Estimation of crustal strength in Izu collision zone

Estimation of crustal strength in Izu collision zone

Koji Shiokawa and Daigoro Hayashi

Department of Physics and Earth Sciences,
University of the Ryukyus,
Nishihara, Okinawa, 903-0213, Japan

Abstract

We used 2D finite element method (FEM) to investigate the crustal strength of the Izu collision zone. Our model primarily based on the crustal structure given by Aoike et al. (2001). We set up standard rock layer properties for simulation. During simulation, cohesion was varied systematically. Simulation results show that failure zone decreases with increasing the convergent displacement in both cases i.e. before and after increasing cohesion. We used Mohr-Coulomb failure criterion and Mohr's circle to understand the reason. It is reasonable that rock layers do not break but flow below more than 30km depth. Further we compared simulated results with the focal mechanism data. Our models show only normal faulting which is not consistent with focal mechanism data. Thus our simulation models probably reveal the crustal strength of Izu collision zone.

Introduction

As Cenozoic strata are heavily deformed in southern Fossa Magna area, strucrural geologists have paid attention to the area for long time. This area is the boundary between northeastern Japan and southwestern Japan in geological meaning, which is important to analyze the Cenozoic structural development in Japanese island, and has been discussed since early 20th century (Amano, 1986).

Izu peninsula, the main part of "Izu-Ogasawara arc", is composed of volcanic complex on Philippine Sea plate produced by the subduction of Pacific plate. As the Philippine Sea plate is oceanic plate, its crust is oceanic and thin. As some parts of the Izu volcanic arc have thick crust because of its igneous activities, the Izu peninsula could not be subducted beneath the Honshu arc, but collided with it (Fig.1). This collision has intermittently been continued since last 17 million years. Koma, Misaka, and Tanzawa mountains are the remnants of the former collision of Izu-Ogasawara islands to the

Received: June 29, 2004

Honshu arc. The migrations of plate boundary with collision have occurred (Fig.2) (Seno, 2001).

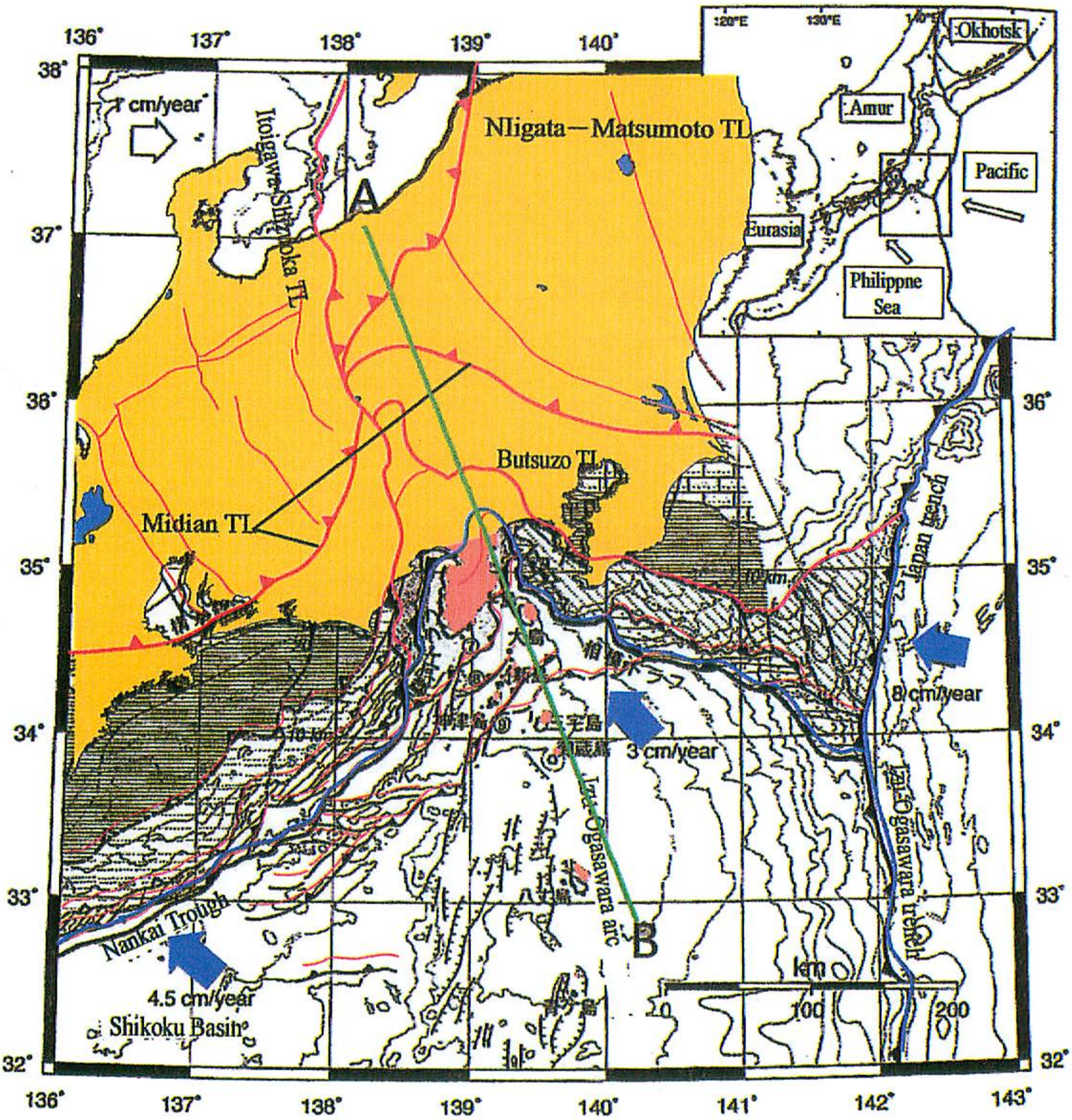


Fig.1 Major tectonic lines in central Japan. A-B is a line of cross section showing in Fig.3 (Aoike et al., 2001).

