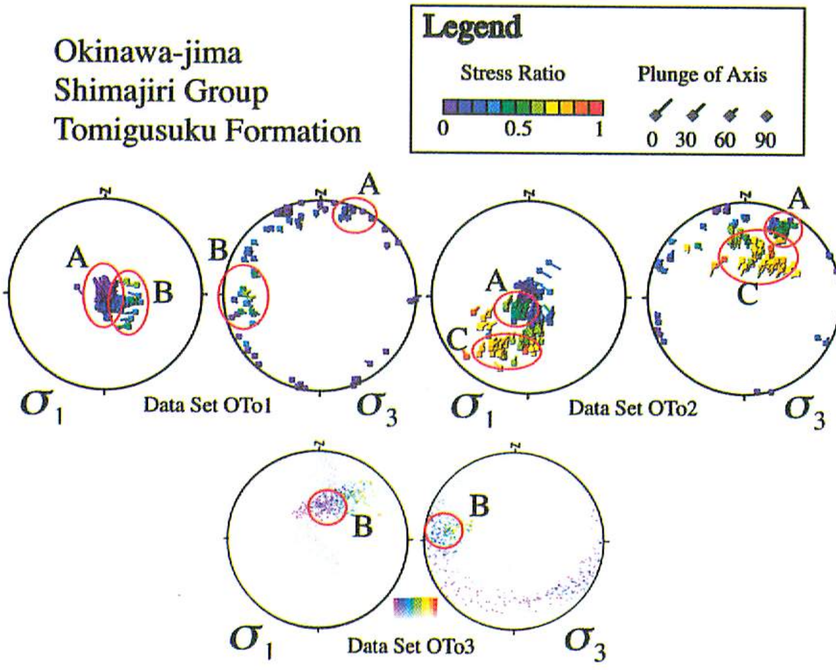

Fig.16. Stress identified by the Multi-inverse method with k=5 and Ginkgo method from the data of the Tomigusuku formation in the Okinawa-jima. The clusters A, B and C are detected from the Tomigusuku formation.

5.1.3. Shinzato formation

The clusters A, B and C are recognized from the Shinzato formation. The stress A has vertical σ_1-axis and the σ_3-axis in N-S direction whose stress ratio is 0.1-0.3. The stress B is of normal faulting regime with its σ_3-axis in E-W whose stress ratio is 0.1-0.5. The data set OSh3 is considered to represent stress B. The stress C is represented by the clusters of violet symbols, which represents axial compression with vertical σ_1-axis and with σ_3-axis showing a great-circle girdle.

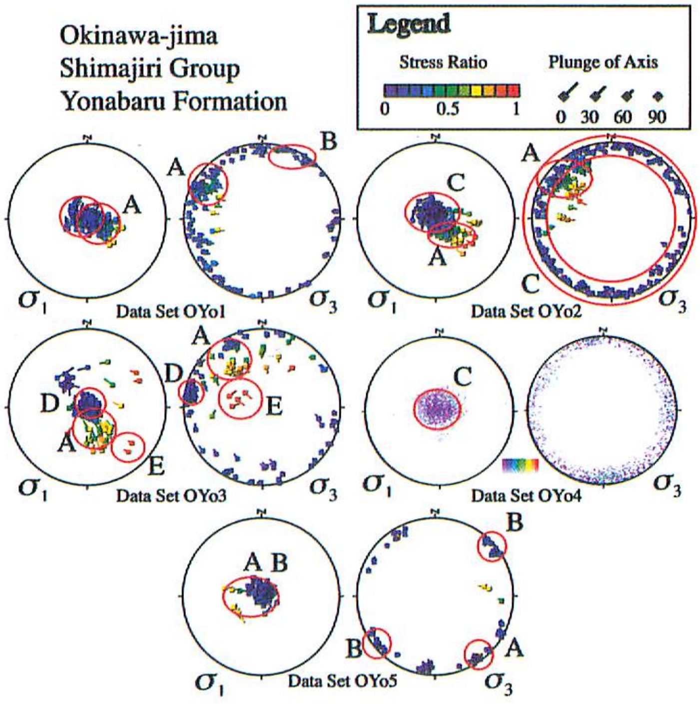

Fig.17. Stress identified by the Multi-inverse method with k=5 and Ginkgo method from the data of the Yonabaru formation in the Okinawa-jima. The clusters A, B, C, D and E are detected from the Yonabaru formation.

5.1.4. Ryukyu group

The clusters A, B, C and D are obtained from the Ryukyu group. The stress A has vertical σ_1-axis and the σ_3-axis in N-S direction whose stress ratio is 0.1-0.3. The stress B is of normal faulting regime with its σ_3-axis in NW-SE whose stress ratio is 0.1-0.5. The stress C is represented by the clusters of violet symbols, which represents axial compression with vertical σ_1-axis and with σ_3-axis showing a great-circle girdle. The stress D has vertical σ_1-axis and the σ_3-axis in NE-SW direction whose stress ratio is 0.1-0.3. The stress D is of normal faulting regime with NE-SW extension.

The extensional stresses A, B and D are correspond with the orientation of active faults cutting the Ryukyu group.

5.2. Aguni-jima

Figure 20 shows results by fault striation analysis in the Aguni-jima. The data set AA yields clusters A and B. The stress A is of normal faulting regime with its σ_3-axis in NW-SE whose stress ratio is 0.1-0.5. The stress B is represented by the clusters of greenish symbols, which represent a triaxial stress with vertical σ_1-axis and NE-SW

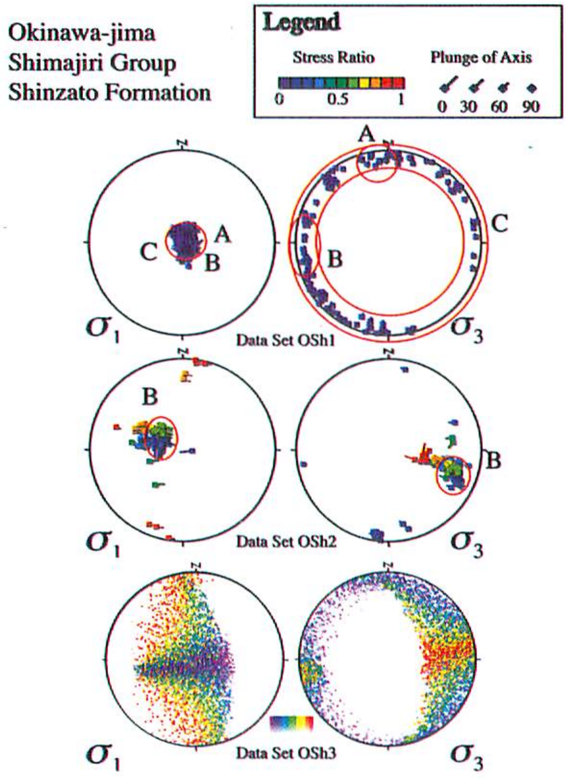

Fig.18. Stress identified by the Multi-inverse method with k=5 and Ginkgo method from the data of the Shinzato formation in the Okinawa-jima. The clusters A, B and C are detected from the Shinzato formation.

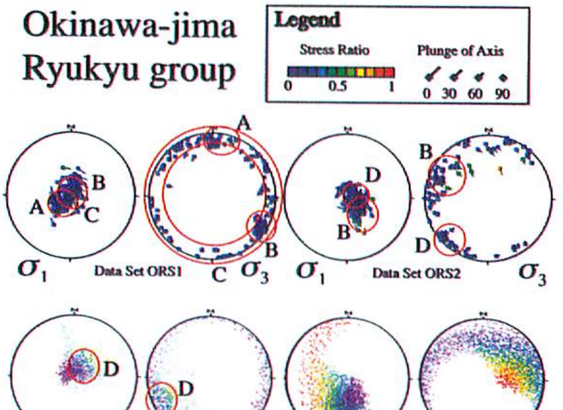

Fig.19. Stress identified by the Multi-inverse method with k=5 and Ginkgo method from the data of the Ryukyu group in the Okinawa-jima. The clusters A, B, C and D are detected from the Ryukyu group.

trending σ_3-axis. The stress B is of normal faulting regime with NE-SW extension.

The data set AR yields clusters A, B and C. The stress A and B are already described. The stress C is represented by the clusters of yellow and light green symbols, which represent triaxial stress with NE-SW trending and 30° plunging σ_1-axis and N-S trending and 30° plunging σ_3-axis. The stress C is of strike-slip faulting regime with NE-SW compression and N-S extension.

