Neotectonics in Southern Ryukyu arc by means of paleostress analysis

5. Tectonic simulation of the Southern Ryukyu arc

Detailed stress transition is found by the Multiple inverse method and the Ginkgo method. It is emphasized that many stress states are existed in the Southern Ryukyu arc after the deposition of the Ryukyu Group. In particular, stress transition in the Yonaguni and Hateruma islands is more complex than that in other islands (*e.g.* Miyako and Ishigaki islands). The stress state of the after Ryukyu Group including strike-slip fault regime in the Yonaguni and Hateruma islands is of particular interest.

The Southern Ryukyu arc is not the simple arc-trench system that is only characterized by the subduction of the Philippine Sea Plate and the rifting of the Okinawa Trough because stress state is changed in the area. The rifting of the Okinawa Trough is migrating to westward (Wang *et al.*, 2000). Collision at Taiwan is also migrating westward by the westward movement of the Philippine Sea Plate (*e.g.* Teng, 1990). We consider that the

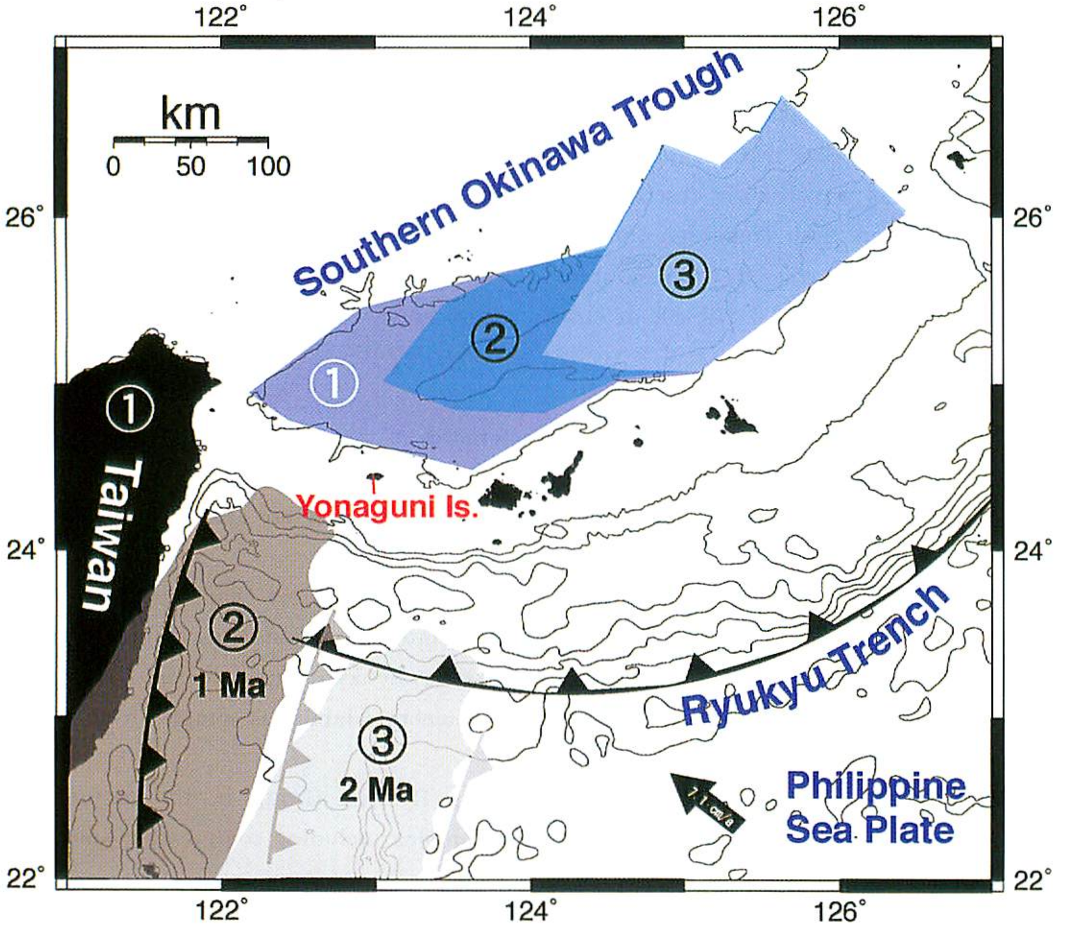

Fig. 16. Interpretation of westward migration the Okinawa Trough and collision at Taiwan; ③ (2 Ma)→ ② (1 Ma)→① (present).

collision at Taiwan approached to the Yonaguni island (Fig. 16).From the migrating rate of the Philippine Sea Plate (Seno *et al.*, 1993), Yonaguni island approached to Taiwan at about 1 Ma ago. Yonaguni island is experienced the complex stress state under the influence of the approach of Taiwan at 1 Ma ago. Furthermore, due to the obliquity of the subduction of the Philippine Sea Plate, major transcurrent fault is existed in the rear of the accretionary prism, dragging the wedge toward Taiwan (Lallemand *et al.*, 1999). A major right-lateral fault named as Yaeyama fault zone (*e.g.* Font *et al.*, 2001) is caused by obliquity of the subduction of the Philippine Sea Plate.

Is the complex stress transition in the Yonaguni and Hateruma islands caused by the westward migration of the Okinawa Trough and Taiwan and the right-lateral shearing along the Ryukyu Trench? Although a great deal has been written about the reconstruction of neotectonics of the Southern Ryukyu arc by the investigation of the rifting of the Okinawa Trough, very little has been stated about the change of neotectonics in the Southern Ryukyu arc by the migration of the Okinawa Trough and Taiwan. We propose that the finding this answer is important to reconstruct the neotectonics of the Southern Ryukyu arc. Therefore, we try to construct the neotectonics of the study area by finding "Did more stresses exist in the Southern Ryukyu arc after the deposition of the Ryukyu Group?" with the finite element method.

5.1. Finite Element Method (FEM)

Finite element method is a well known method which is broadly used in most of the branches of applied science, engineering, medical sciences or even in economics. The method is also rapidly used to the numerical calculations in the structural geology and tectonics. The following paragraphs are referred from Ramsay and Lisle (2000).

Tectonic simulation introduced a method of modeling the deformation within a body which involves solving some type of boundary value problem. These are problem of determining the distribution of values of some unknown (*e.g.* displacements, strains or stresses) inside a volume of rock from knowledge of these or other deformation parameters at the boundaries of that volume. The technique is the mathematical equivalent of constructing physical models, where displacements or force are imposed to the sides of a box containing clay or some other analogue material with a view to determining the internal distribution of deformation quantities such as displacements, strains or stresses. The variation of these quantities could be complex, depending on the geometry of the body, the applied stresses and the mechanical structure of the body (Ramsay and Lisle, 2000).

Based on the coordinates of the nodes, simple profile map with the same scale of x-axis and y-axis can be drawn by *net.func*. After getting the input data, the finite element method programs *elas.f*, calculates stress fields of models. Program *net.func* is used to draw geometrical structure of models. Program *band.f* is used to determine the minimum value *ibw* of the difference among the nodes of respective triangles. Calculating time depends on the value of the *ibw*. If *ibw* is large, calculating time becomes long. In this program, boundary condition file, material propaties and data files are used to simulate the maximum principal stress (σ_1) and minimum principal stress (σ_2). Using the principal stresses, *stress.func* draws the stress distribution.

5.2. Modeling

Assuming lithosphere as a thin elastic plate, 2D plane stress models are simulated with the finite element method to compare with the detected stresses by the fault-slip analysis. We think that this method is valid to analyze horizontal stress axes in model. In this paper, three models -1, 2 and 3 are used by the westward migration of the rifting of Okinawa Trough and the collision area between the Philippine Sea plate and the Eurasian Plate.

Model -1 (Fig. 17) shows the geological model around the Southern Ryukyu arc at present. Model -2 (Fig. 18) shows the 1 Ma ago model that the collision zone at Taiwan is located near the Yonaguni island. Model -3 (Fig. 19) shows the 2 Ma ago model which is the model before the collision zone approached to the Yonaguni island. Model -1 contains 265 nodes, 464 elements, Model -2 contains 240 nodes, 423 elements and Model -3 contains 271 nodes, 483 elements. Furthermore, we have treated three types of boundary condition; (a) subdction of Philippine Sea Plate only, (b) collision at Taiwan and suction force of Eurasian Plate (Opening of Okinawa Trough) and (c) collision at Taiwan and suction force of Eurasian Plate and shear along southwestern part of the Ryukyu Trench. In Model -1c, d and e of the models imposed weak, intermediate and strong shear along the Ryukyu Trench, respectively

5.3. Boundary condition

The boundary conditions used are either displacement or force. In all models (Figs. 17, 18 and 19), the northern boundary (*AE, AE'* or *AE"*) and southern boundary (*BC, BC'* or *BC"*) are not movable to N-S direction. The eastern boundary (*AB, AB'* or *AB"*) is not movable to E-W direction. This boundary is divided into two segments as described below. But the boundary is divided into three segments to give shear.

As the kinematics of the collision in Taiwan (segment *CD, CD'* or *CD"*) is well known (*e.g.* Angelier *et al.* 1986, 1990), we use displacement as boundary condition along *CD, CD'* or *CD"*. We take 7000 m to a N310° E direction (Seno, 1993) as the displacement for one hundred thousand years along *CD, CD'* and *CD"*.

Along the Ryukyu Trench (segment *DE, DE'* or *DE"*), force boundary condition is used. When the normal stress transmitted from the subducting plate to the edge of the overriding plate is lower than the mean lithostatic pressure ($\sigma_n < P_l$), the difference is a tensile stress which, corresponds to a suction force (Fig. 20c). When the normal stress is equal to the mean lithostatic pressure, difference is 0. In other wards, no suction force is exerted (Fig.

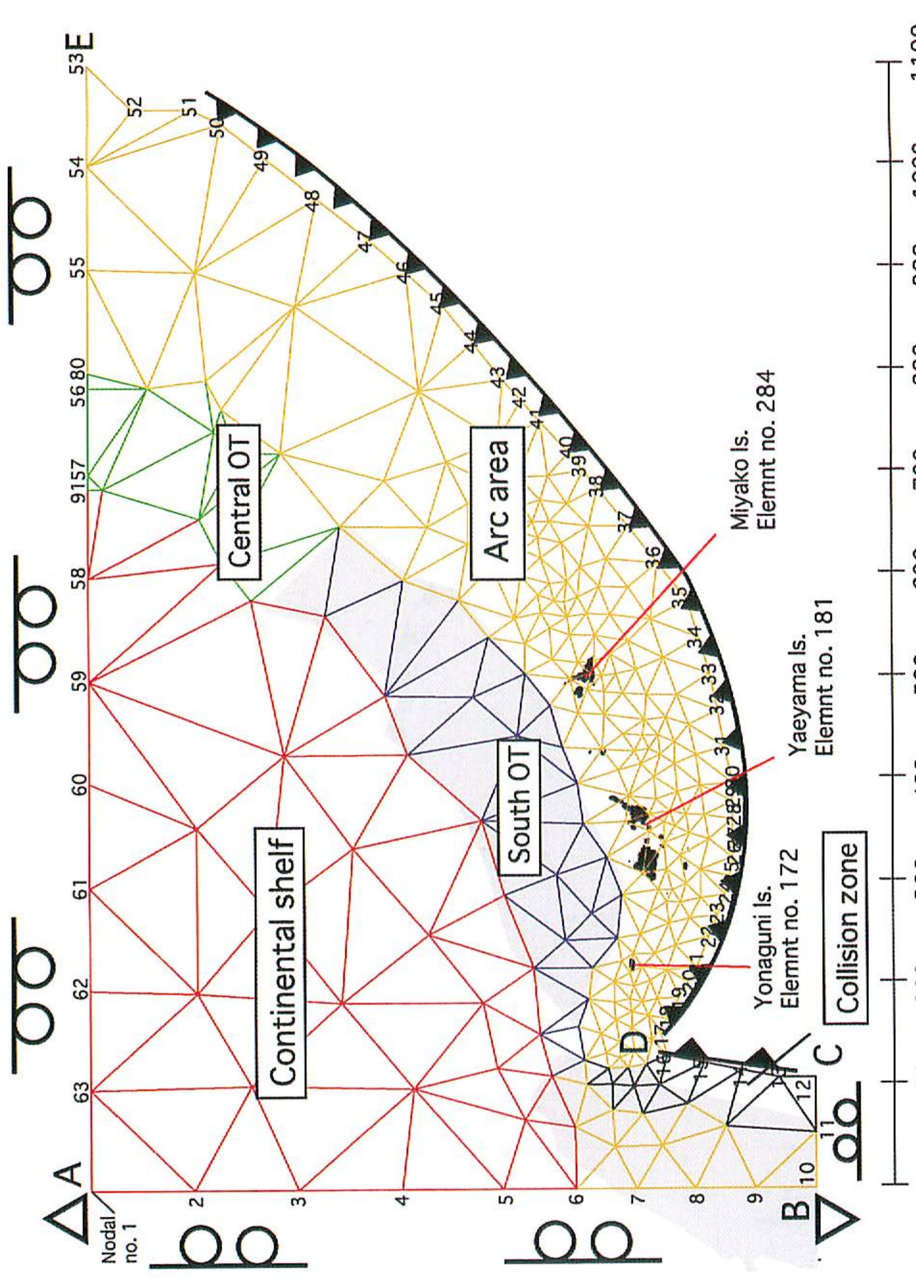

Fig. 17. Finite element modeling of the present model around the Southern Ryukyu arc (Model -1). It contains 265 nodes and 464 elements.