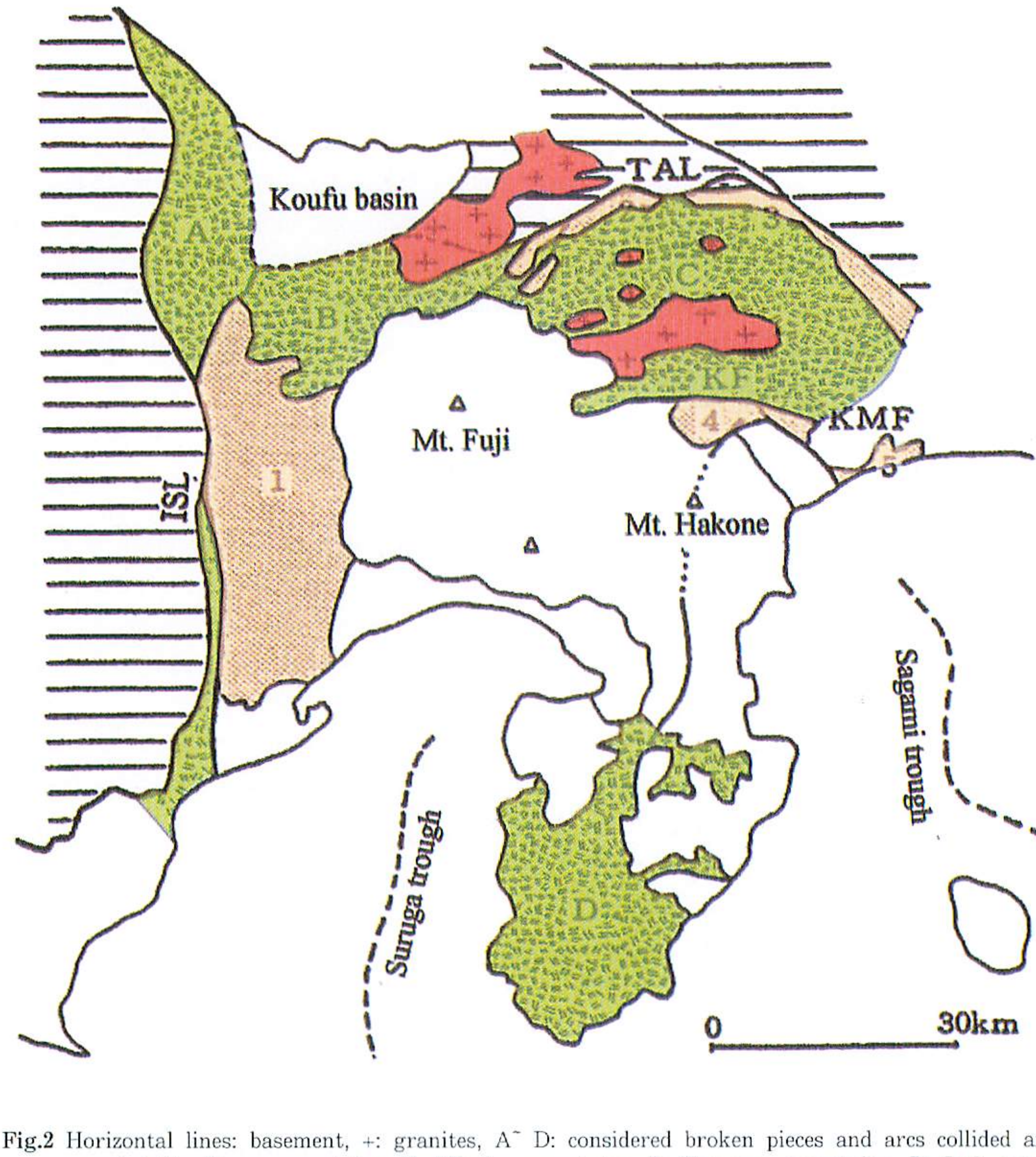


Fig.2 Horizontal lines: basement, +: granites, A~ D: considered broken pieces and arcs collided and accreted (A: Koma mountains, B: Misaka mountains, C: Tanzawa mountains, D: Izu), sandy parts: sediments filling the troughs formed by arc collisions (1: Fujikawa, 2: Nishikatsura, 3: north eastern Tanzawa, 4: Ashigara, 5: Ooiso), solid lines: major faults (dashed parts are estimated, ISL: Itoigawa-Shizuoka tectonic line, TAL: Tonoki-Aikawa tectonic line, KF: Kannawa fault, KMF: Kouzu-Matsuda fault) (Amano, 1986).