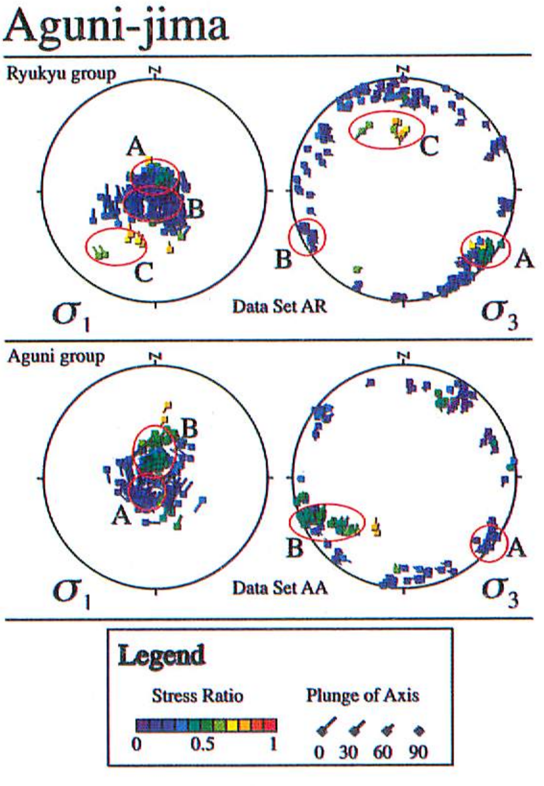

Fig.20. Stress identified by the Multi-inverse method with k=5 and Ginkgo method from the data of the Aguni-jima. The clusters A, B and C are detected from the Aguni group and Ryukyu group.

5.3. Kume-jima

Figure 21 shows results by fault striation analysis in the Kume-jima. The stresses A, B, C, D and E are identified in this island. The stress A is represented by the clusters of blue symbols. The stress A is of normal faulting regime with its σ_3-axis in NNE-SSW whose stress ratio is 0.1-0.3. The stress B is represented by the clusters of light blue symbols, which represent a triaxial stress with vertical σ_1-axis and WNW-ESE trending σ_3-axis. The stress B is of normal faulting regime with WNW-ESE extension. The stress C is of normal faulting regime with its σ_3-axis in NW-SE whose stress ratio is 0.1-0.3.

The stress D is of normal faulting regime with its σ_3-axis in NE-SW and its stress ratio is 0.2-0.6. The stress E is represented by the clusters of violet symbols, which represents axial compression with vertical σ_1-axis and with σ_3-axis showing a great-circle girdle.

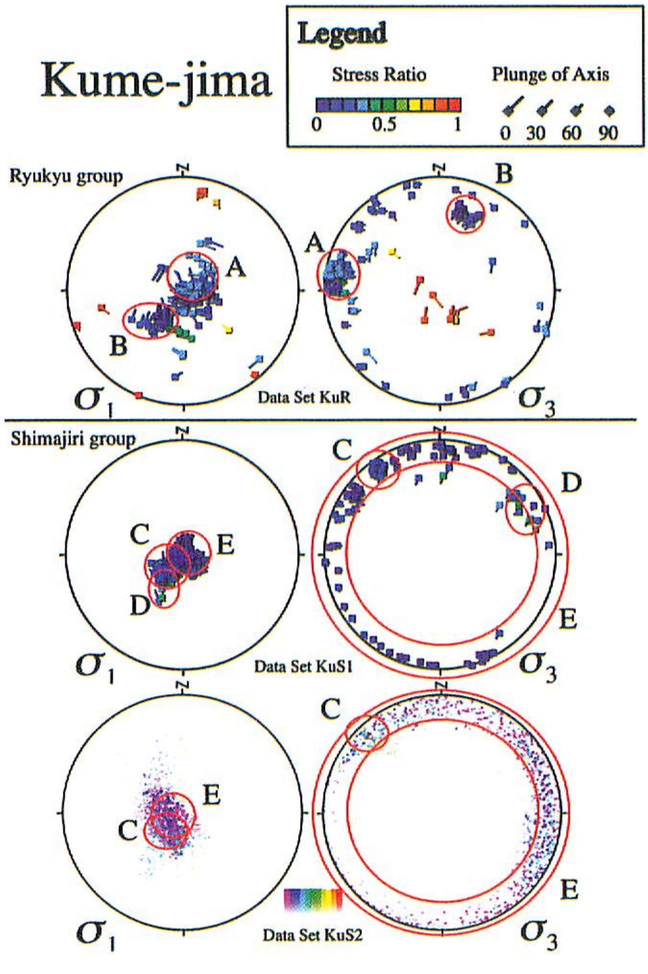

Fig.21. Stress identified by the Multi-inverse method with k=5 and Ginkgo method from the data of the Kume-jima. The clusters A, B, C, D and E are detected from the Shimajiri group and Ryukyu group.

5.4. Yoron-jima

Figure 22 shows results by fault striation analysis in the Yoron-jima. The stresses A and B are identified in this island. The stress A is represented by the clusters of bluish symbols. The stress A is of normal faulting regime where σ_3-axis is oriented in NW-SE and its stress ratio is 0.1-0.5. The stress B is represented by the clusters of bluish symbols, which represent a triaxial stress with vertical σ_1-axis and ENE-WSW trending σ_3-axis. The stress B is of normal faulting regime with ENE-WSW extension.

5.5. Okinoerabu-jima

Figure 23 shows results by fault striation analysis in the Okinoerabu-jima. Three stress states are identified in this island. The stress A is of normal faulting regime with its σ_3-axis in N-S whose stress ratio is 0.2-0.6. The stress B is represented by the clusters of bluish symbols, which represent a triaxial stress with vertical σ_1-axis and NE-SW trending σ_3-axis. The stress B is of normal faulting regime with NE-SW extension. The stress C is represented by the clusters of orange and light green symbols, which represent triaxial stress with NE-SW trending σ_1-axis and vertical σ_3-axis. The stress C is of reverse faulting regime with NE-SW compression.

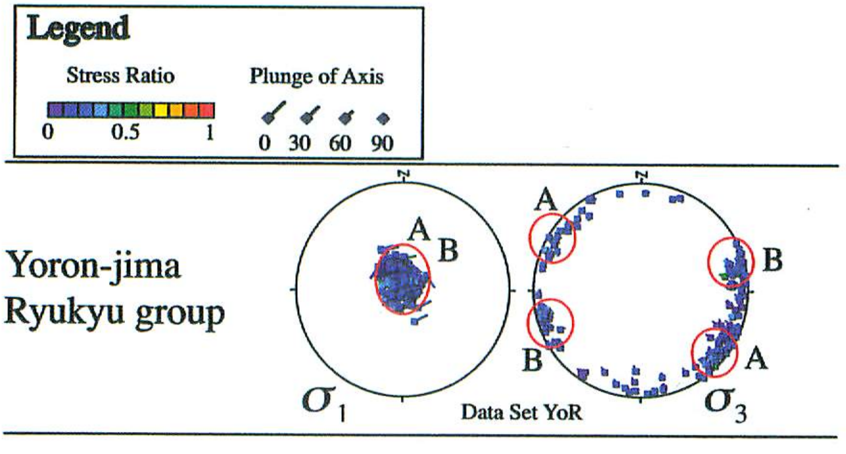

Fig.22. Stress identified by the Multi-inverse method with k=5 and Ginkgo method from the data of the Yoron-jima. The clusters A and B are detected from the Ryukyu group.

5.6. Tokunoshima

Figure 24 shows results by fault striation analysis in the Tokunoshima. The stresses A and B are identified in this island. The stress A and B are represented by the clusters of bluish symbols. The stress A is of normal faulting regime where σ_3-axis is oriented in NW-SE and stress ratio is 0.1-0.5. The stress B is normal faulting regime, too where σ_3-axis is oriented in NNE-SSW.

5.7. Kikai-jima

The results of fault striation analysis in the Kikai-jima are shown in Fig.25. The stresses A and B are identified in this island. The stress A is of normal faulting regime with its σ_3-axis in NNE-SSW where stress ratio is 0.1-0.5. The stress B is of normal faulting regime with NE-SW extension and stress ratio at 0.1-0.5. The data set KiS3 is represented to resemble to stress B.

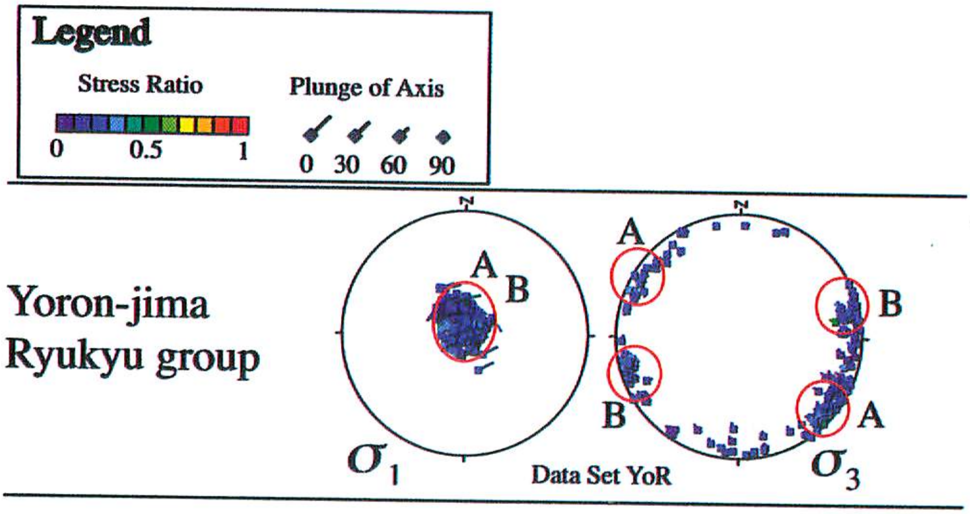

Fig.23. Stress identified by the Multi-inverse method with k=5 and Ginkgo method from the data of the Okinoerabu-jima. The clusters A, B and C are detected from the Ryukyu group.