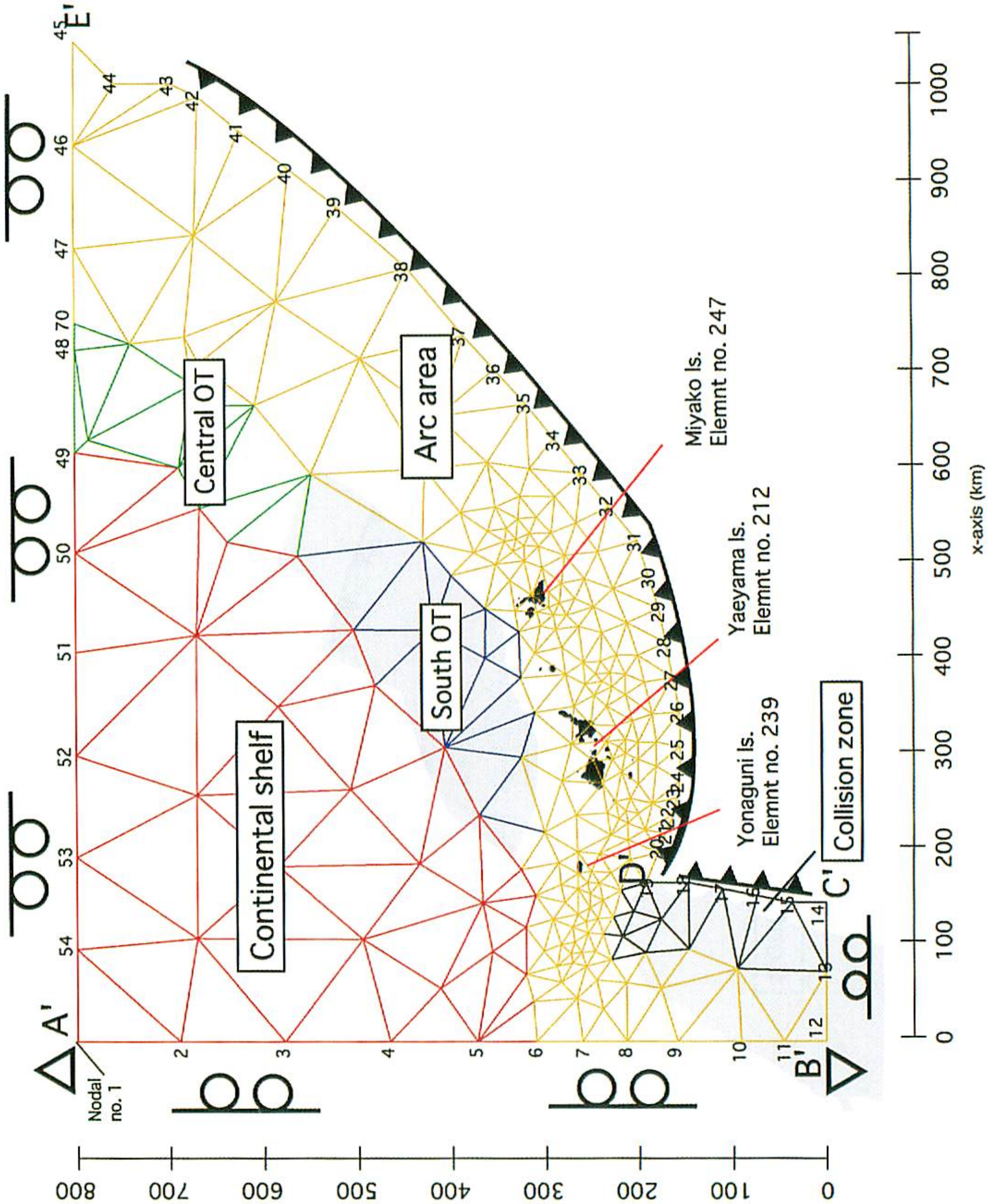

Fig. 18. Finite element modeling of the 1 Ma ago model (Model -2). It contains 240 nodes and 423 elements.

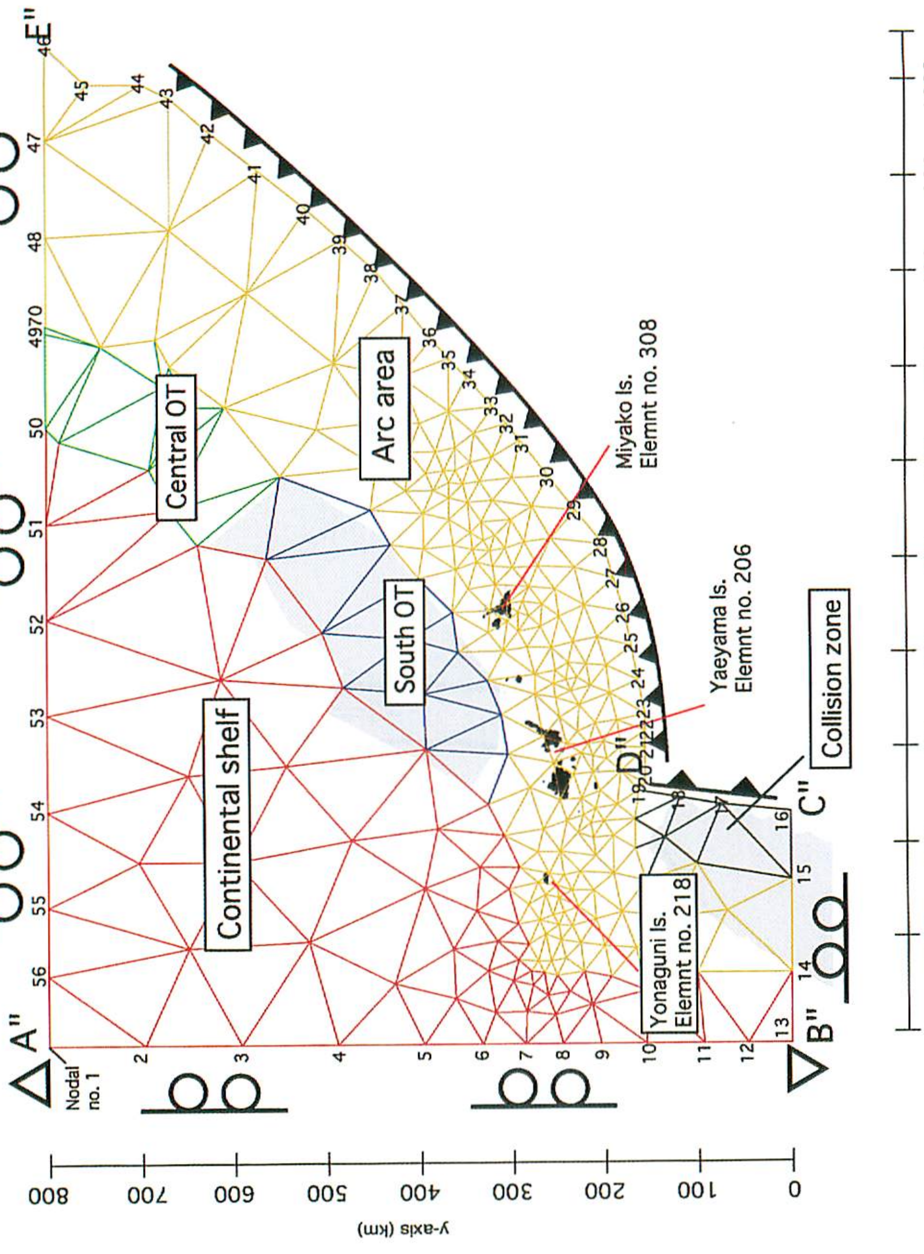

Fig. 19. Finite element modeling of the 2 Ma ago model (Model -3). It contains 271 nodes and 483 elements.

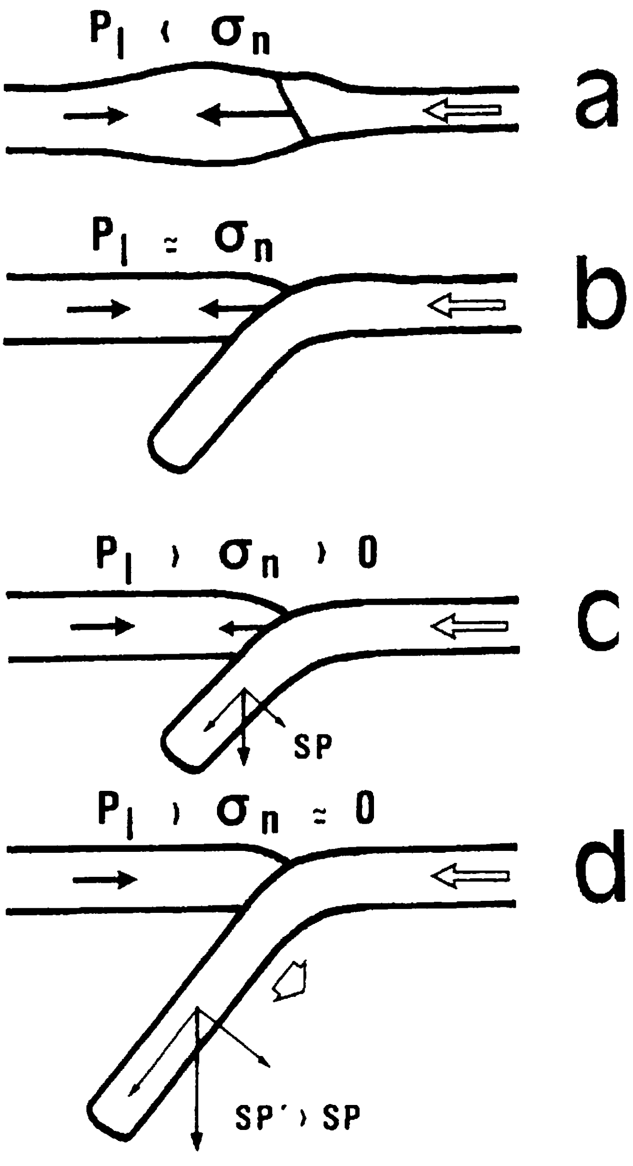

Fig. 20. Cartoons illustrating the relative importance of the lithostatic pressure p_l in the overriding plate and the normal stress σ_n transmitted from the subducting plate, for several geodynamic situations: (a) collision, (b) ridge subduction, (c) short slab subduction, (d) long slab subduction. SP: weight of the slab (slab pull) taken from Viallon et al. (1986).

20b). In the extreme case, the normal stress is 0, so that no stress is transmitted from the subducting plate to the overriding plate and the suction force is equal to the mean lithostatic pressure in the overriding plate (Fig. 20d). The value of the mean lithostatic pressure P_l is 922 MPa which is given by Viallon *et al.* (1986). In the boundary condition a and b, we do not impose shear stress along *DE*. However, we give shear stress along southwestern part of Ryukyu Trench in boundary condition (c) because a major transcurrent right-lateral strike-slip fault accommodates the strain partitioning caused by an oblique convergence of 40° along most southwestern part of the Ryukyu Trench in the Eurasian Plate (Lallemand, 1999).