We used 2D finite element method (FEM) to simulate the failured element distribution in the Izu collision zone. This study also focuses to estimate the crustal strength of the Izu collision zone. We construct our simulation model based on the crustal structure given by Aoike et al.(2001), where standard rock layer properties are adopted for simulation. During simulation, value of cohesion is changed systematically. Since cohesion is directly related to failure condition, cohesion is important to investigate the crustal strength.

Our study area is a blank area of earthquake, which there are many earthquakes close to both sides. In the study area, Pacific plate is subducting under the Philippine Sea plate, while the Izu-Ogasawara arc is colliding to the Honshu arc. Thus great earthquakes must happen around the study area in future. Although we cannot still specify the exact rock layer properties of crust, when we can do, it brings valuable data to structural geology and useful to the prediction of earthquakes.

Geological setting

Except for Mt. Fuji, Mt. Hakone which are Quaternary volcanoes and terrace deposits, formations distributing in Izu collision zone are divided into two. One consists mainly of volcanic and pyroclastic rocks, which are mostly produced by submarine volcanic activities caused by the subduction of Pacific plate, while the other is composed mainly of clastic sediments, which are trough sediments or trench slop sediments (Fig.2).

The collision between Izu-Ogasawara arc and southwest Japan started from middle Miocene. Collisions and accretions of volcanic body have been repeated several times. Koma, Misaka, and Tanzawa mountains are the remnants of Izu-Ogasawara volcanic body accreted to the Honshu arc. Since these mountain areas are the results of the former collision of the Izu block, the Izu-Ogasawara arc is the multiple collision zone with Eurasia plate (Niitsuma & Matsuda, 1984; Soh, 1986; Amano et al. 1986).

Today many researchers agree that the Nankai trough and the Sagami trough are the limits of northern Philippine Sea plate where plate boundary is not clear. If the southern Fossa Magna is the multiple collision zone to the Izu arc, this belt-like wide area is the plate boundary. Thus the subduction boundary moves from north to south: from Itoigawa -Sizuoka tectonic line to Akebono thrust, and to Tonoki-Aikawa tectonic line, and to Kannawa fault・Kouzu-Matsuda fault (Amano, 1986).

Simulation

Modeling

We suppose that the Izu collision zone is composed of elastic materials, which is divided into a number of triangle elements.

We prepare a simulation model of study area shown in Fig.3, referring the crustal

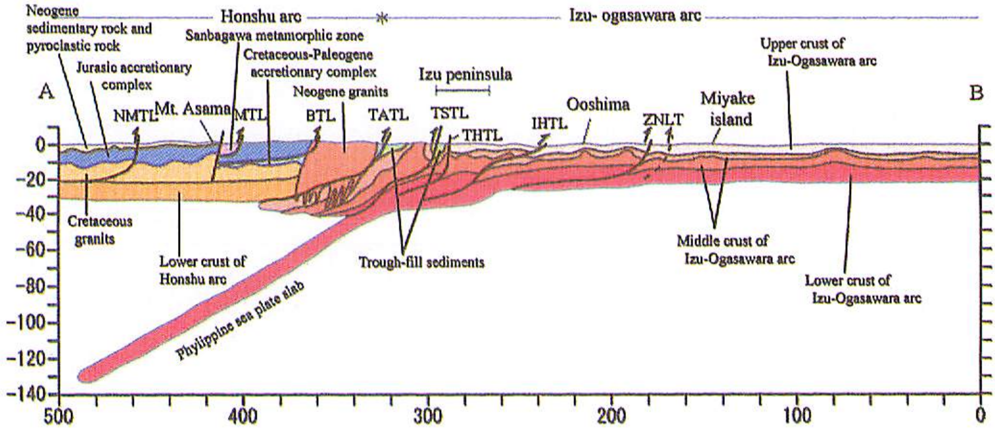


Fig.3 NMTL: Niigata-Matsumoto tectonic line, MTL: Median tectonic line, BTL: Butsuzo tectonic line, TATL: Tonoki-Aikawa tectonic line, TSTL: Tagonoura-Sakou tectonic line, THTL: Tanna-Hirayama tectonic line, IHTL: Irou-Higashi Izu tectonic line, ZNTL: Zenisu-Niijima tectonic line and showing A-B line in Fig.1 (Aoike et al, 2001).

cross section after Aoike (2001). To simplify the mode, depth is 70 km and the length is 505 km from north to south. Model profile is divided to five rock layers, that is upper crust, middle crust, lower crust, Neogene granites and mantle. The upper crust includes the Izu-Ogasawara arc upper crust, Neogene sedimentary and pyroclastic rock, Jurassic accretionary complex and Sanbagawa belt. The middle crust is composed of the Izu-Ogasawara arc middle crust, trough sediments, Cretaceous granite group and Cretaceous to Paleogene accretionary complex. The lower crust comprises the Izu-Ogasawara arc lower crust, Philippine Sea plate slab and the Honshu arc lower crust. The Neogene granites are the independent rock layers. The mantle is sandwiched between slab and the Mohorovicic discontinuity in the profile model.

Simulation model is partitioned into 1158 nodal points and 2069 elements as shown in Fig.4.