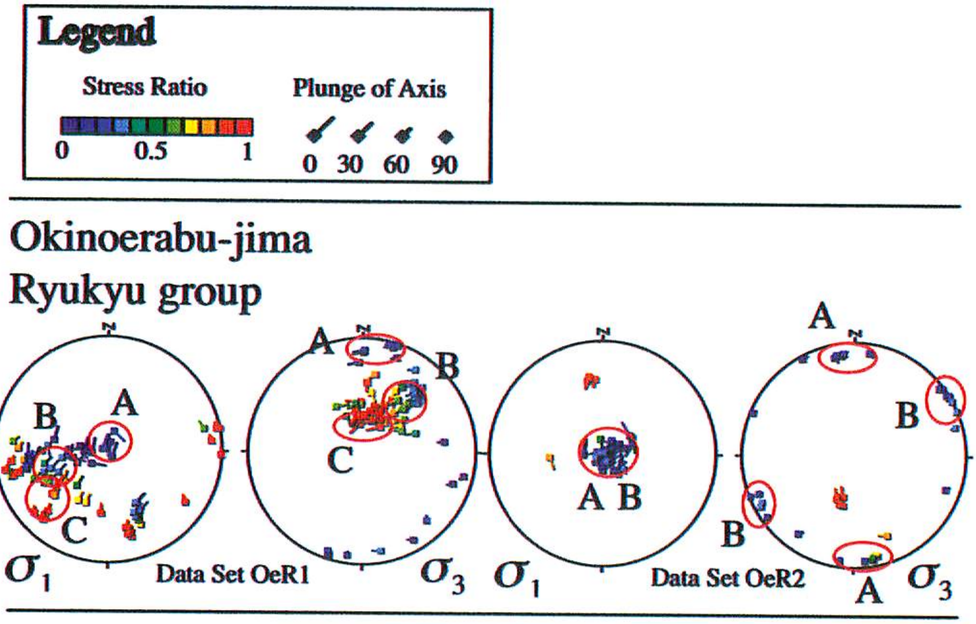

Fig.24. Stress identified by the Multi-inverse method with k=5 and Ginkgo method from the data of the Tokunoshima. The clusters A and B stand out from the Ryukyu group.

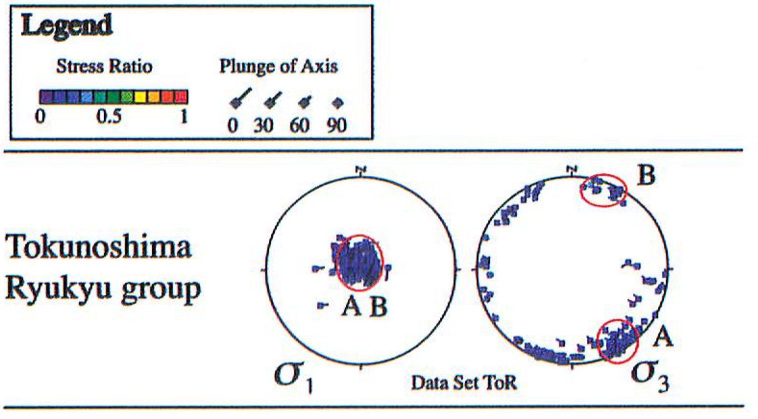

Fig.25. Stress identified by the Multi-inverse method with k=5 and Ginkgo method from the data of the Kikai-jima. The clusters A and B are detected from the Shimajiri group and Ryukyu group.

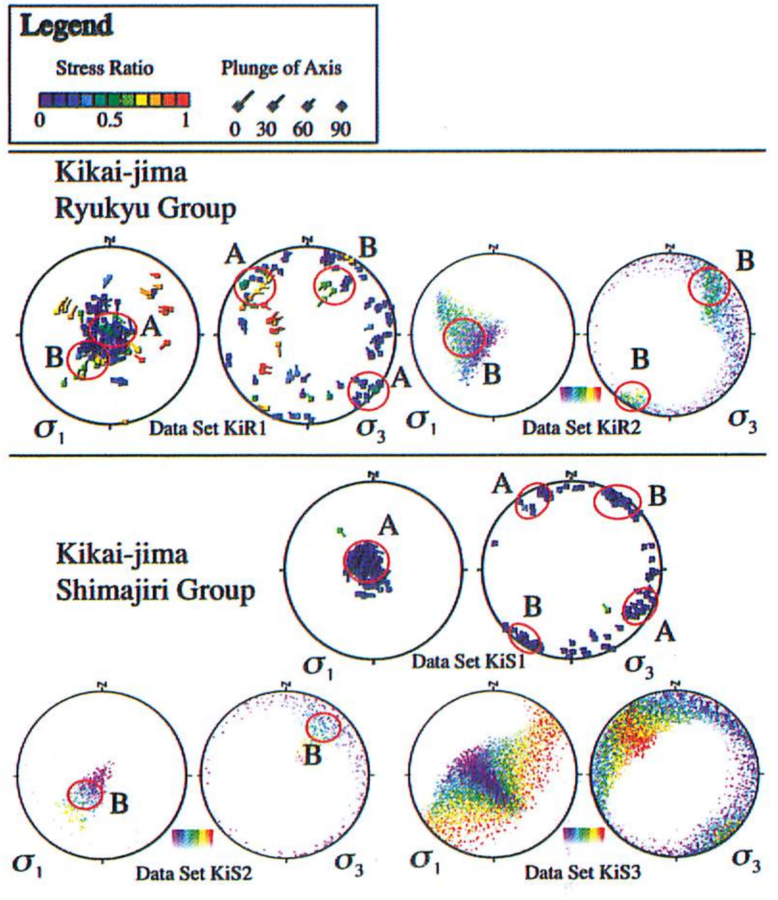

Fig.26. Stress identified by the Multi-inverse method with k=5 and Ginkgo method from the data of the Takara-jima. The clusters A and B are detected from the Takarajima group and Ryukyu group.

5.8. Takara-jima

Figure 26 shows results by fault striation analysis in the Takara-jima. The stresses A and B are identified in this island. The stress A is of normal faulting regime where σ_3-axis is oriented in NW-SE and stress ratio is 0.1-0.5. The stress B is normal faulting regime, too where σ_3-axis is oriented in NNE-SSW.

5.9. Tanegashima

The results of fault striation analysis in the Tanegashima are shown in Fig. 27. The clusters A, B, C, D, E, F, G and H are obtained in this island. The stress A is of normal faulting regime with the stress ratio around 0.5 and the σ_3-axis is oriented in NW-SE. The stress B is of normal faulting regime with its σ_3-axis in NE-SW where stress ratio is 0.1-0.6. The stress C is represented by the clusters of greenish symbols, which represent triaxial stress with vertical σ_1-axis and E-W trending σ_3-axis. The stress C is of normal faulting regime with E-W extension. The stress D is represented by the clusters of greenish and yellow symbols, which represent triaxial stress with N-S trending σ_1-axis and E-W trending σ_3-axis. The stress D is of strike-slip faulting regime. The stress E is

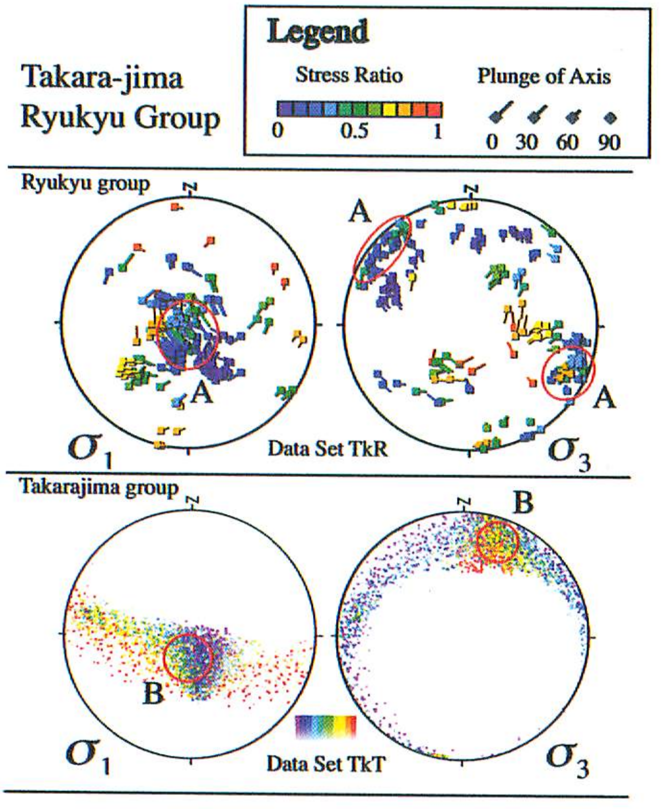

Fig.27. Stress identified by the Multi-inverse method with k=5 and Ginkgo method from the data of the Tanegashima. The clusters A, B, C, D, E, F, G and H are detected from each formation.