Models are composed of five zones, that is, Collision zone, Arc area, Central Okinawa Trough, Southern Okinawa Trough and Continental shelf which shows different physical properties (Table 7).

Table 7. Material properties used in the finite element modeling. (a) After rifting of Okinawa Trough. (Model -1 a, b, c, d, e, Model -2 a, b, d and Model -3 a, b) (b) Before rifting of Okinawa Trough. (Model -2 c, e and Model -3 c)

(a)

Area	Young's modulus (GPa)	Poisson's ratio	Density (kg/m^3)	Yield stress (MPa)
S1 (Arc area)	30	0.25	2540	240
S2 (Collision zone)	10	0.25	2540	240
S3 (South Okinawa Trough)	5	0.25	2540	120
S4 (Central Okinawa Trough)	7.5	0.25	2540	120
S5 (Continental shelf)	40	0.25	2540	260

(b)

Area	Young's modulus (GPa)	Poisson's ratio	Density (kg/m^3)	Yield stress (MPa)
S1 (Arc area)	30	0.25	2540	240
S2 (Collision zone)	10	0.25	2540	240
S3 (South Okinawa Trough)	29.5	0.25	2540	120
S4 (Central Okinawa Trough)	28.5	0.25	2540	120
S5 (Continental shelf)	40	0.25	2540	260

5.3.1. Model -1 (Present model)

At nodal points 1, 2, 3, 4, 5, 6, 7, 8, 9 and 10, displacements are fixed to E-W direction (x- direction). At nodal points 1, 10, 11, 12, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 80 and 91, displacements are fixed to N-S direction (y- direction). Nodal numbers 1 and 10 are fixed to all directions. In the model, Miyako island is located at the element number 284, Yaeyama islands are located around the element number 181 and Yonaguni island is located at the element number 172 (Fig. 17).

Model -1 a (Subduction only)

We imposed displacement boundary conditionto give the effect of collision between the

Philippine Sea Plate and Eurasia Plate in all nodes *CD*. Nodal points 14, 15, 16 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51 and 52 are given the displacement 7000 m to the N310° direction.

Model -1 b (Subduction and suction force)

Nodal points 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51 and 52 are given the external force 922 MPa which is perpendicular to the Ryukyu Trench to give the suction force (arc-normal pull) along the Ryukyu Trench. Nodal numbers 13, 14, 15 and 16 are given the displacement 7000 m to the N310° to give the effect of collision between Philippine Sea Plate and Eurasia Plate.

Model -1 c, d and e (Subduction and suction force and shear)

Nodal points 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51 and 52 are given the external force 922 MPa which is perpendicular to the Ryukyu Trench. Nodal points 13, 14, 15 and 16 are given the displacement 7000 m to the N310° direction. In c, nodal points 18, 19 and 20 are given shear. In d, nodal points 18, 19, 20, 21, 22, 23, 24 and 25 are given shear. In e, nodal points 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29 and 30 are given the shear. Shear given along the Ryukyu Trench is applied as component which is parallel to Ryukyu Trench in the convergent rate of the Philippine Sea Plate.

5.3.2. Model -2 (1 Ma ago model)

Nodal points 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11 and 12 are not movable to E-W direction (x- direction) and nodal points 1, 13, 14, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, and 70 are not movable to N-S direction (y- direction). Nodal points 1 and 13 are fixed. In the model, Miyako island is located in element number 247, Yaeyama islands are located around element number 212 and Yonaguni island is located in element number 239 (Fig. 18).

Model -2 a (Subduction only)

We imposed displacement boundary condition to give the effect of collision between the Philippine Sea Plate and Eurasia Plate in all nodes *C'D'*. Nodal points 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43 and 44 are given the displacement 7000 m to the N310° direction.

Model -2 b and c (Subduction and suction force)

Nodal points 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43 and 44 are given external force 922 MPa which is perpendicular to Ryukyu Trench. Nodal points 15, 16, 17, 18 and 19 are given the displacement 7000 m to the N310° direction.

Model -2 d and e (Subduction and suction force and shear)

Nodal points 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43 and 44 are given external force 922 MPa. Nodal pots 15, 16, 17, 18 and 19 are given the displacement 7000 m to the N310° direction. Nodal points 20, 21, 22 and 23 are given the shear by oblique subduction of the Philippine Sea Plate.

5.3.3. Model -3 (2 Ma ago model)

Nodal points 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12 and 13 are not movable to x- direction and nodal points 1, 13, 14, 15, 16, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56 and 70 are not movable to y- direction. Nodal points 1 and 13 are fixed. In the model, Miyako island is located in element number 308, Yaeyama islands are located around element number 206 and Yonaguni island is located in element number 218 (Fig. 19).

Model -3 a (Subduction only)

We imposed displacement boundary condition to give the effect of collision between the Philippine Sea Plate and Eurasia Plate in all nodes of *C"D"*. Nodal points 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44 and 45 are given the displacement 7000 m to the N310° direction.

Model -3 b and c (Subduction and suction force)

Nodal points 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44 and 45 are given the external force 922 MPa which is perpendicular to Ryukyu Trench. Nodal points 17, 18 and 19 are given the displacement 7000 m to the N310° direction.

5.4. Stress fields calculated by finite element method

In order to obtain a physically reasonable model, we have tested the influence of various parameters and boundary condition whose results are presented as follows.

5.4.1. Present model (Model -1)

Fig. 21 a, b, c, d and e display the results for a model which represents the tectonic situation referring to the present geological model around the Southern Ryukyu arc. Thin bars displayed in the model show directions of horizontal stress axes. Red bar shows extension and black bar shows compression.

Model -1 a (Fig. 21 a)

Miyako island, Yaeyama island and Yonaguni island are characterized by the uniform

NW-SE compression. The stress patterns are directly caused by the subduction of the Philippine Sea Plate.

Model -1 b (Fig. 21 b)

Miyako island area is characterized by NE-SW extension. Yaeyama islands area is characterized by NE-SW to ENE-WSW extension. Stress pattern in the Yonaguni island area is different from that of Miyako and Yaeyama islands which is characterized by NW-SE extension. The direction of extension is changed from ENE-WSW to WNW-ESE in 123.5° E. The direction of extension shown in the Southern Ryukyu arc is parallel to the axis of the Southern Ryukyu arc.

Model -1 c (Fig. 21 c)

Stress pattern is similar to that of model -1 b.

Model -1 d (Fig. 21 d)

Yonaguni island is characterized by ENE-WSW extension. Iriomote island is characterized by WNW-ESE extension and Ishigaki island is characterized by ENE-WSW extension. Miyako island is characterized by NE-SW extension.

Model -1 e (Fig. 21 e)

Yonaguni island is characterized by ENE-WSW extension. Yaeyama islands is characterized by E-W to ENE-WSW extension. Miyako island area is characterized by NE-SW extension.

5.4.2. 1 Ma ago model (Model -2)

Figs. 22 a, b, c, d and e display the results for the 1 Ma ago model (model -2).

Model -2 a (Fig. 22 a)

Stress pattern in the area (Miyako island, Yaeyama island and Yonaguni island) is the same as Model -1 a; uniform NW-SE compression. These stress patterns are also directly caused by the subduction of the Philippine Sea Plate.

Model -2 b (Fig. 22 b)

Miyako island area is characterized by NE-SW extension. Yaeyama islands area is characterized by ENE-WSW to WNW-ESE extension. Iriomote island is characterized by WNW-ESE extension and Ishigaki island is characterized by ENE-WSW extension. Stress pattern in the Yonaguni island area is different from that of the Miyako and Yaeyama islands. Stress pattern is characterized by NNE-SSW to NNW-SSE compression and WNW-ESE to ENE-WSW extension. Stress pattern in the Yonaguni island is complex.

Model -2 c (Fig. 22 c)

Yonaguni island is characterized by NW-SE compression and NE-SW extension. Yaeyama and Miyako islands are characterized by NW-SE extension.

Model -2 d (Fig. 22 d)

Yonaguni island is characterized by NNW-SSE compression and ENE-WSW extension. In Yaeyama islands, Iriomote and Ishigaki islands are characterized by WNW-ESE extension and Hateruma island is characterized by NNE-SSW compression and NNW-SSE extension. Miyako island is characterized by NE-SW direction.

Model -2 e (Fig. 22 e)

Yonaguni island is characterized by NNW-SSE compression and ENE-WSW extension. In Yaeyama islands, Iriomote and Ishigaki islands are characterized by WNW-ESE extension and Hateruma island is characterized by NNE-SSW compression and NNW-SSE extension. Miyako islands is characterized by NW-SE extension.

5.4.3. 2 Ma ago model (Model -3)

Figs. 23 a, b and c display the results for the 2 Ma ago model (Model -3).

Model -3 a (Fig. 23 a)

The area (Miyako island, Yaeyama island and Yonaguni island) is characterized by the uniform NW-SE compression. The stress pattern is directly caused by the subduction of the Philippine Sea Plate. Although the Miyako and Yaeyama islands are characterized by NW-SE compression, Yonaguni island is characterized by WNW-ESE compression. The stress pattern is changed from NW-SE to WNW-ESE to westward. As a whole, the stress pattern is directly caused by the subduction of the Philippine Sea Plate.

Model -3 b (Fig. 23 b)

Miyako island area is characterized by NE-SW extension. In the Yaeyama islands area, the eastern area is characterized by E-W to WNW-ESE extension and the western area is characterized by NW-SE to WNW-ESE extension. Stress pattern in the Yonaguni island area is different from that of the Miyako and Yaeyama islands. Stress pattern is characterized by NNW-SSE compression and ENE-WSW extension.

Model -3 c (Fig. 23 c)

Yonaguni island is characterized by NW-SE compression and NE-SW extension. Iriomote, Ishigaki and Miyako slands are characterized by NW-SE extension and Hateruma island is characterized by NW-Se extension.

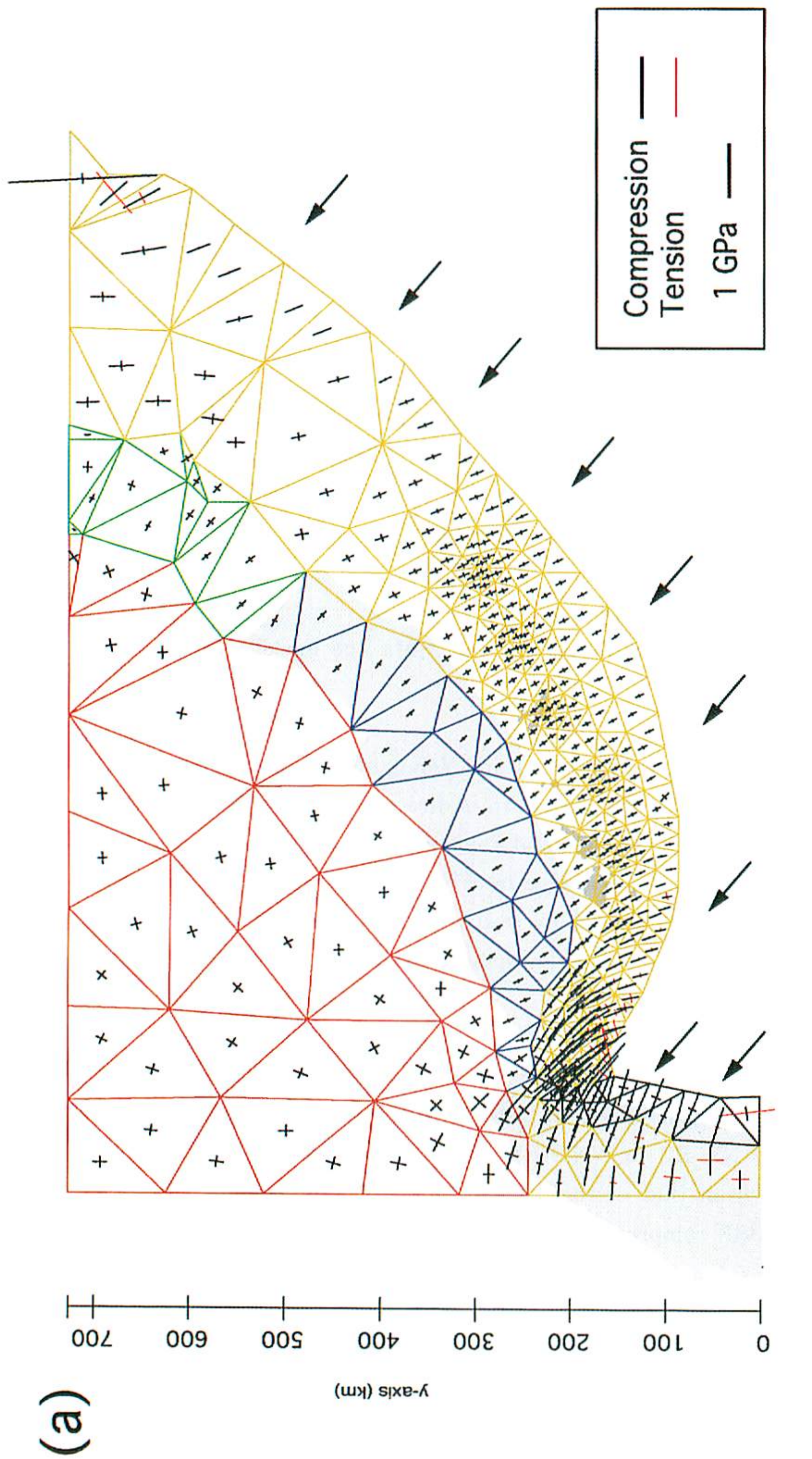

Fig. 21. Stress distribution of Model -1. (a) Considering subduction.