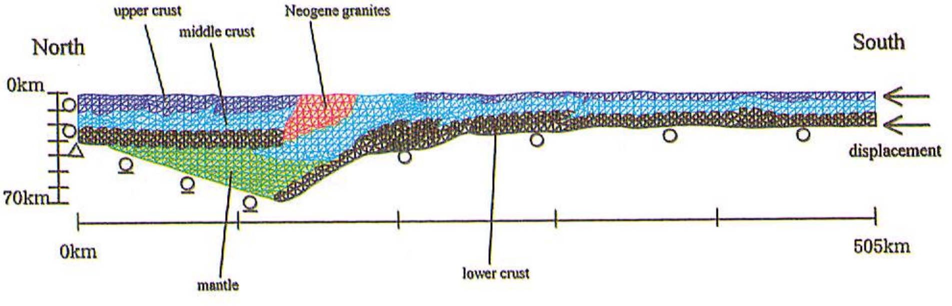


Fig.4 Model partition and boundary condition based on the profile shown in Fig.3.

Model A and B

We simulate a model of Izu collision zone using suitable rock layer properties shown on Table 1. This is called model A. Then we increase the cohesion of every rock layers except for mantle to 50 MPa, while the cohesion of mantle is increased from 30 to 90 MPa shown on Table 2, which is called model B.

Table 1 Rock layer property of model A.

	poisson's ratio	den,siy (kg/m^3)	Young's modulus(GPa)	cohesion (MPa)	angle of internal friction(deg)
uppercrust	0.25	2600.0	30.0	10.0	30.0
middle crust	0.25	2700.0	35.0	15.0	30.0
lower crust	0.25	2800.0	40.0	20.0	30.0
Neogene granites	0.25	2700.0	35.0	15.0	30.0
mantle	0.30	3100.0	60.0	30.0	40.0

Table 2 Rock layer property of model B.

	poisson's ratio	den,siy (kg/m^3)	Young's modulus(GPa)	cohesion (MPa)	angle of internal friction(deg)
uppercrust				50.0	
middle crust				50.0	
lower crust				50.0	
Neogene granites				50.0	
mantle				90.0	

Cohesion and angle of internal friction are the constants described in the Mohr-Coulomb criterion.

$$\tau = c + \sigma \tan \Phi$$

τ; shear stress, c ; cohesion, σ; normal stress, Φ; angle of internal friction

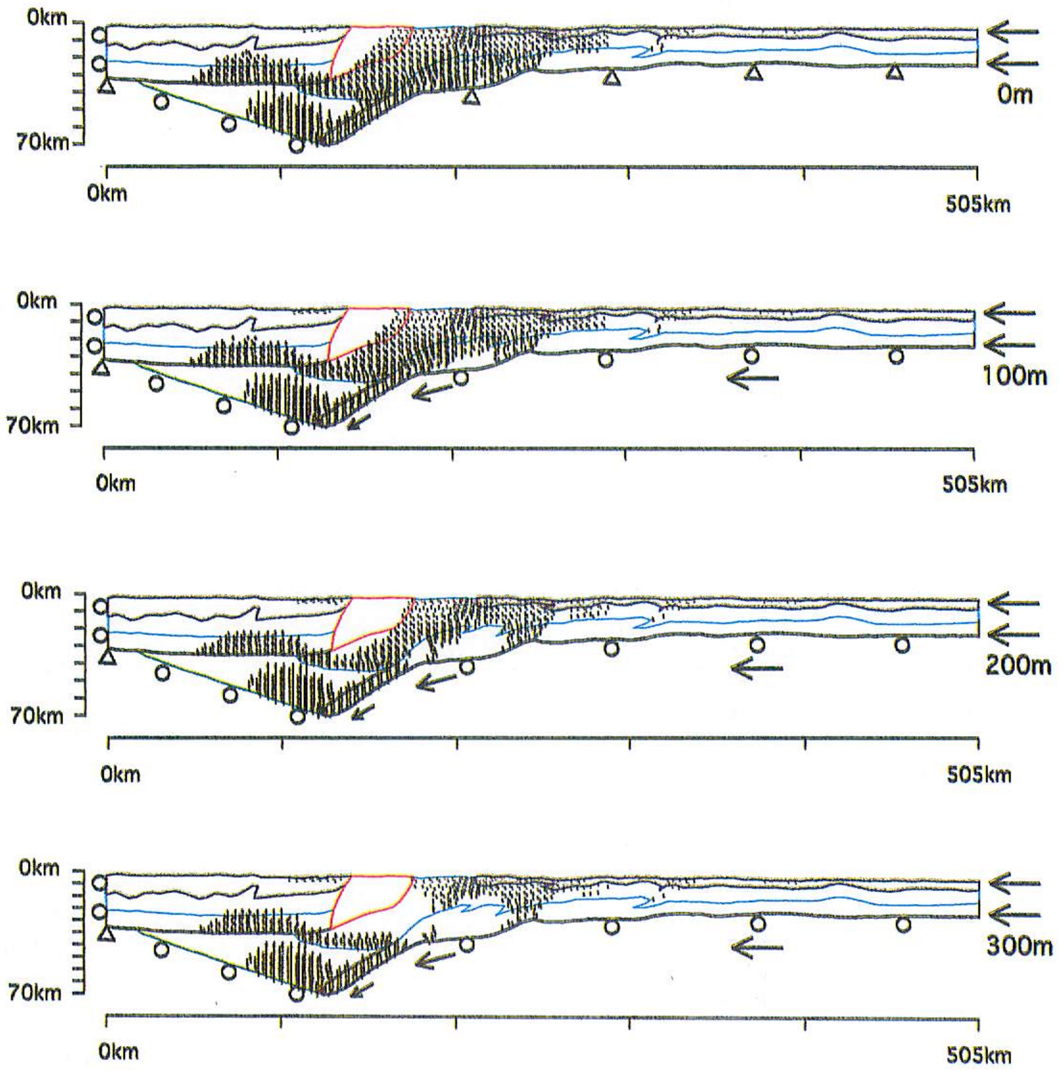
The equation shows the failure line in σ - τ diagram. The stress field beyond the line indicates failure zone.