of normal faulting regime with its σ_3-axis in N-S where stress ratio is 0.1-0.3. The stress F is represented by the clusters of orange symbols, which represent triaxial stress with NE-SW trending σ_1-axis and vertical σ_3-axis. The stress F is of reverse faulting regime with NE-SW compression. The stress G is reverse faulting regime, too where σ_1-axis is oriented in N-S. The stress H is represented by the clusters of greenish and yellow

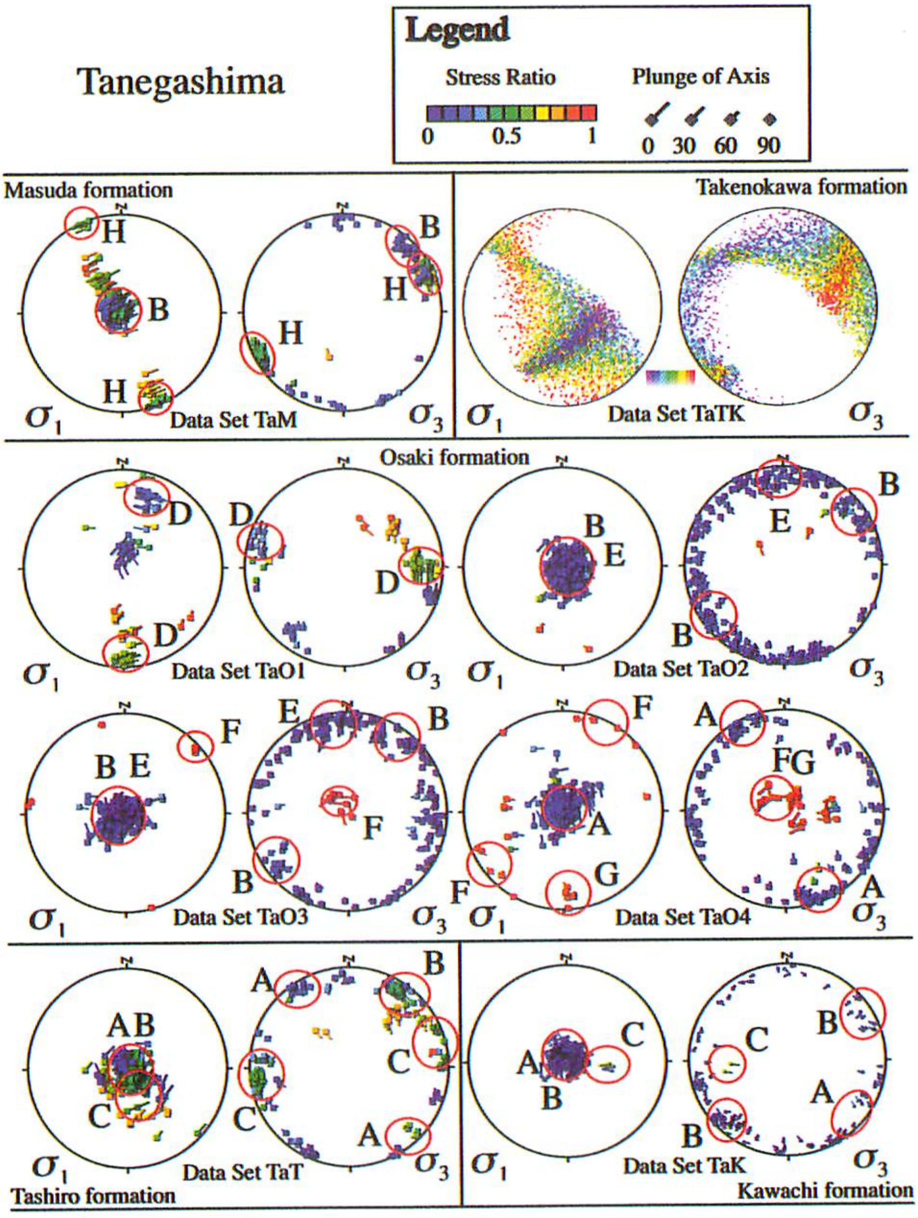

Fig.28. Synthesis of stress pattern in the northern and central Ryukyu arc by fault-striation analysis. Stress patterns are indicated by the red arrows. Upside-down image of cone shows axial compression.

symbols, which represent triaxial stress with NNW-SSE trending σ_1-axis and ENE-WNW trending σ_3-axis. The stress H is of strike-slip faulting regime.

5.10. Stress history by the fault-striation analysis

The detected paleostresses from the northern and central Ryukyu arc in this study are shown in Fig. 28. It is important to decide the age and order of stresses. However, it is difficult to determine the age of stresses because the age of stress can not be decided by the fault itself. The age and order of the detected stresses are fixed by the stratigraphic relation of the formation where the detected stresses are included. The direction of stresses are also inferred by the earthquake focal mechanism. Cross-cut relationships are not observed among the surveyed faults.

In Okinawa-jima, seven stress states are detected. The compressional stress regime which directs NW-SE and NE-SW is observed in the Tomigusuku and Yonabaru formation. It is considered that the compressional stress state is the oldest during the period of the Shimajiri group in the island because this stress regime is not observed in the upper formation. The lack of the E-W extension in the youngest formation of Ryukyu group suggests that the stress is older than the detected stresses in the Ryukyu group. N-S, NE-SW and NW-SE extensions are corresponds to the extensions which are expected by the EW, NE and NW trending active faults which cut the Ryukyu group of the south part of the Okinawa-jima (Research group for Active Faults of Japan, 1991).

NE-SW extension is the latest stress regime in the Okinawa-jima, because NE-SW extension is coincides with the T axes derived from the focal mechanism solution of shallow earthquake near the island (Kubo and Fukuyama, 2003).
The order of age of other stresses is difficult to decide because cross-cut relationship of the faults is not observed in the island.

The stress transition is considered as follows from old to new; (1) compressional stress regime, (2) E-W extension, (3) complex stress state (N-S and NW-SE extensions and axial compression with vertical σ_1) and (4) NE-SW extension.

In other surveyed islands of the central Ryukyu arc, on the whole, arc-parallel and arc-perpendicular extensions are detected. It is considered that the stress field in the islands of the central Ryukyu arc, except for Takara-jima, changes from arc-perpendicular extension to arc-parallel extension because the arc-parallel extension coincides with the T axes of the focal mechanism solution (Kubo and Fukuyama, 2003).

Takara-jima is located on the volcanic front where NW-SE extension is obtained from the data of the Ryukyu group and NE-SW extension from the data of the Takarajima group. The NW-SE extension in the Ryukyu group is corresponds to the T axes of the focal mechanism solution (Kubo and Fukuyama, 2003).

Eight stress states are detected in Tanegashima. The E-W extension are obtained from the data within the Tashiro and Kawachi formation. The lack of the E-W extension in the Osaki, Masuda and Takenokawa formations suggests that the stress is older than the formations. The compressional stress regime oriented NNW-SSE and NE-SW is obtained from the Osaki formation. It is considered that the compressional stress state is the older than the other detected stresses because the compressional stresses are not observed from the upper formations. The lack of the N-S and NW-SE extension in the Masuda and Takenokawa formations suggests that the stresses are older than the formations. Same as the central Ryukyu arc, NE-SW and NW-SE extensions are obtained from all the formations of Kukinaga group. On the other hand, it is considered that NE-SW extension is the latest stress regime in the Tanegashima, because this NE-SW extension corresponds to the extension expected by the active faults which cut NW