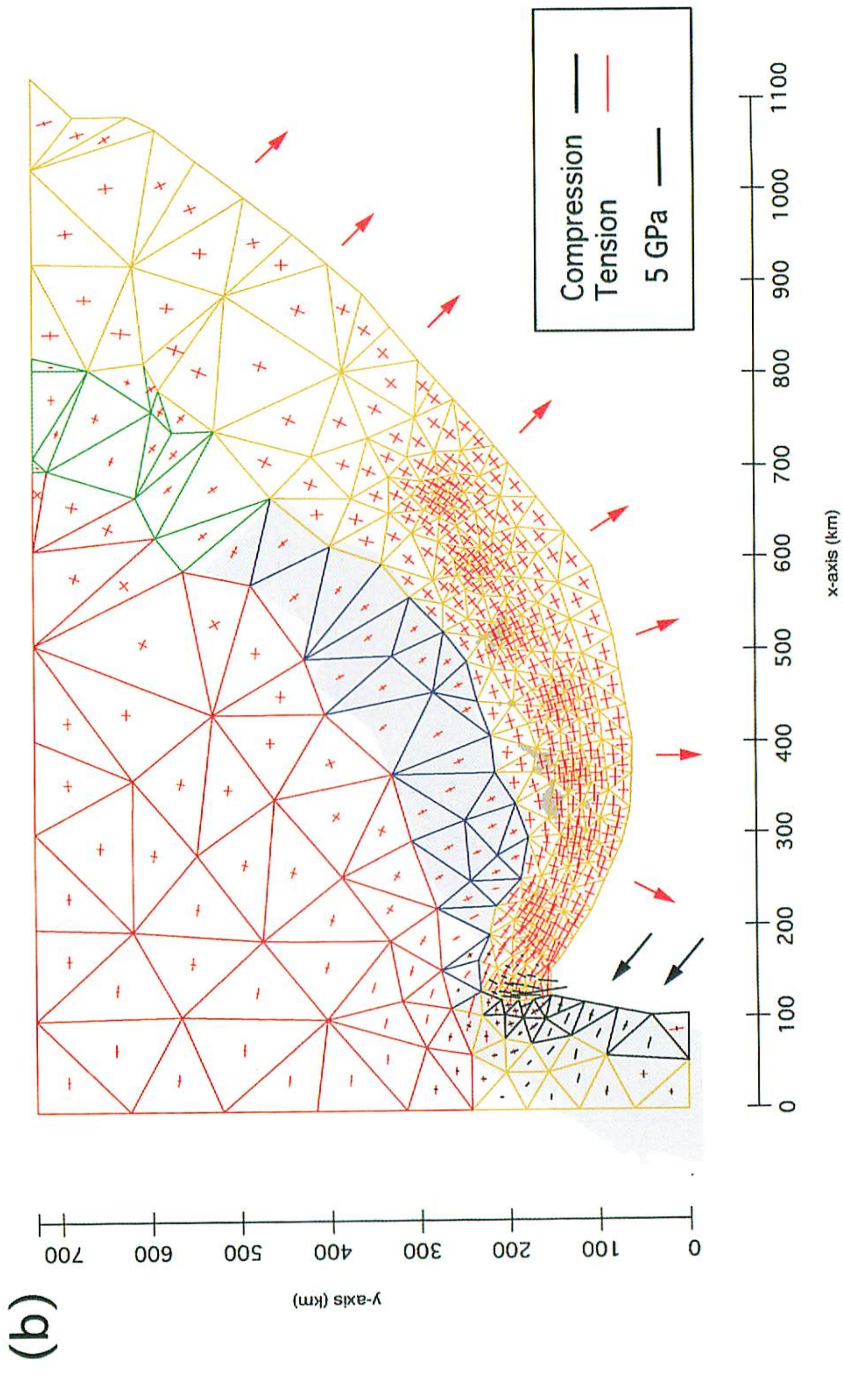

Fig. 21. (b) Considering subduction and suction force.

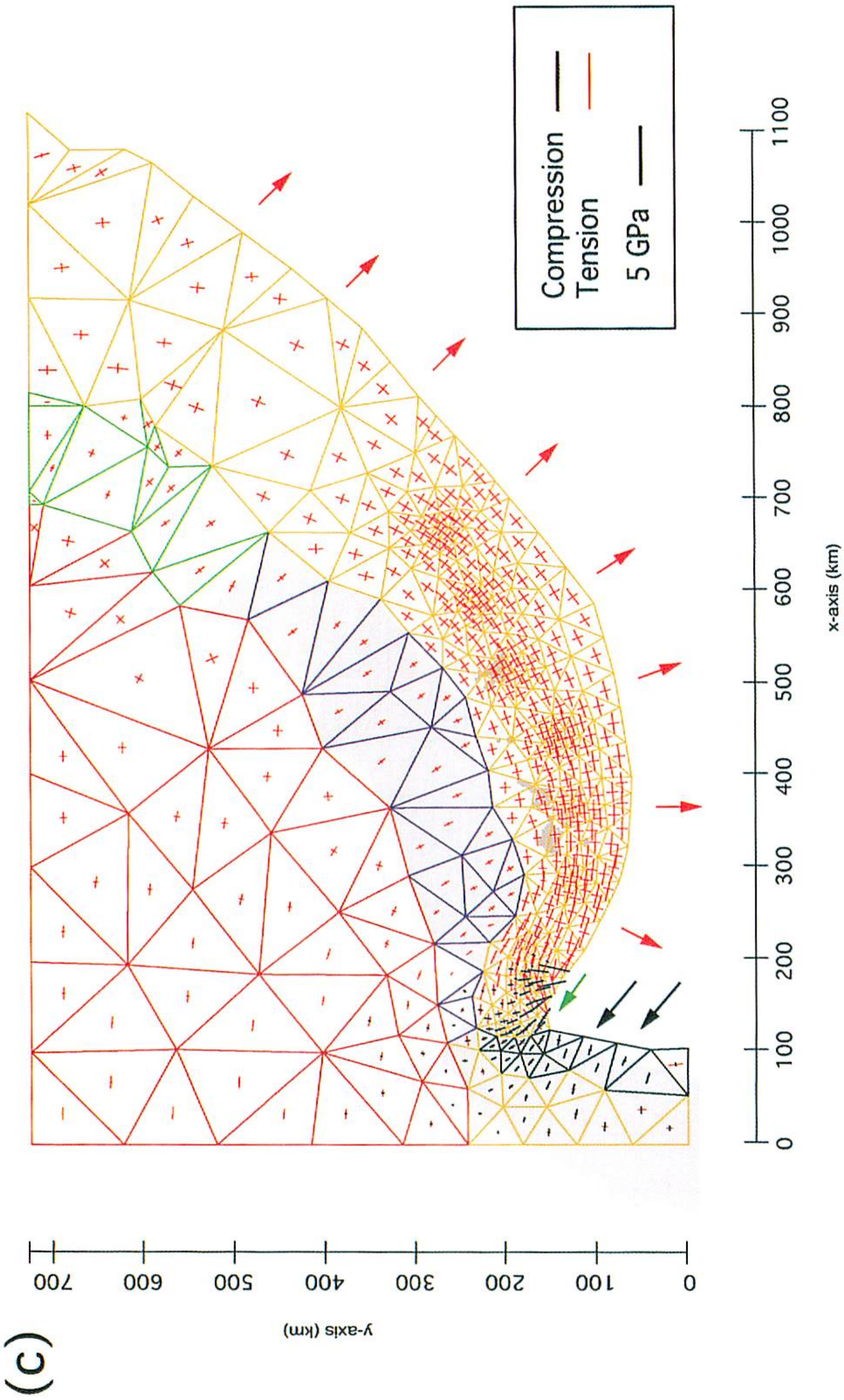

Fig. 21. (c) Considering subduction, suction force and low shear.

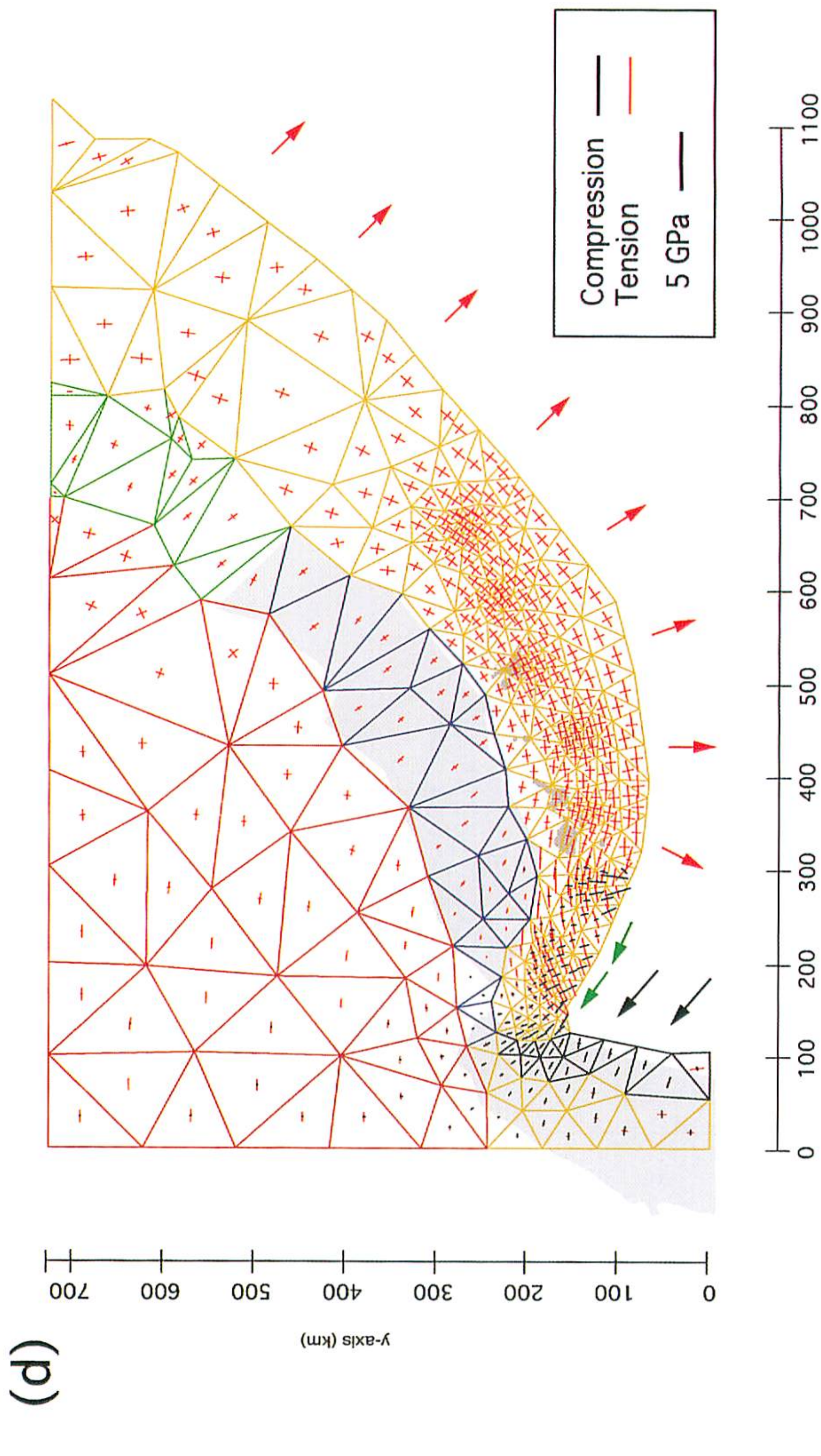

Fig. 21. (d) Considering subduction, suction force and middle shear.