Boundary condition

In order to realize the natural situation, we imposed a boundary condition representing the present day plate kinematics in the Izu collision zone. As shown in Fig.4, upper surface is free, but bottom is fixed vertically. The nodes along the left side boundary can only move vertically, whereas from the right side of the model, we impose convergent displacements whose value changes progressively from 0m to 500m at interval of 100m.

Result

Crossed bars show maximum compressive stress σ_1 (longer bar) and minimum compressive stress σ_3 (shorter bar) in the failured elements in Figs. 5 and 6. Directions of longer bar and shorter bar indicate the direction of σ_1 and σ_3, where black bars indicate compressive and red express tensile.



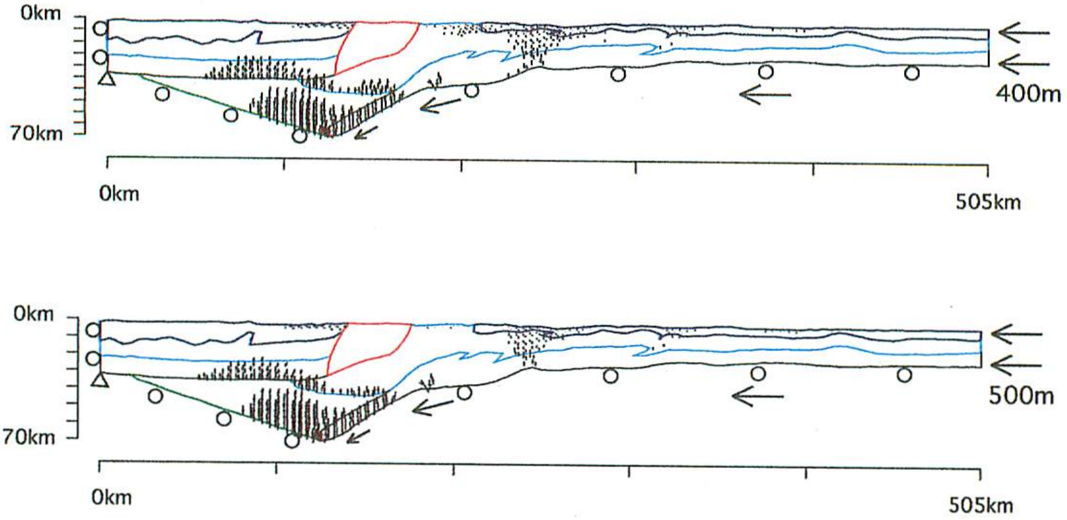
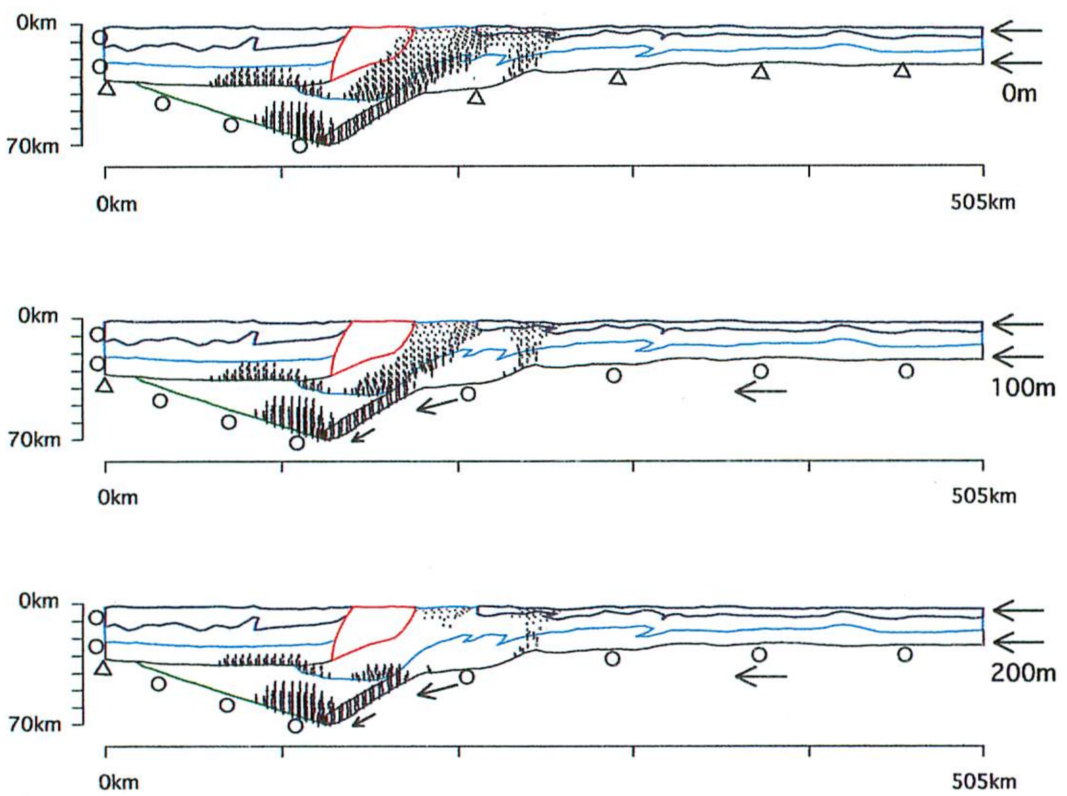