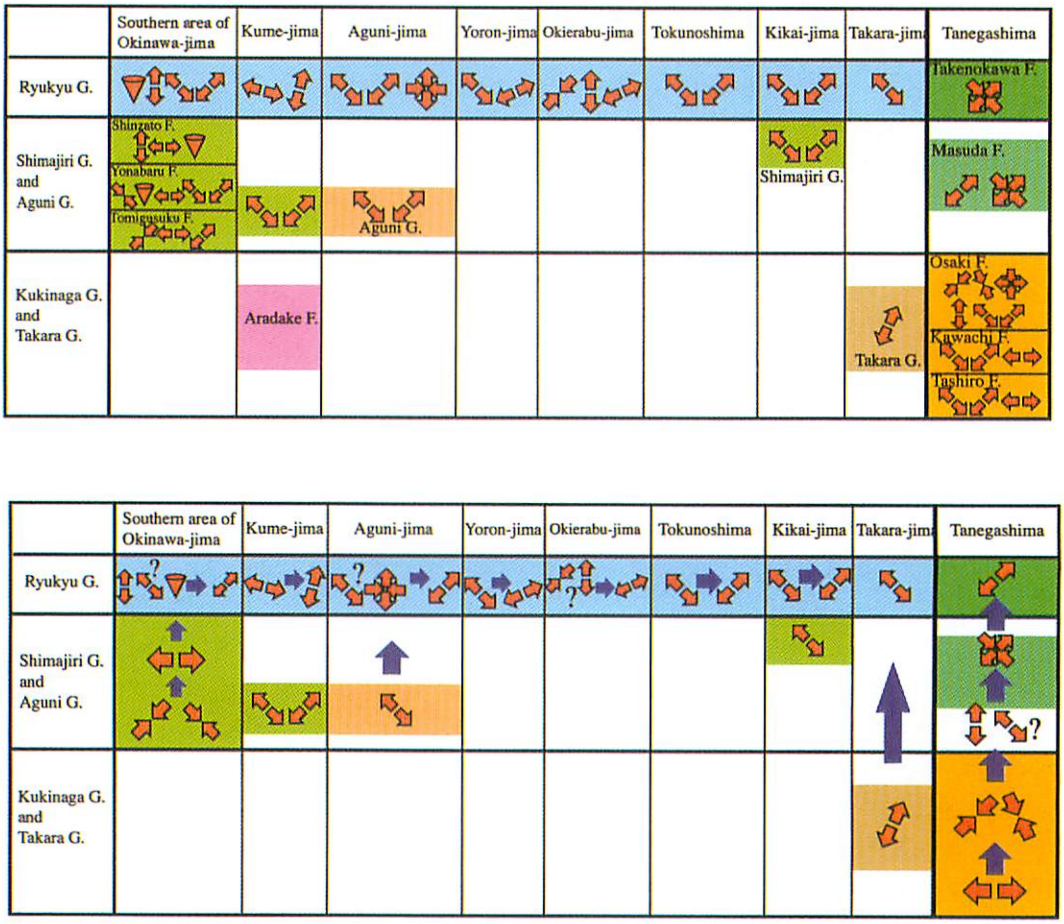

Fig.29. Stress transition in the northern and central Ryukyu arc by fault-striation analysis. Stress patterns are indicated by the red arrows.

trending in the island (Research group for Active Faults of Japan, 1991), and by the T axes derived from focal mechanism solution of shallow earthquake (Kubo and Fukuyama, 2003).

The stress transition is described as follows from old to new; (1) E-W extension, (2) compressional stress regime, (3) complex stress state (N-S and NW-SE extension), (4) strike-slip faulting regime and (5) NE-SW extension.

As the result of the fault-striation analysis and considering the earthquake focal mechanism, the deduced stress transition around the northern and central Ryukyu arc are summarized as fellows.

(1) The compressional stress stage occurred in the central and northern Ryukyu arc from late Miocene to early Pliocene.

(2) The E-W extension is observed from the northern Ryukyu arc during the middle Miocene and from the central Ryukyu arc during the Pliocene to early Pleistocene.

(3) The arc-parallel and arc-perpendicular extensions are obtained from the surveyed islands of the central and northern Ryukyu arc.

(4) In the volcanic front, the stress before the deposition of the Ryukyu group is arc-parallel extension and the stress after the deposition of the Ryukyu group is arc-perpendicular extension.

(5) Same as the southern Ryukyu arc (Otsubo and Hayashi, 2003), various stress states are existed in the central Ryukyu arc after the deposition of the Ryukyu group.

(6) The latest stress detected from the central and northern Ryukyu arc is the arc-parallel extension.

6. Discussion

6.1. Comparison with previous studies

Several researchers have studied using fault analysis in the northern and central Ryukyu arc (Fabbri, 2000; Fournier et al., 2001; Teramae and Hayashi, 2002). Fabbri, (2000) and Fournier et al. (2001) tried to detect paleostress by Angerlier's inversion method (Angelier, 1979; 1984; 1990) in Tanegashima and Okinawa-jima, respectively. In Tanegashima, Fabbri (2000) has detected two stages of extension, arc-parallel and arc-perpendicular extension. Fournier et al. (2001) have obtained three stages of extensional stress from about 450 tectonic joints and striated fault planes measured in 20 localities scattered in southern part of the Okinawa-jima. The first stage is of N40° W to N20° E extension during the late Miocene, the second stage is of N20° E extension during the late Pliocene to early Pleistocene, and the last stage is of N20° W extension during latest Pleistocene to present-day.

Although arc-parallel and arc-perpendicular extensions are concordant with my result, there are several problems in their studies In the first problem, Fournier et al. (2001) did not measure fault-slip data in the late Pleistocene deposits, Ryukyu group. They assumed that the direction of extension is perpendicular to the strike of the major normal faults and joints in the Ryukyu group. In the second problem, applied by Fabbri, (2000) and Fournier et al. (2001) the method (classic inversion method) has several methodological problems as pointed out by Yamaji (2001). The classic inversion method is assumed that all faults are moved in a single stress state. Precise stress state must be detected from the heterogeneous fault-slip data by the Multi-inverse method (Yamaji, 2000) and Ginkgo method (Yamaji, 2003a). We insist that the stress transition in the northern and central Ryukyu arc is more complex than that inferred by the previous authors.

6.2. Comparison with southern Ryukyu arc

Otsubo and Hayashi (2003) have tried to detect the paleostress in the southern Ryukyu arc by the Multi-inverse method and Ginkgo method. They detected 23 stresses in the southern Ryukyu arc to divide into three zones; MY zone (Miyako-jima and Yaeyama islands excluding for Hateruma-jima), HA zone (Hateruma-jima) and YO zone (Yonaguni-jima).

Arc-perpendicular and arc-parallel extensions are obtained within the Ryukyu group in the central Ryukyu arc. Most stresses are detected as same as within the Ryukyu group in the southern Ryukyu arc except for Hateruma-jima and Yonaguni-jima (Otsubo and Hayashi, 2003). Since Hateruma-jima is located near the Ryukyu trench, the stress state of the Hateruma-jima is affected by the location and is different from the other islands. The stress state of the Yonaguni-jima is affected by the westward migration of the rifting of the Okinawa Trough and the collision to Taiwan (Otsubo and Hayashi, 2003).

The stress state of the Yaeyama group and Nosoko formation, which deposited in almost the same time or before the deposition of the Kukinaga group in Tanegashima, are detected as extension or strike-slip fault regime. It is considered that the compression is a characteristic stress state in the northern and central Ryukyu arc. Furthermore, it is considered that the stress state of the northern and central Ryukyu arc is different from the southern Ryukyu arc before the deposition of the Ryukyu group. After the deposition of the Ryukyu group, the detected stress field in this study is roughly similar to the stress field of the southern Ryukyu arc.

There are some differences in the stress state between the southern Ryukyu arc and central Ryukyu arc. The opening of the Okinawa Trough is considered to be of late Miocene (Lee et al., 1980; Letouzey and Kimura, 1986; Sibuet et al., 1987). The southern Okinawa Trough is separated from the middle and northern Okinawa Trough by the magnetic anomaly study (Hsu et al., 2001). The paleomagnetic data suggested that the organization of the southern Okinawa Trough is different from that of the middle and northern Okinawa Trough (Miki, 1995).

Since there is difference between the detected stresses of the Ryukyu group and the detected stresses of before the deposition of the Ryukyu group, the stress field before deposition of the Ryukyu group of the northern and central Ryukyu arc is different from that of the southern Ryukyu arc.

6.3. E-W extension in the northern and central Ryukyu arc

The stress states of the Kukinaga group in the Tanegashima and the Shimajiri group in the Okinawa-jima are detected E-W extension. We think that E-W extension is the oldest stress among the detected stresses in the northern Ryukyu arc. We suppose that this extension is related to the opening of the Japan Sea. Hsu et al. (2001) described that the Miocene extension for the middle and northern Okinawa Trough was possibly related to the opening of the Japan Sea.

The other E-W extension in the central Ryukyu arc occurred after the compressional stress field. As the E-W extension occurred during Pliocene to early Pleistocene, the E-W extension is probably caused by the opening of the Okinawa Trough.

6.4. Compressional stress field in the northern and central Ryukyu arc

Compressional stress field is detected in the northern and central Ryukyu arc from the fault-striation analysis. Since the compressional stress state is obtained from the Osaki formation in the Tanegashima and the Tomigusuku and Yonabaru formations in the Okinawa-jima, the compressional stress state gives development of the faulting in the northern and central Ryukyu arc during the late Miocene to early Pliocene.

In the Shimajiri group of the Miyako-jima, the mesoscale fold is reported (Kizaki, 1985). The fold axis is oriented NE-SW. It is presumed that the folding in the Miyako-jima is formed by the same compressional stress field detected in the northern and central Ryukyu arc.