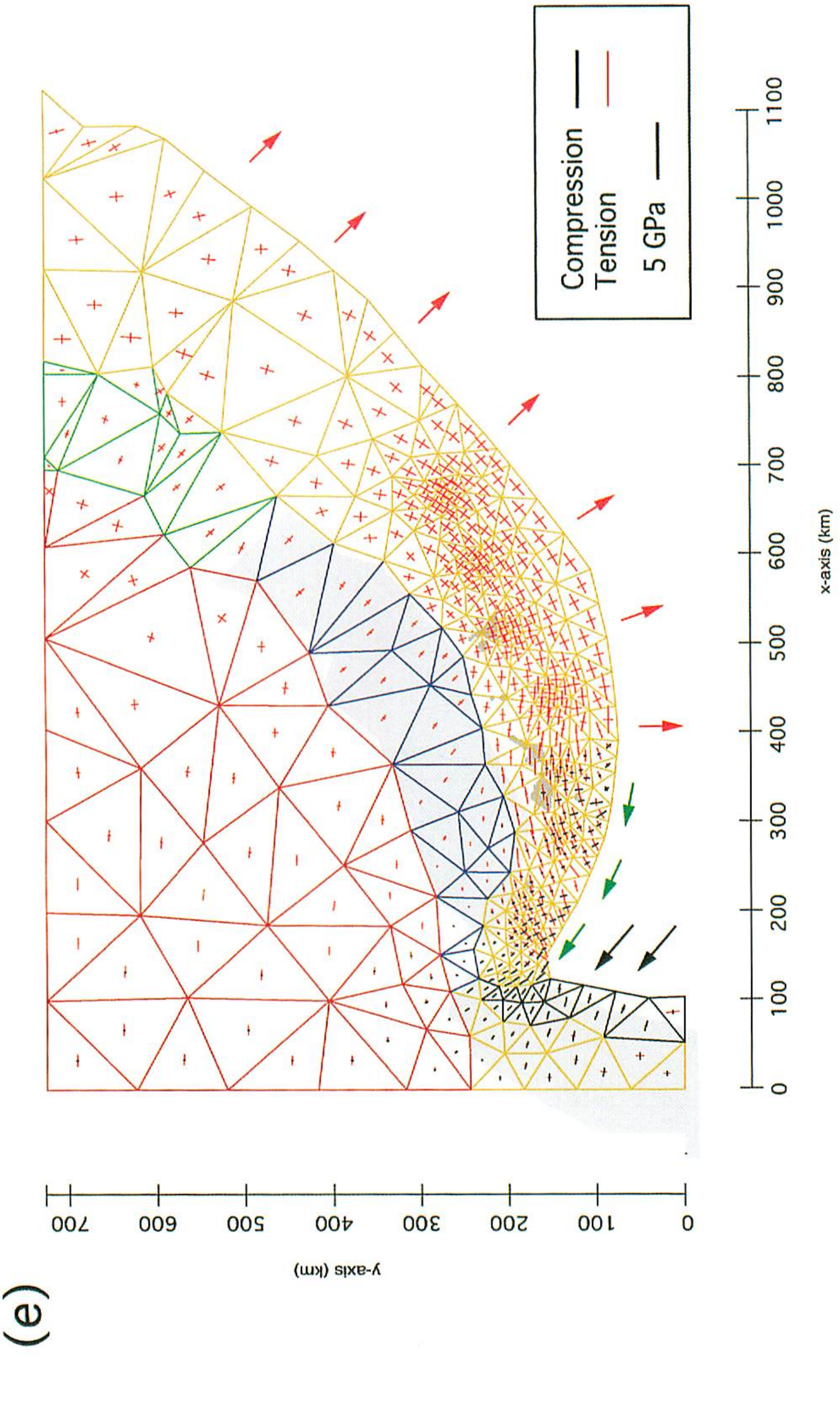

Fig. 21. (e) Considering subduction, suction force and high shear.

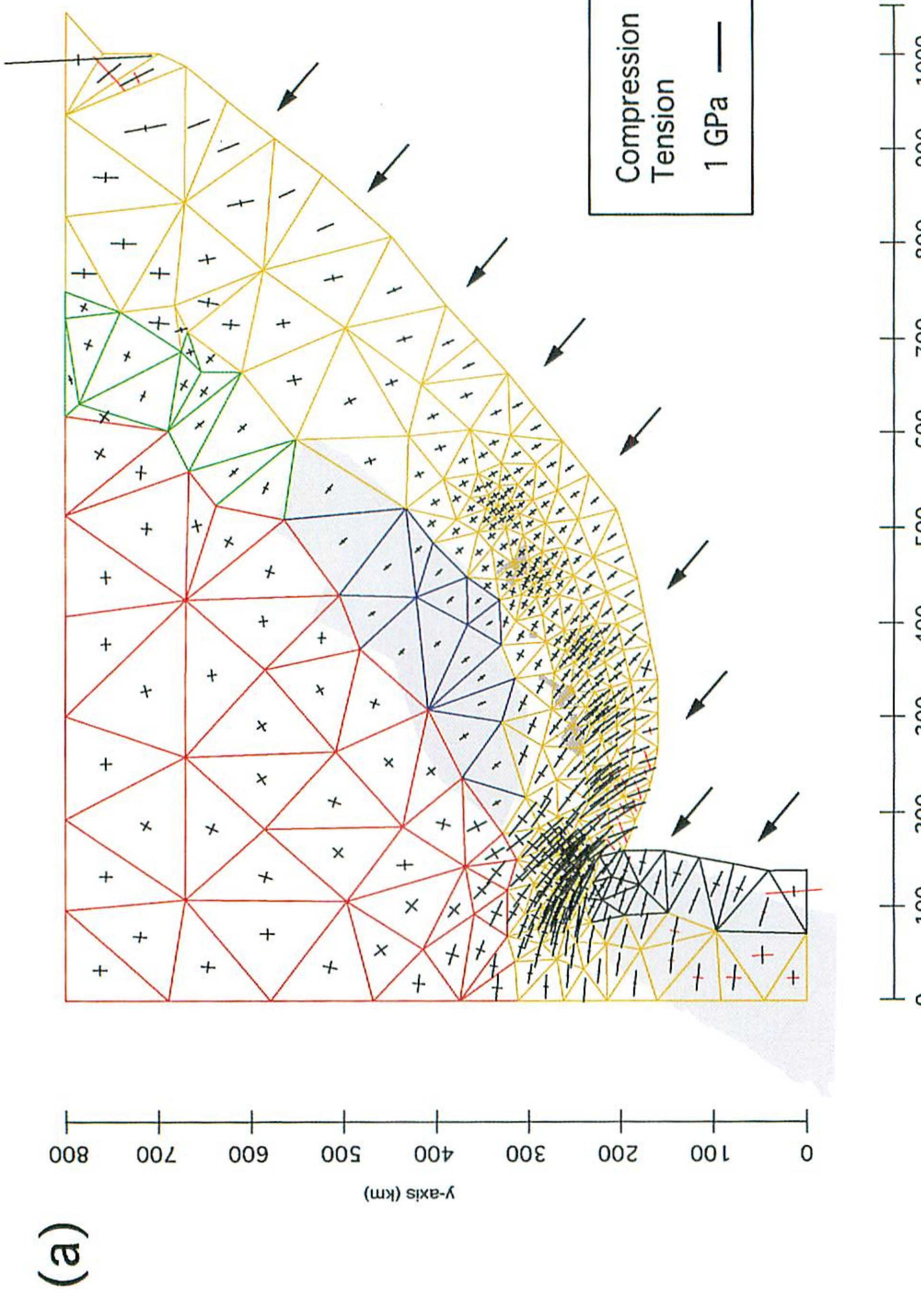

Fig. 22. Stress distribution of Model -2. (a) Considering subduction.

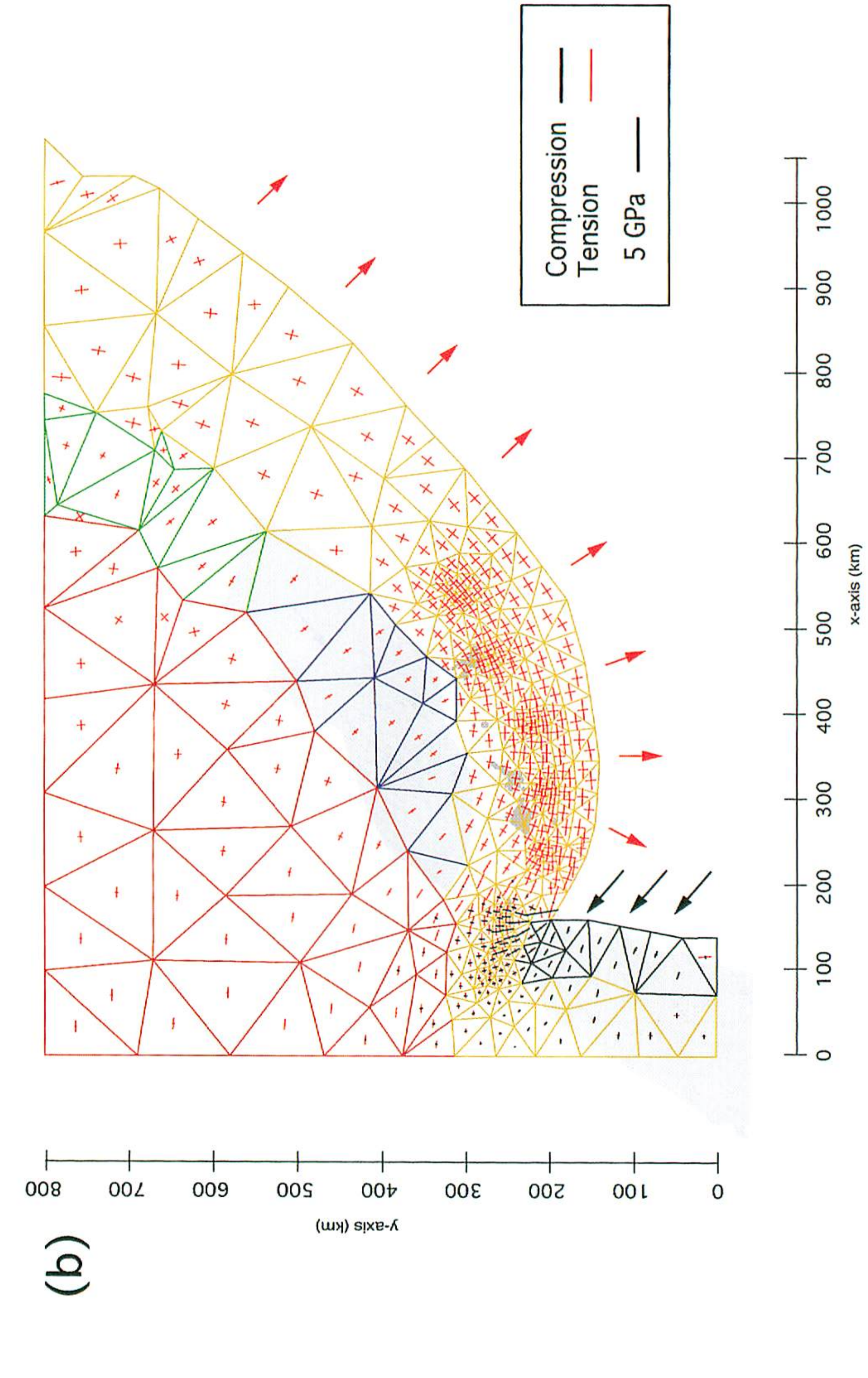

Fig. 22. (b) Considering subduction and suction force.