Fig.5 mode A. Distribution of failured elements on the σ - τ plane under the displacement boundary conditions 0m to 500m.



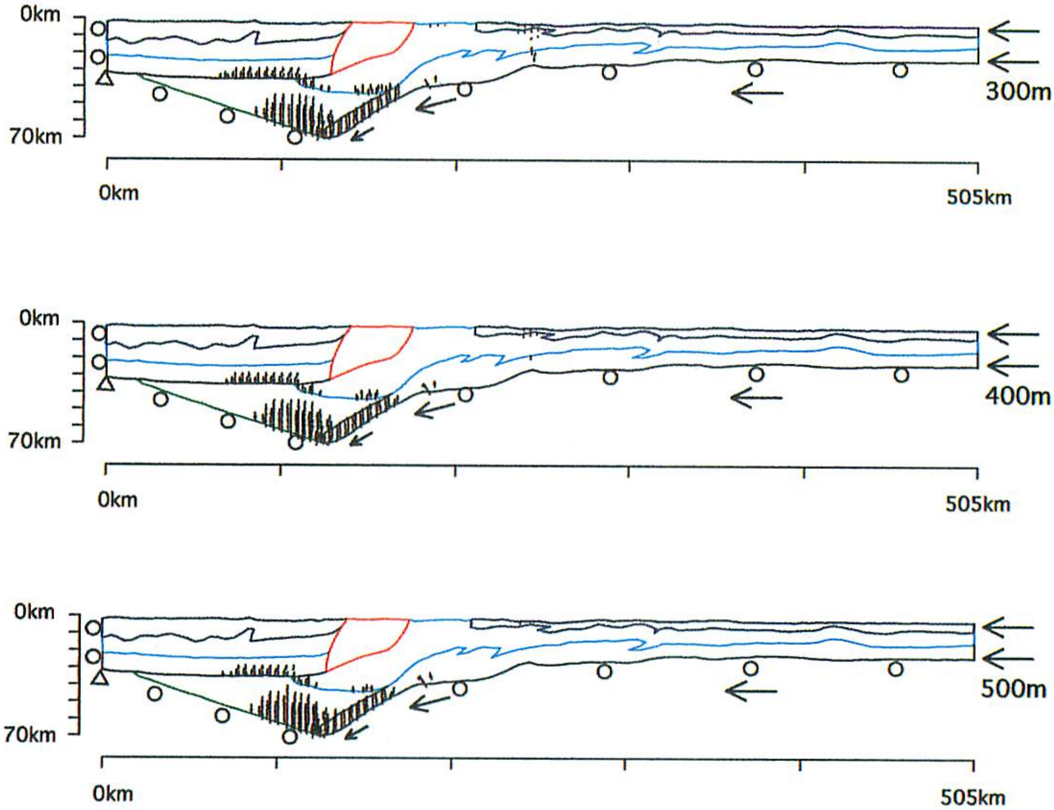


Fig.6 model B. Distribution of failured elements on the σ - τ plane under the displacement boundary conditions 0m to 500m.

Model A

When displacement increases from 0m to 500m, number of failured elements decreases. Especially when we imposed maximum displacement 500m, most failures were varnished.

Compressive stress is mainly obtained, while tensile stress is obtained near surface and 200km away from the origin except for the case under 500m displacements.

Model B

We also find tensile stress, but failures decrease more than in model A. Most failures varnish at displacement 200m.

Discussion

We will explain why if the boundary displacement increases, the numbers of failured elements decrease. Mohr-Coulomb criterion in σ - τ diagram are shown in Fig.7. The intersection of vertical axis and the failure line means cohesion. When cohesion is increased, the failure line move upward away from the Mohr circle, then failure is difficult to occur. Thus we increase the cohesion of crust in order to increase the strength of crust.