It is considered that this compression is related to the formation of the Taiwan-Shinji Fold belt in the backarc. The deformation of the fold belt is dated at 5-8 Ma (Itoh and Arato, 1999). The late Miocene folding is provoked by the resumption of subduction of the Philippine Sea Plate (Itoh et al., 1997).

Yamaji (2003b) detected the compression at the lowest formation of Miyazaki group in southeast Kyushu by the Multi-inverse method. Yamaji (2003b) suggested that the compression leads the faulting in the Miyazaki group at about 5-6 Ma and this compression is simultaneous with the formation of the Taiwan-Shinji Fold belt in the back arc. We support this opinion, and suggest that this compression is continued to the early Pliocene in the central Ryukyu arc and affected to the Shimajiri group in the Miyako-jima.

6.5. Arc-perpendicular and arc-parallel extensions in the Ryukyu arc

Arc-perpendicular and arc-parallel extensions are detected in all the surveyed islands. Arc-perpendicular extension is presumably related to the subduction of the Philippine Sea plate which has subducted beneath the Eurasia plate to NW at speeds of 5-7 cm/yr (Seno et al., 1993) to produce "trench retreat" (Hu et al., 1996).

Arc-parallel extension is related to the stretching of the Ryukyu arc in response to the opening of the Okinawa Trough. This extension is derived from a consequence of an arc-parallel stretching (Fabbri, 2000). The detected arc-parallel extension is the latest stress state in the Ryukyu arc. Kubo and Fukuyama (2003) investigated the stress field along the Ryukyu arc and the Okinawa Trough using the focal mechanism solution of shallow earthquake. They considered that the opening process of the Okinawa Trough should play an important role in this arc-parallel extension. The arc-parallel extension is observed in the entire region of the Ryukyu arc. This stress field is clearly separated from the back-arc extensional stress field in the Okinawa Trough by the volcanic chain (Kubo and Fukuyama, 2003).

6.6. Detected stress field from the Ryukyu group

We have obtained many stresses from the Ryukyu group in the central Ryukyu arc. Most detected stresses in the Ryukyu group are arc-perpendicular and arc-parallel extensions, while several detected stresses are different from the orientation of the extensions.

Although we have obtained arc-perpendicular and arc-parallel extensions from the Ryukyu group, these from Kume-jima show a little difference in orientation. The reason is that the Kume-jima is located near the Okinawa Trough. The Ryukyu group in the Kume-jima is tilted 10 - 20°. Structural difference between the Ryukyu group in the Kume-jima and that in other island supports this explanation.

In Aguni-jima, the normal and strike-slip fault stress regime are obtained in the Ryukyu group. NW-SE extension and strike-slip stress regimes correspond to the stresses expected by the NE trending active faults in the Ryukyu group (Research group for Active Faults of Japan, 1991). The active fault in Agun-jima is oblique-normal fault (Research group for Active Faults of Japan, 1991). The strike-slip stress regime activates this active fault. The active fault in Aguni-jima is not active recently. Since this active fault has not cut coral reef terrace, this fault is assumed low activity and has not been active in the past 10 ka (Research group for Active Faults of Japan, 1991).

NE-SW compression is obtained from Okinoerabu-jima, which is probably related to the subduction of the Daito Ridge. The subduction of the Daito Ridge have affected the state of stress in this island. Global Positioning System (GPS) data (Nakamura and Kawashima, 2000) suggest that the compressional strain is dominant and its maximum axis is oblique to the trench.

6.7. Rotation in the northern Ryukyu arc

Strike-slip fault regime is obtained within the Takenokawa, Masuda and Osaki formation in the Tanegashima. This stress regime is probably caused by counterclockwise rotation in the northern Ryukyu arc. Tanegashima undergone the paleomagnetic rotation of about 30° (Kodama et al., 1991). South Kyushu rotated counterclockwise with respect to the north Kyushu during the past 2 Ma (Kodama et al., 1995). This rotation started simultaneously with the rifting of the northern Okinawa Trough, which started around the Pliocene-Pleistocene boundary.

Miki (1995) reported that the central Ryukyu arc had not experienced any significant rotation between 6-10 Ma, whereas the southern Ryukyu arc had rotated 25° clockwise on the basis of the paleomagnetic data.

6.8. Tectonic evolution of the Ryukyu arc

The stress states in this study have a genetical relation to the subduction of the Philippine Sea plate beneath the Eurasia plate and the crustal extension in the Okinawa Trough.

As mentioned above, stress transition since middle Miocene is found by measurement of the fault-slip data in the northern and central Ryukyu arc. The fault-striation analysis leads the following tectonic evolution in the central and northern Ryukyu arc.

E-W extension occurred in the northern Ryukyu arc in middle Miocene, which may be related to the opening of the Japan Sea. The compressional stress field occurred in late Miocene to early Pliocene (5-8 Ma), which was simultaneous with the formation of the Taiwan-Shinji Fold Belt. E-W extension occurred in Pliocene, which was related to the opening of the Okinawa Trough. At around 2 Ma, complex stress regime occurred in the Ryukyu arc. In this time, activity of the Okinawa Trough was resumed and the deposition of the Ryukyu group was started. In the northern Ryukyu arc, strike-slip stress regime occurred from 2 Ma ago. NE-SW extension, arc-parallel extension is the latest stress regime in the central and northern Ryukyu arc. This arc parallel extension is observed in the whole Ryukyu arc. It implies that there are the major difference in stress regime between southern Ryukyu arc and central and northern Ryukyu arc before the deposition of the Ryukyu group.

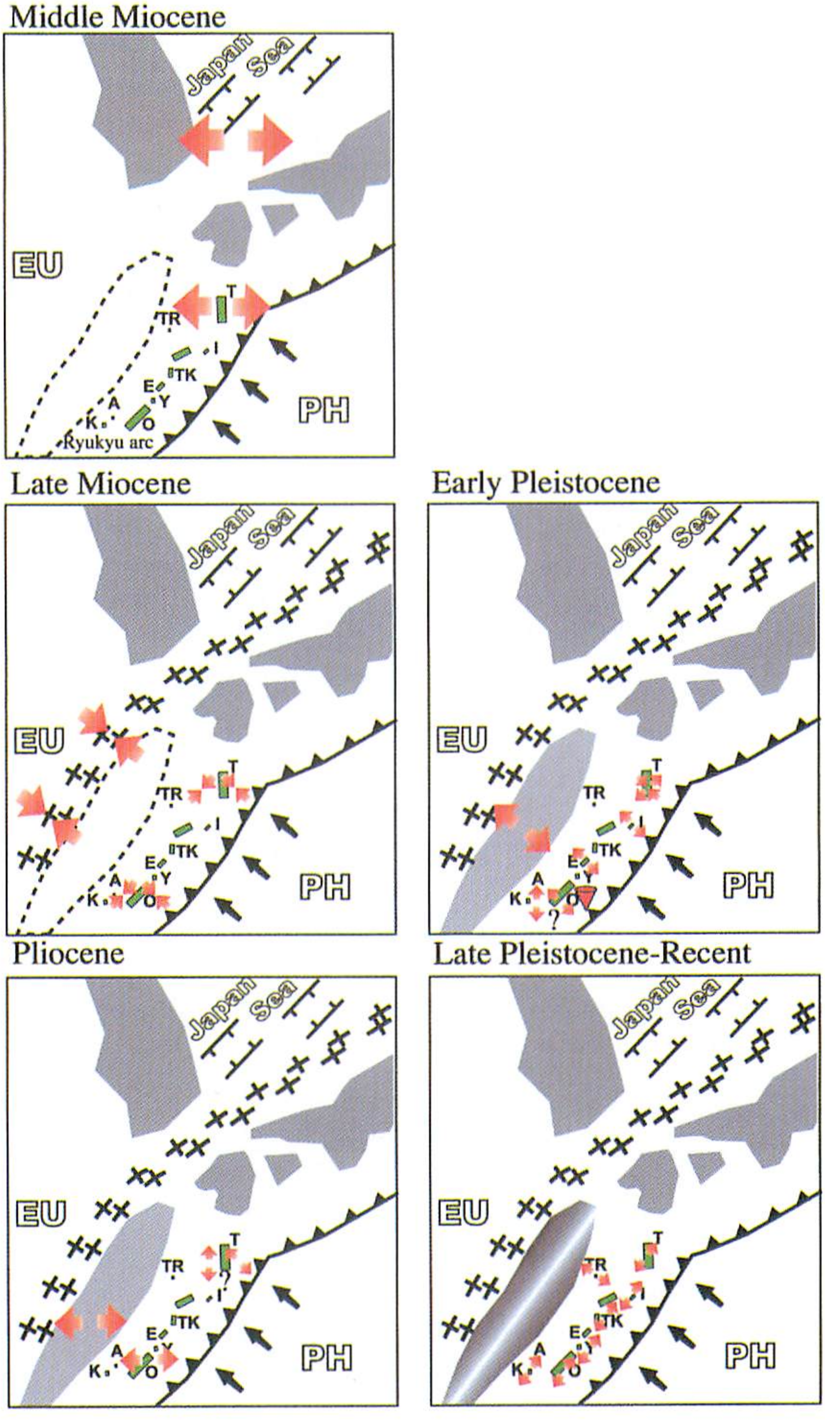

Fig.30. Schematic to show the tectonic evolution from middle Miocene to Recent around the northern and central Ryukyu arc. EU: Eurasia plate, PH: Philippine Sea plate, T: Tanegashima, TR: Takara-jima, I: Kikai-jima, TK: Tokunoshima, E: Okinoerabu-jima, Y: Yoron-jima, O: Okinawa-jima, A: Aguni-jima, K: Kume-jima.