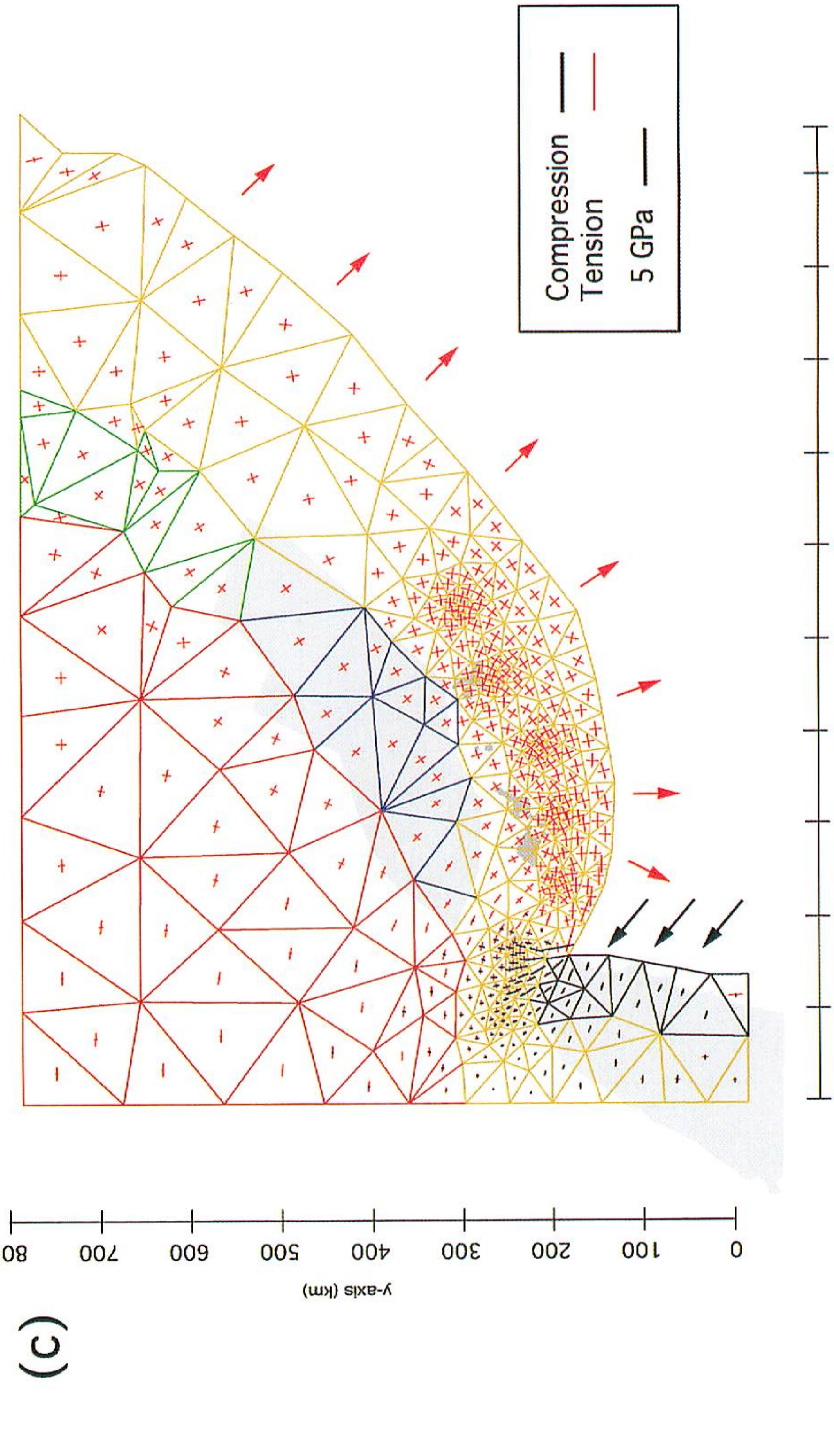

Fig. 22. (c) Considering subduction and suction force.

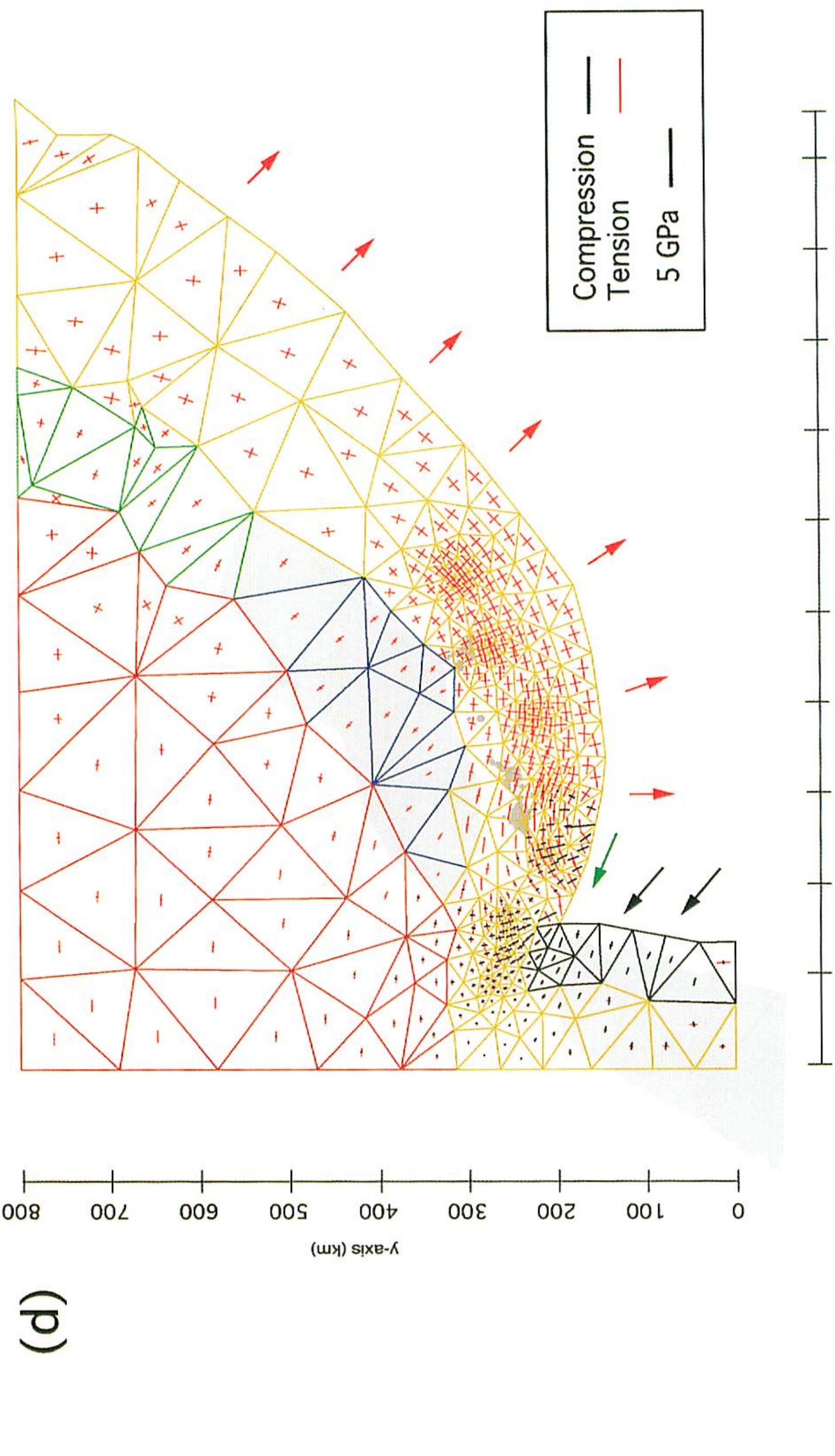

Fig. 22. (d) Considering subduction, suction force and shear.

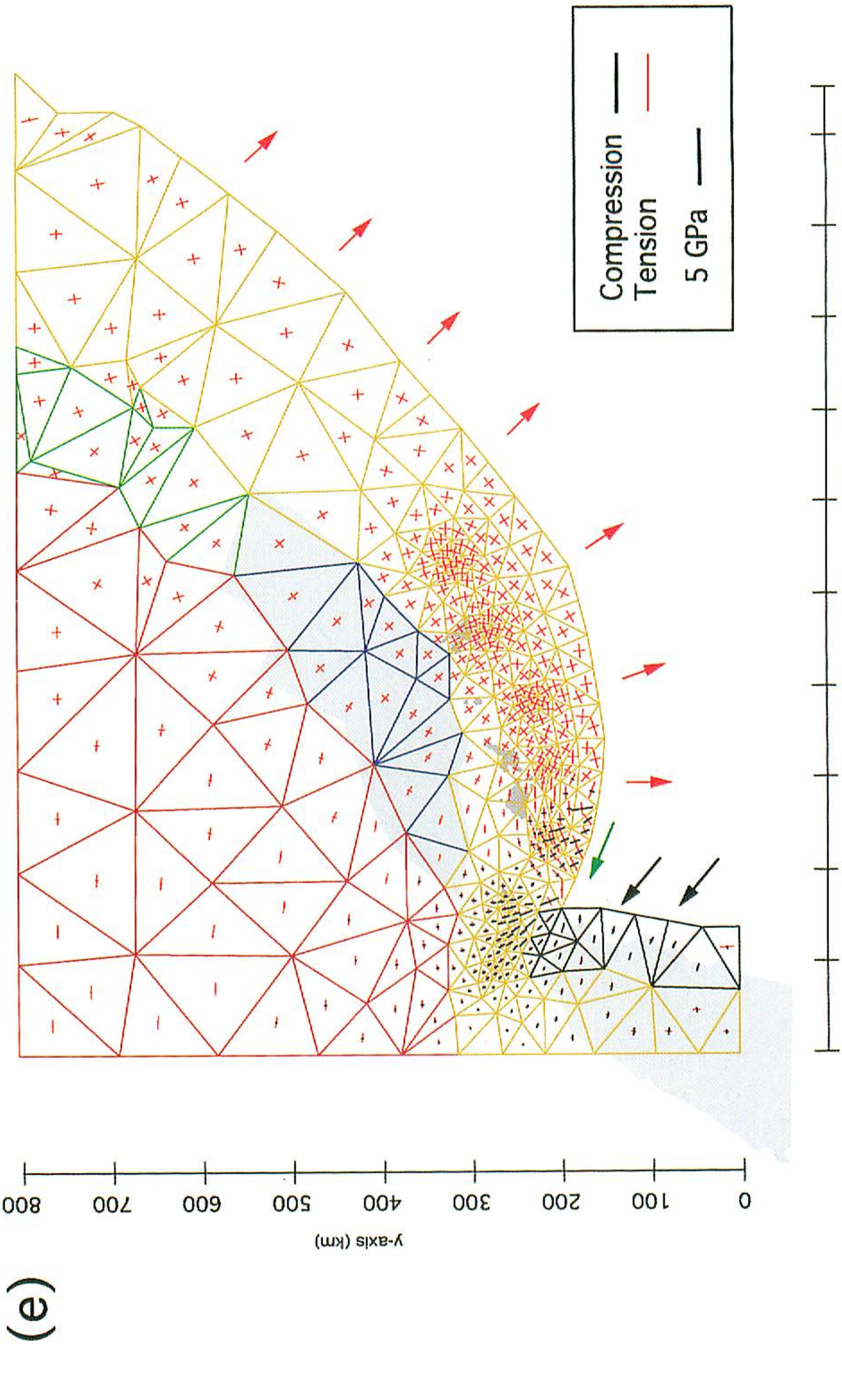

Fig. 22. (e) Considering subduction, suction force and shear.