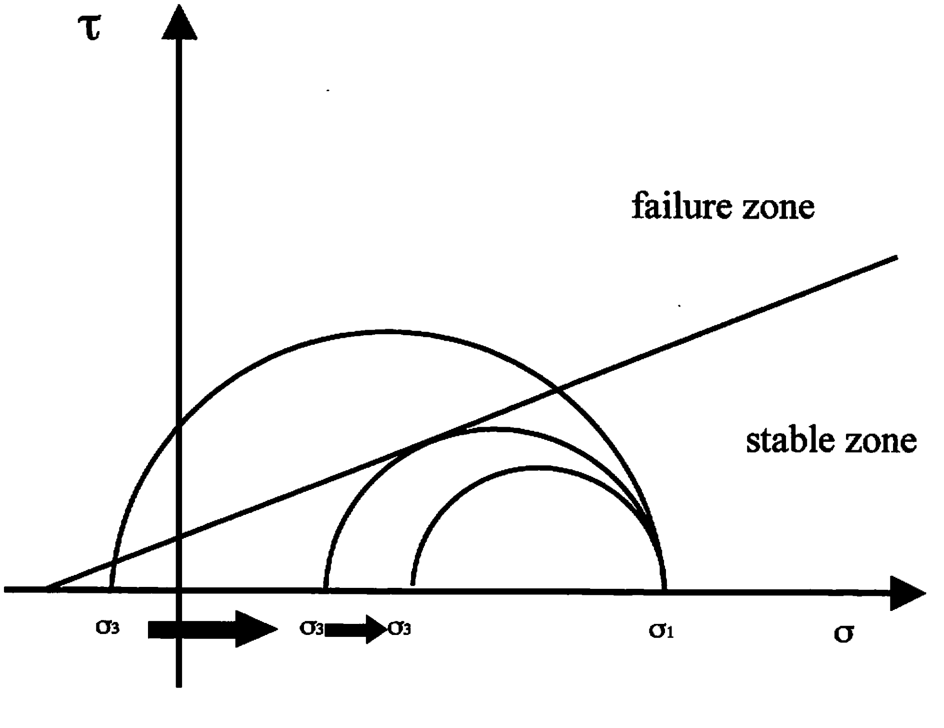


Fig.7 Mohr-Coulomb failure criterion.

σ_1 is resulted from gravity, while σ_3 is due to the horizontal displacement. When we gradually increase the value of displacement boundary condition, σ_3 increase but σ_1 dose not change. Thus the differential stress, $\sigma_1 - \sigma_3$, becomes smaller, that is, the radius of Mohr's circle, $(\sigma_1 - \sigma_3)/2$, becomes smaller. Then the Mohr' circle does not touch the failure line, failures varnish (Fig.7). As the value of displacement is increased from 0m to 500m, the radius of Mohr's circle decreases as shown in Figs.8 to 13.

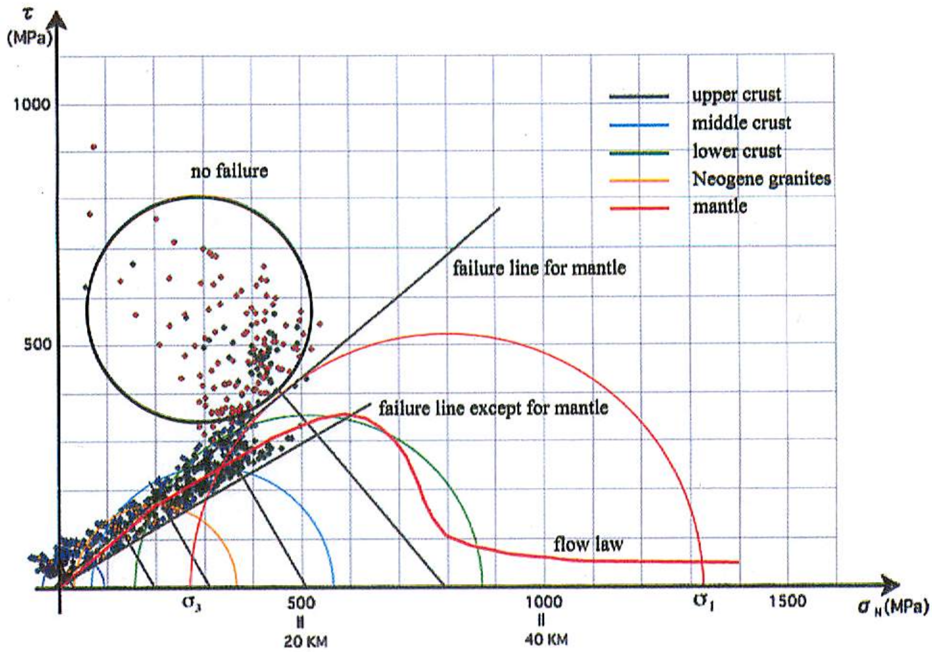


Fig.8 Distribution of failured elements on the σ - τ plane under the displacement 0m. Circles of various colors indicate average Mohr's circle.