7. Conclusion

The conclusions of this study are summarized as follows:

(1) Using the Multi-inverse method and Ginkgo method, the paleostress field is obtained which is more complex than that proposed by the previous studies.

(2) The fault-slip data in the Ryukyu group are collected in the central Ryukyu arc, similar to the southern Ryukyu arc.

(3) The E-W extension occurred in the northern Ryukyu arc in middle Miocene.

(4) The compressional stress state occurred in the central and northern Ryukyu arc from the late Miocene to early Pliocene.

(5) The E-W extension occurred in the central Ryukyu arc in Pliocene.

(6) Around at 2 Ma, complex stress regime occurred in the Ryukyu arc.

(7) The arc-parallel extension is the latest stress in the central and northern Ryukyu arc, similar to the southern Ryukyu arc.

(8) The stress field before the deposition of the Ryukyu group in the northern and central Ryukyu arc is different from that in the southern Ryukyu arc.

(9) Complex stress state in the Okinoerabu-jima is derived from the subduction of the Daito Ridge.

(10) In the volcanic front, the stress state before the deposition of the Ryukyu group is arc-parallel extension and the stress state after the deposition of the group is arc-perpendicular extension.

ACKNOWLEDGEMENTS

We wish to thank to Associate Professor A. Yamaji of Kyoto University for permitting to use Multi-inverse method and helpful advice about the result by the Multi-inverse method and Ginkgo method. We also thank Prof. M. Kimura of University of the Ryukyus for his comments.

REFERENCES

Aiba, J., and E. Sekiya., 1979, Distribution and characteristics of the Neogene sedimentary basins around the Nansei Shoto (the Ryukyu Islands). *J. Jpn. Assoc. Pet. Tecthnol.*, 44, 97-108. (in Japanese with English abstract)

Anderson, E.M. 1951, The Dynamics of Faulting and Dyke Formation with Application to Britain, 2nd ed. Oliver & Boyd, Edinburgh. 206 pp.

Angelier, J., 1979, Determination of the mean principal stresses for a given fault population. *Tectonophysics*, 56, T17-T26.

Angelier, J., 1984, Tectonic analysis of fault slip data sets. *Jour. Geophys. Res.*, 89, 5835-5848.

Angelier, J., 1990, Inversion of field data in fault tectonics to obtain the regional stress-Ⅲ. A new rapid direct inversion method by analytical means. *Geophysical Journal International* 103, 363-376.

Angelier, J., 1994, Fault slip analysis and paleostress reconstruction. In: Hancock, P.L. (Ed), *Continental deformation*, Pergamon Press, Oxford, 53-101.

Daishi, M., Hayashi, M., Kato, Y., 1987, Radio-metric ages of some Cenozoic volcanic rocks from Ryukyu Islands. *Journal of Mineralogy, Petrology and Economic geology*, 82, 370-381. (in Japanese with English abstract)

Ehara, Y., Iryu, Y., Nakamori, T and Odawara, K., 2001, Pleistocene coral reef deposits (the Ryukyu Group) on Kume-jima, Okinawa Prefecture, Japan. *Galaxea*, 3, 13-24. (in Japanese)

Fabbri, O., 2000, Extensional deformation in the northern Ryukyu arc indicated by mesoscale fractures in the middle Miocene deposits of Tanegashima Island, Japan. *Jour. Geol. Soc. Japan.*, 106, 234-243.

Fabbri, O., Fournier, M., 1999, Extension in the southern Ryukyu arc (Japan): Link with oblique subduction and back arc rifting. *Tectonic*, 18, 486-497.

Fournier, M., Fabbri, O., Angelier, J and Cadet, J.P., 2001, Regional seismicity and on-land deformation in the Ryukyu arc: Implications for the kinematics of opening of the Okinawa Trough. *J. Geophys Res.*, 106, 13751-13768.

Flint, D. E., Saplis, R. E. and Corwin, G., 1959, Military geology of the Okinawa-jima, Ryukyu-retto. 5, *Geol. Surv. Branch, Intell. Div. Office Eng. Hq., U. S. Army Forces, Far East, Personnel of U. S. Geol. Surv.*, 88p.

Furukawa, H., 1979, Quaternary Geologic History of the Ryukyu Island. *Bull. Sci. Eng. Div., Univ.* Ryukyus, 27,99-161.

Hayasaka, S., 1969, Molluscan fauna of the Kukinaga Group in Tane-ga-shima, South Kyushu, Japan. *Rep. Fac. Sci. Kagoshima Univ. (Earth Sci. & Biol.)*, 2, 33-52.

Hayasaka, S., 1973, Pliocene marine fauna from Tane-ga-shima, South Kyushu, Japan. Sci. Rep. Tohoku Univ., Ser. 2, Spec. 6, 97-167.

Hirata, K., 1967, Distribution of Raised Reef Limestone and Present Reef-Building Activity in Takara-jima and Kodakara-jima, Nansei Islands, Japan. *Science reports of Kagoshima University*, 16, 75-107. (in Japanese with English abstract)

Hsu, S.K., Sibuet, J.C., Shyu, C.T., 2001. Magnetic inversion in the East China Sea and Okinawa Trough: tectonic implications. *Tectonophysics* 333, 111-122.

Hu. J. C., Angelier, J., Lee. J. C., Chu. H. T., Byrne, D., 1996, Kinematics of convergence, deformation and stress distribution in the Taiwan collision area: 2-D finite-element numerical modeling. *Tectonophysics*, 255, 243-268.

Ikeda, S., Kasuya, M. and Ikeya, M., 1991, ESR ages of middle Pleistocene corals from the Ryukyu Islands. *Quatern. Res.*, 36, 61-71.

Iryu, Y., Nakamori, T., Yamada, T., 1998, Pleistocene reef complex deposits in the Central

Ryukyus, Southwestern Japan. In: Camoin G, Davies PJ (eds) Reefs and Carbonate Platforms in the Pacific and Indian Oceans. Spec Publ Int Ass Sed, Vol 25. Blackwell Science, Oxford, pp 197-213.

Iryu Y. and Yamada, T., 1991, A preliminary report on Pleistocene sea level changes recorded in the Ryukyu Group on Toku-no-shima and Okierabu-jima, Ryukyu Islands. Essays in Geology --Professor Hisao Nakagawa Commemorative Volume (Professor Hisao Nakagawa Taikan Kinenjigyo-kai), 73-83. (in Japanese with English)

Itoh, Y., Arato, H., 1999, Tectonic stress around the southern part of Japan Sea since the Pliocene; western Kyushu, San'in, and Hokuriku offshore areas. *Chishitsu News*, 541, 25-31 (in Japanese).

Itoh, Y., Nakajima, T., Takemura, A., 1997, Neogene deformation of the back-arc shelf of Southwest Japan and its impact on the paleoenvironments of the Japan Sea. Tectonophysics, 281m 71-82.

Kaneko, N. 1994, Stratigraphy of the Ryukyu Group in southern Okinawa Island, Southwest Japan. *Abstract of the 101th Annual Meeting of the Geological Society of Japan*, 61-1. (in Japanese)

Kaneko, N., Ito, T., 1995, Strontium isotopic composition of basal part of the Ryukyu Group, in southern Okinawa Island, Southwest Japan. *Abstract of the 102th Annual Meeting of the Geological Society of Japan*, 116-6 (in Japanese).

Kaneko, N., Ito, T., 1996, Basal layer of the Ryukyu Group, in southern Okinawa Island, Southwest Japan, *Inventory of Quaternary Outcrops : Tephras in Japan : Japan association for Quaternary research 40th anniversary special publication*, p.320. (in Japanese)

Kawana, T., 1989, Quaternary crustal movements in the Ryukyu Islands. Chikyu 11, 618-630 (in Japanese).

Kimura, M., 1985, Back-arc rifting in the Okinawa Trough. *Mar. Pet. Geol.* 2, 222-240.

Kizaki, K. Furukawa, H., Taira, H., Ohde, S., 1984, Dating of the Riukiu Limestone. *Bull. Fac. Sci., Univ. Ryukyus*, 37, 29-41.

Kizaki, K. 1985, Geology of the Ryukyu Island Arc. Okinawa Times, 278 pp. (in Japanese)

Kizaki, K., 1986, Geology and tectonics of the Ryukyu Islands, *Tectonophysics*, 125, 193-207.