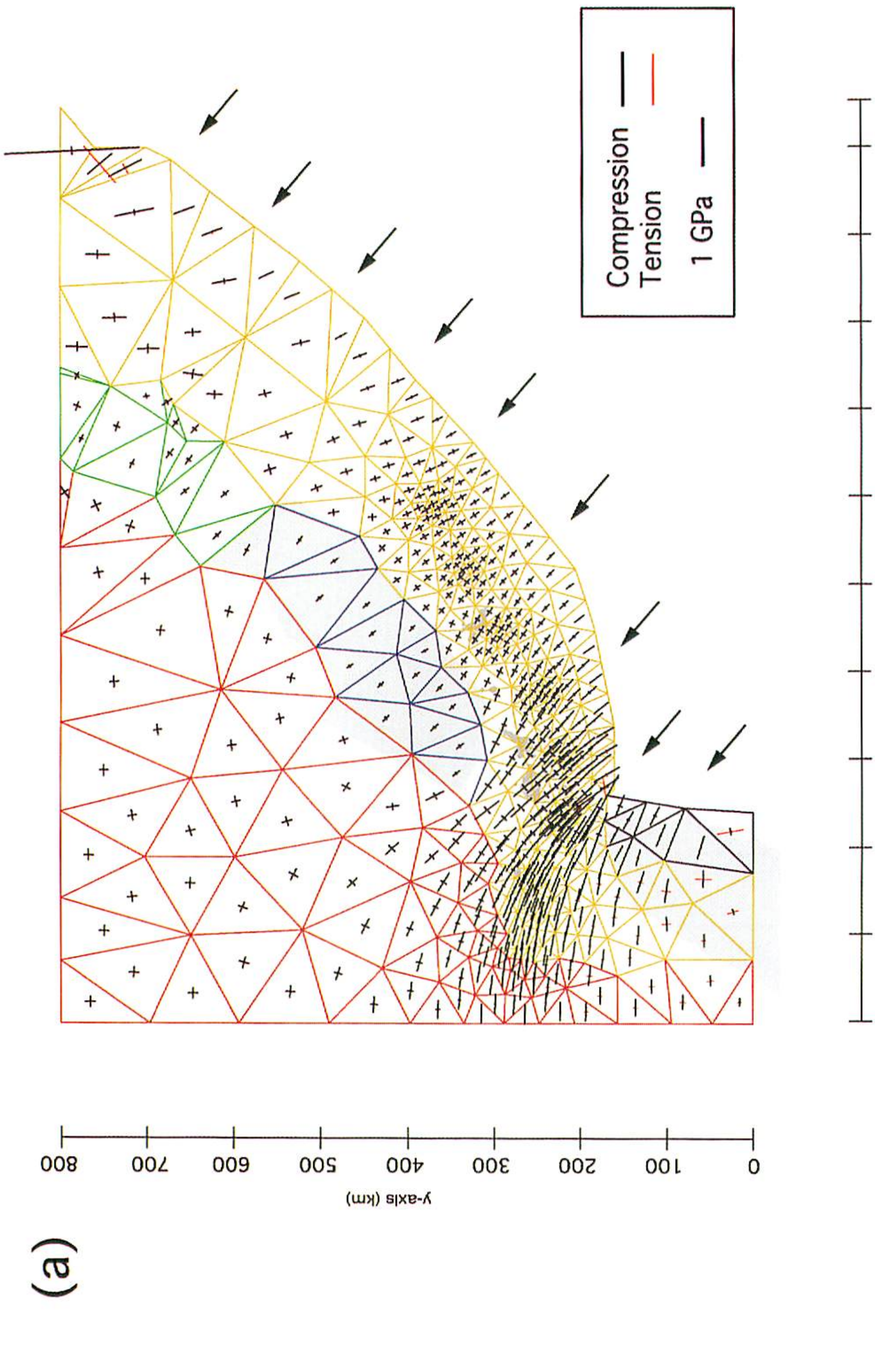

Fig. 23. Stress distribution of Model -3. (a) Considering subduction.

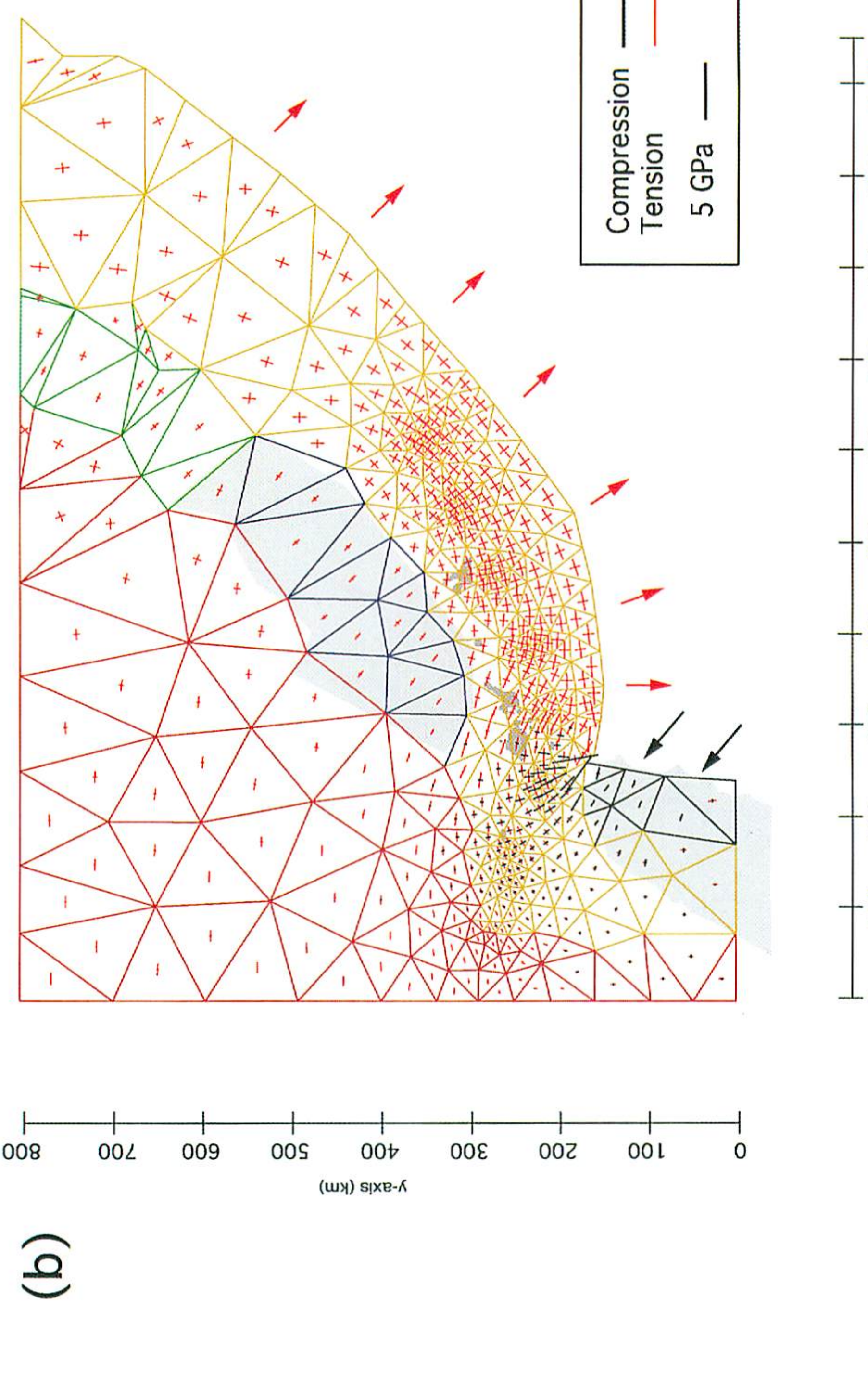

Fig. 23. (b) Considering subduction and suction force.

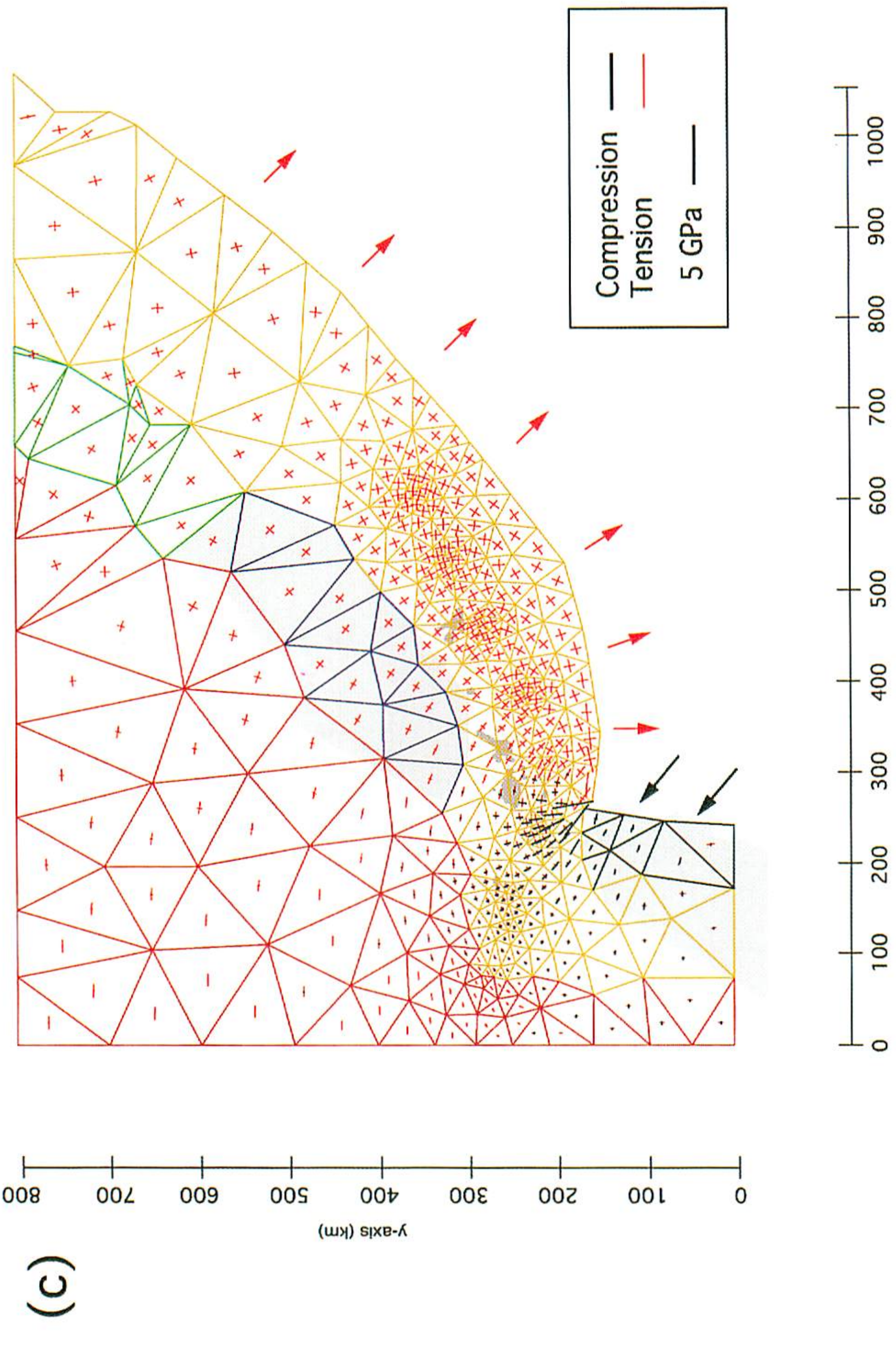

Fig. 23. (c) Considering subduction and suction force.

6. Discussion

6.1. Comparison with previous studies

In the Southern Ryukyu arc, Kuramoto and Konishi (1989) proposed an interpretation for the tectonics based on the paleostress by conjugate fault method and the interpretation of seismic reflection profiles. They proposed that the recent stress field in the Southern Ryukyu arc is under tensile stress whose axial direction is parallel to the Southern Ryukyu arc, and that an E-W dextral slip shear zone is developing at its western extremity, *e.g.* Yonaguni island and westward to Taiwan. They proposed that the Southern Ryukyu arc becomes a sliver migrating westward. This sliver started to migrate westward about 4 Ma ago, when the relative motion between the Philippine Sea Plate and the Eurasian Plate changed its direction from S-N to SE-NW. They explained that this is caused by the oblique subduction of the Philippine Sea plate. Fabbri and Founier (1999) tried to detect paleostress by Angelier's inversion method. They denied the sliver of the Southern Ryukyu arc because tensile stress detected from Miocene to early Pleistocene is perpendicular to the Southern Ryukyu arc and because the stresses found by Kuramoto and Konishi (1989) are not found.

However, their studies have two serious problems. In the first problem, Kuramoto and Konishi (1989) and Fabbri and Founier (1999) did not measure fault-slip data in the Ryukyu Group and Holocene deposits. They inferred that the direction of extension is perpendicular to the strike of the major normal faults and joints in the Ryukyu Group and Holocene deposits. However, the hypothesis is doubtful. Furthermore, Fabbri and Founier (1999) considered that the detected stress pattern (NW-SE extension) is constant from Miocene to Pleistocene. It is reasonable if faults are created by single stress state (Engelder, 1992). We measure the slip data of fault in the Ryukyu Group to detect stresses after the deposition of the Ryukyu Group. Many stress states are obtained in the Southern Ryukyu arc after the deposition of Ryukyu Group, because stress state are heterogeneous (*e.g.* Fig. 13 b). Thus, the stress transition proposed by them (Kuramoto and Konishi, 1989; Fabbri and Founier, 1999) is doubtful.

In the second problem, their methods (conjugate fault method and classic inversion method) have several methodological problems which are pointed out by Yamaji (2001). We show the detailed stress transition by the Multiple inverse method and Ginkgo method which can detect detailed stress from the heterogeneous fault-slip data. We suggest that the stress transition in the Southern Ryukyu arc is more complex than that of previous studies. Although many stresses were detected from the underlying strata (*e.g.* Nosoko Formation), plural stresses are also detected in the after Ryukyu Group (Figs. 14 and 15). Particularly, the after Ryukyu Group stress field in the Southern Ryukyu arc is divided into three zones; Miyako island and Yaeyama islands excluding for Hateruma island (MY zone), Hateruma island (HA zone) and Yonaguni island (YO zone). Stress pattern including strike-slip faulting regime is a peculiarity of the Hateruma island (MY zone), Hateruma island (HA zone) and Yonaguni island (YO zone). After Ryukyu Group stress transition in MY zone in this study (from NW-SE extension to NE-SW extension) may be identical with that of the previous studies, *e.g.* Kuramoto and Konishi (1989) and Fabbri and Founier (1999). We suggest complex tectonic setting after the deposition of the Ryukyu Group.

6.2. Arc-parallel extension in the Southern Ryukyu arc

From the fault-slip analysis, latest stress field in the Southern Ryukyu arc is found as the arc-parallel extension. Miyako and Yaeyama islands is characterized by NE-SW extension and Yonaguni island is characterized by NW-SE extension (Fig. 15). We construct the latest stress field in the Southern Ryukyu arc by considering the stress pattern detected by the fault-slip analysis and that simulated by the finite element method. Stress field shown in Model -1 b and c corresponds to that detected by the fault-slip analysis (Figs. 21 b and c). We proposed that the stress field is caused by the response to the increasing curvature of the whole arc accompanying the still active back arc basin (Okinawa Trough) such as the opinions by Fabbri and Fournier (1999) and Fabbri (2000). Fabbri (2000) called the extension as arc-parallel stretching. Because Southern Ryukyu arc is bend like "V" in 123.5° E (Fig. 1), stress pattern in the Yonaguni island (NW-SE extension) must be opposite to that in the Miyako and Yaeyama islands (NE-SW extension) (Fig. 15).

6.3. Complex stress state in western area from 123.5° E at after Ryukyu Group

From the stress pattern calculated by the finite element method (Figs. 22 b, c and 23 b), we suggest that the complex stress state in the western area from 123.5° E (YO zone) at after Ryukyu Group must be concerned with the westward migration of the Okinawa Trough and collision at Taiwan. Strike-slip faulting regime at the after Ryukyu Group is created by the collision at Taiwan.

In contrast to this, the stress transition in the eastern area from 123.5° E (MY zone) is simpler than that in the western area. From the stress pattern given by the finite element method, it is inferred that the collision at Taiwan had no effect in the eastern area from 123.5° E (MY and HA zones) after the deposition of the Ryukyu Group. The stress transition of the after Ryukyu Group from NW-SE extension to NE-SW extension in MY zone is affected by the rifting of the Okinawa Trough. We change the values of Young's modulus of the zone of the Okinawa Trough to the value of the continental shelf zone or arc zone to realize the embryonic stage of the Okinawa Trough. Stress pattern in MY zone is changed from NW-SE to NE-SW by changing the value of Young's modulus (Figs. 22 c and e). Thus the after Ryukyu Group stress transition from NW-SE extension to NE-SW extension found in MY zone is a key in the argument of the beginning of the Okinawa Trough. Some previous works (Letouzey and Kimura, 1985; Kimura, 1990; Furukawa *et al.*, 1991) proposed that the rifting of the Okinawa Trough occurred about 2 Ma ago, based on the geologic and seismic observations. Furthermore, Park *et al.* (1998) proposed that the rifting occurred after deposition of the Shimajiri Group from the seismic reflection survey. However we suggest the later start of the active rifting of the Okinawa Trough which is different from the previous works.

6.4. Is the Southern Ryukyu arc a forearc sliver?

As already stated, Kuramoto and Konishi (1989) proposed the sliver migration to westward which caused by the oblique subduction of the Philippine Sea plate in the Southern Ryukyu arc. We also find out the stresses which were detected by them in after Ryukyu Group. As has been pointed out by them, "Is the Southern Ryukyu arc a forearc sliver?", we simulate the oblique subduction of the Philippine Sea plate in the Southern Ryukyu arc by the finite element method (Figs. 21a, 22a and 23a). However, the stress pattern simulated by the finite element method does not support the results proposed by Kuramoto and Konishi (1989) because the stresses detected by them (E-W dextral slip developing at its western extremity, Yonaguni island and westwards to Taiwan and arc parallel extension in eastern island from Iriomote island) do not coincide with that from FEM. We deny that the Southern Ryukyu arc is a forearc sliver.

6.5. Unique stress field detected in Hateruma island

Two strike-slip fault regimes are detected in the Hateruma island. Stress field in the Hateruma island is different from those in other islands, Miyako island, Yaeyama islands and Yonaguni island. It is caused by shear stress under the influence of oblique subduction because the Hateruma island is located near the Ryukyu Trench. If shear stress is given along the part under 45° between the Ryukyu Trench and angle of subduction of the Philippine Sea Plate in the Ryukyu Trench, the stress pattern applied shear is correspond to that of the stresses detected in the Hateruma island. On the basis of the above result simulated by the finite element method, stress pattern in the island may be changed from strike-slip faulting regime to normal faulting regime. This is caused by that shear zone occurred by the oblique subduction of the Philippine Sea Plate moved to westward.

6.6. Neotectonics in the Southern Ryukyu arc deduceed by stress field

As mentioned above, stress transition in the after Ryukyu Group is found by the measurement of the fault-slip data in the Ryukyu Group and Holocene deposits. Comparison between stress pattern detected by the fault-slip analysis and that simulated by the finite element method leads the following neotectonic evolution in the Southern Ryukyu arc 1 Ma ago (Fig. 24).

Stress transition from NW-SE extension to NE-SW extension in after Ryukyu Group in the Miyako island is caused by the rifting of the Okinawa Trough at about 1 Ma ago based on the comparison between stress detected by the fault-slip analysis and the one simulated by the finite element method. In tectonic evolution around the area, we suggest

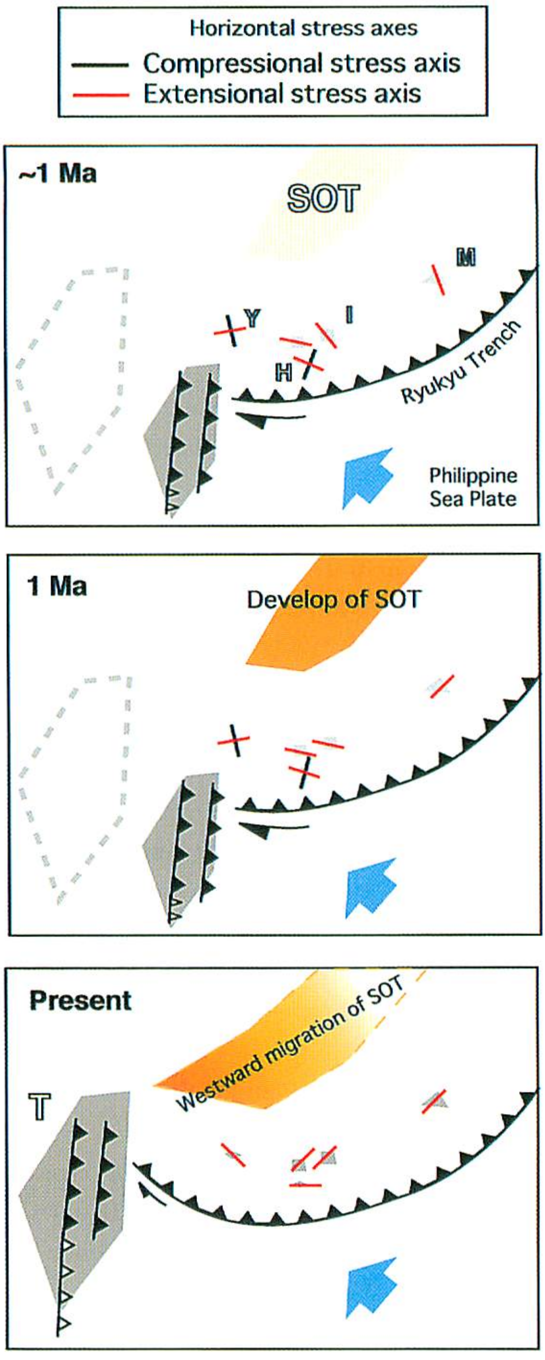

Fig. 24. Schematic diagram to show the tectonic evolution around the Southern Ryukyu arc. Neo stress field 1 Ma ago is explained by three factors: (1) Rifting of Okinawa Trough, (2) Westward migration of the rifting Okinawa Trough and Taiwan, (3) Shear along Ryukyu Trench by the oblique subduction of the Philippine Sea plate.

SOT: Southern Okinawa Trough, I: Ishigaki island, M: Miyako island, T: Taiwan, Y: Yonaguni island. Black and red bars indicate the direction of horizontal stress axes detected by fault-slip analysis.

that the rifting of the Southern Okinawa Trough was probably developed after the deposition or syn-deposition of the Ryukyu Group during the late Pleistocene (***Stage 1***, before 1 Ma ago). Yonaguni island (western area in the Southern Ryukyu arc) suffered the complex stress field including the strike-slip faulting regime by the westward migration of the collision at Taiwan. Hateruma island is affected by the oblique subduction of the Philippine Sea Plate (***Stage 2***, before 1 Ma ago).Then, arc parallel stretching has been occurring in relation to the increasing curvature of the whole arc accompanying active Okinawa Trough (Stage 3, present).

7. Conclusions

Conclusions are summarized as follows.

(1) The slip data of fault in the Ryukyu Group are measured.

(2) Detailed stress transition based on the stress given by the Multiple inverse method and Ginkgo method is more complex than those of the previous studies. Stress field of the after Ryukyu Group is divided into three zones; Miyako island and Yaeyama islands excluding for Hateruma island (MY zone), Hateruma island (HA zone) and Yonaguni island (YO zone).

(3) Latest stress field in the Southern Ryukyu arc is arc-parallel extension and the stress field is caused by the response to the increasing curvature of the whole arc accompanying the still active back arc basin (Okinawa Trough).

(4) Complex stress state in the western area from 123.5° E (YO zone) at the after Ryukyu Group must be concerned with the westward migration of the rifting of the Okinawa Trough and the collision at Taiwan.

(5) Stress pattern simulated by finite element method do not support the stresses detected by Kuramoto and Konishi (1989) (E-W dextral slip in the Yonaguni island and arc parallel extension in the eastern island from the Iriomote island).

(6) Two strike-slip faulting regimes in the Hateruma island are different from those of other islands and may be caused by the fact that the Hateruma island is located near the Ryukyu Trench.

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