Koba, M., Nakata, T., Takahashi, T., 1982, Late Holocene eustatic sea-level changes deduced from geomorphological features and their ^{14}C dates in the Ryukyu Islands, Japan. *Palaeoclimatol. Palaeogeogr. Palaeoecol.* 39, 231-260.

Kodama, K., Ozawa, T., Inoue, K., Maeda, Y., Takeuchi, T., 1991, Paleomagenetism and post-middle Miocene counter-clockwise rotation of Tanegashima island off Kyushu, Japan. *Jour. Geomagn. Geoelectr.*, 43, 721-740.

Kodama, K., Nakamura, K., 1993, Paleomagnetic evidence for post-late Miocene intra-arc rotation of south Kyushu, Japan. *Tectonics*, 12, 35-47.

Kodama, K., Tashiro, H., Takeushi, T., 1995, Quaternary counterclockwise rotation of south Kyushu, southwest Japan. *Geology*, 23, 823-826.

Konishi, K. 1965, Geotectonic framework of the Ryukyu Islands (Nansei Shoto). *Journal of Geography*, 71, 437-57.

Kubo, A., Fukuyama, E. 2003, Stress field along the Ryukyu Arc and the Okinawa Trough inferred from moment tensors of Shallow earthquakes. *Earth and Planetary Science Letters*, 210, 305-16.

Kuramoto, S. and Konishi, K. 1989, The southwest Ryukyu Arc is a migrating microplate (forearc sliver). *Tectonophysics* 163, 75-91.

Lee, C.S., Shor, G.G., Bibee, L.D., Lu, R.S., and Hilde, T.W.C., 1980, Okinawa Trough, origin of a back-arc basin. *Mar. Geol.*, 35,219-241.

Letouzey, J., Kimura, M., 1985, Okinawa Trough Genesis: structure and evolution of a backarc basin developed in a continent. *Mar. Pet. Geol*, 2, 111-130.

Letouzey, J., Kimura, M., 1986, The Okinawa Trough: genesis of a back-arc basin developing along a continental margin. *Tectonophysics*, 125, 209-230.

Macneil, F.S. 1960. The Tertiary and Quaternary Gastropoda of Okinawa. *US Geological Survey Professional Paper* 339, 1-148.

Marrett, R. and Allmedinger, R.W., 1990, Kinematic analysis of fault-slip data. *Jour. Struct. Geol.*, 12,973-986.

Matsumoto, Y., 1983, The Cenozoic volcanism in the Ryukyu Islands, Japan. *The Memories of the Geological Society of Japan*. 22, 81-91. (in Japanese with English)

Miki, M., Matsuda, T., Otofuji, Y., 1990, Opening mode of the Okinawa Trough: paleomagnetic evidence from the South Ryukyu Arc. *Tectonophisics*, 175, 335-347.

Miki, M., 1995, Two-phase opening model for the Okinawa Trough inferred from paleomagnetic study of the Ryukyu arc. *J. Geophys. Res.*, 100, 8169-8184.

Nakamori, T. 1986. Community structures of Recent and Pleistocene hermatypic corals in the Ryukyu Islands, Japan. *Science Reports of the Tohoku University, Second Series* (Geology) 56, 71-133.

Nakamura, M. and Kawashima, 2000, Horizontal Movement of Nansei Islands Inferred from GPS Data. *Bull. Fac. Sci., Univ. Ryukyus*, 70, 63-72.

Nakamura, Y., Kameo, K., Asahara, Y. and Ozawa, T., 1999, Stratigraphay and geologic age of the Neogene Shimajiri Group in Kumejima Island, Ryukyu Islands, southwestern Japan. *Jour. Geol. Soc. Japan*, 105, 757-770.

Nakagawa, H., 1967, Geology of Tokunoshima, Okierabu-jima, Yoronto, and Kikai-jima, Amami Gunto, part I, *Tohoku Univ., Inst. Geol. Pal., Contr.* 63, 1-39. (in Japanese with English)

Nakagawa, H., and Murakami, 1975, Geology of Kumejima, Okinawa Gunto, Ryukyu Islands, Japan, *Tohoku Univ., Inst. Geol. Pal., Contr.* 68, 1-17. (in Japanese with English)

Ninagawa, K., Kitahara, T., Toyoda, S., Hayashi, K., Nishido, H., Kinjo, M., Kawana, T., 2001, Thermoluminescence dating of the Ryukyu Limestone. Quaternary Science Reviews, 20, 829-833.

Odawara, K. and Iryu, Y., 1999, Pleistocene coral reef deposits (the Ryukyu Group) on Yoron-jima, Kagoshima Prefecture, Japan. *Jour. Geol. Soc. Japan,* 105, 273-288.

Omura, A., 1982, Uranium series ages of the "Kametsu Formation", Riukiu Limestone on Tokuno-shima, Ryukyu Islands. *Trans. Proceed. Palaeontol. Soc. Japan, N S.,* no. 101, 327-333.

Otsubo, M., Hayashi, D., 2001, Miocene to Pleistocene stress field transitions, around the Miyako-jima Island, South Ryukyu, Japan. *Bull. Fac. Sci., Univ. Ryukyus,* 72, 97-110.

Otsubo, M., Hayashi, D., 2003, Neotectonics in Southern Ryukyu arc by means of paleostress analysis. *Bull. Fac. Sci., Univ. Ryukyus,* 76, 1-73.

Research Group for Active Faults of Japan, 1991, Active faults in Japan. Sheet maps and inventories. Revised Edition, TokyoUniversity Press, 442p. (in Japanese)

Sado, K., Kameo, K., Konishi, K., Yuki, T., Tsuji, Y., 1992, A New Age Assignment of Riukiu Limestone (Pleistocene) by Calcareous Nannofossils from the Borehole Cores at Irabu Island, South Ryukyus, *Japan. Journal of Geography* 101, 127-32.

Sato, T., Nakagawa, H., Komatsubara, J., Matsumoto, R., Iryu, Y., Matsuda, H., Omura, A., Odawara, K. and Takeuchi, R., 2004, Geological age of the Chinen Formation in the southern Okinawa-jima based on calcareous microfossils. *Jour. Geol. Soc. Japan,* Vol.110, No.1, 38-50. (in Japanese with English)

Seno. T., STEIN, S. and GRIPP, A. E., 1993, A model for the motion of the Philippine Sea plate consistent with NUVEL-1 and geological data. *J. Geophys. Res.,* 98, 17941-17948.

Sibuet, J. C., Letouzey, J., Barbrier, F., Charvet, J., Foucher, J. P., Hilde, T. W. C., Kimura, M., Chiao, L.-Y., Marsset, B., Muller, C. Stephan, J. F., 1987, Back arc extension in the Okinawa Trough. *J. Geophys. Res.* 92, 14, 041-14, 063.

Takayasu, 1976, Reconstruction of the Quaternary stratigraphy in the Okinawa-jima. *Geological Studies of the Ryukyu Islands.* 1, 79-96. (in Japanese)

Takayasu, 1978, On the change of sedimentological properties in the "Ryukyu Limestone" of Okinawa-jima. *Geological Studies of the Ryukyu Islands.* 3, 119-122. (in Japanese with English)

Teramae, N., Hayashi, D., 2002, Paleostress analysis around southern area of Okinawa-jima, Central Ryukyu, Japan. *Bull. Fac. Sci., Univ. Ryukyus,* 74, 33-48.

Ujiie, H., 1994, Early Pleistocene birth of the Okinawa Trough and Ryukyu Island Arc at the northwestern margin of the Pacific: evidence from Late Cenozoic planktonic faraminiferal zonation, *Palaeogeography, Palaeoclimatology, Palaeoecology,* 108, 457-474.

Uyeda, S., 1977, Some basic problems in trench-arc-back-arc-system. In: Talwani, M., Pitman III, W. C. (Eds.), Island Arcs, Deep Sea Trenches and Beck-Arc basins. Maurice

Ewing Ser., vol. 1. American Geophysical Union, Washington, DC, pp. 1-14.

Yamada, T., Fujita, K. and Iryu, Y., 2003, The Ryukyu Group (Pleistocene coral reef complex deposits) on Toku-no-shima, Kagoshima Prefecture, *Japan. Jour. Geol. Soc. Japan,* Vol.109, No.9, 495-517. (in Japanese with English)

Yamaji, A., 2000, Multiple inverse method applied to mesoscale faults in mid Quaternary sediments near the triple trench junction off central Japan. *Journal of Structural Geology,* 22, 429-40.

Yamaji, A., 2001, Review on fault striation analysis. *Jour. Geol. Soc. Japan,* Vol.107, No.7, 461-479. (in Japanese with English)

Yamaji, A., 2003a, Are the solutions of stress inversion correct? Visualization of their reliability and the separation of stresses from heterogeneous fault-slip data. *Journal of Structural Geology,* 25, 241-52.

Yamaji, A., 2003b, Slab rollback suggested by latest Miocene to Pliocene forearc stress and migration of volcanic front in southern Kyushu, northern Ryukyu Arc. *Tectonophysics,* 364, 9-24.