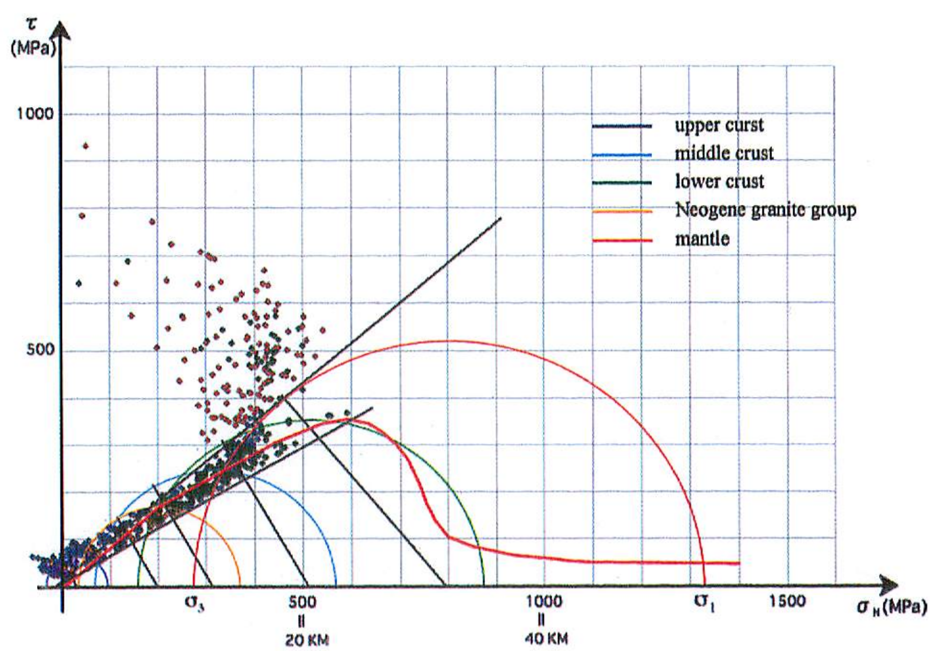


Fig.9 A distribution as shown in Fig.8 except for under the displacement 100m.

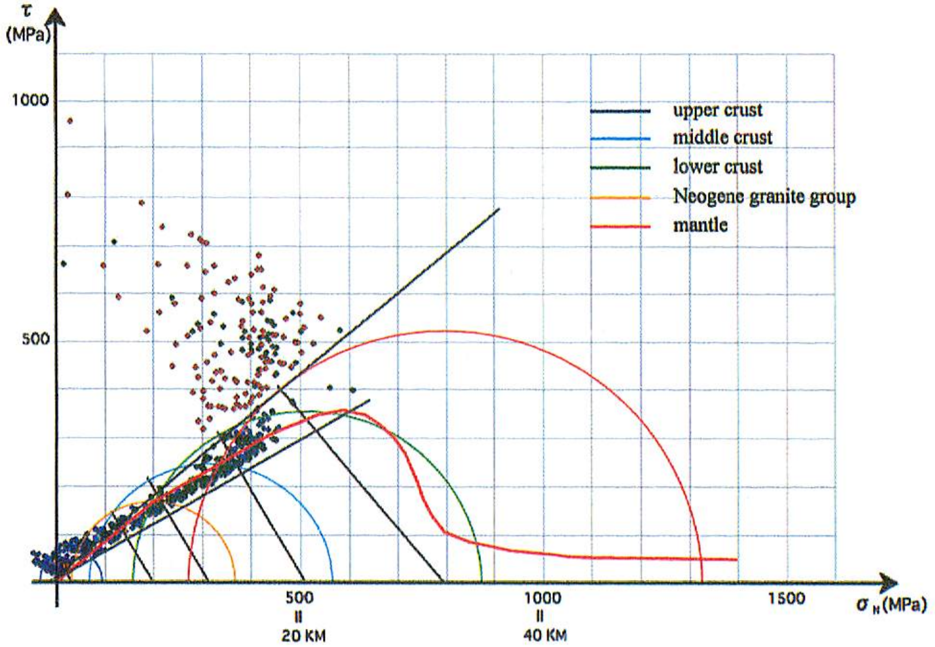


Fig.10 A distribution as shown in Fig.8 except for under the displacement 200m.

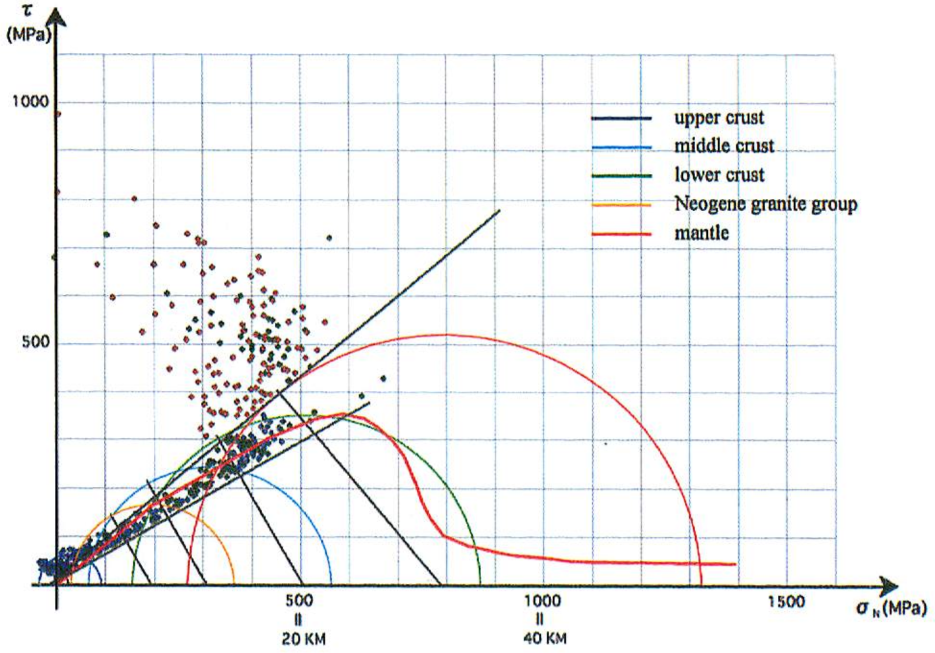


Fig.11 A distribution as shown in Fig.8 except for under the displacement 300m.

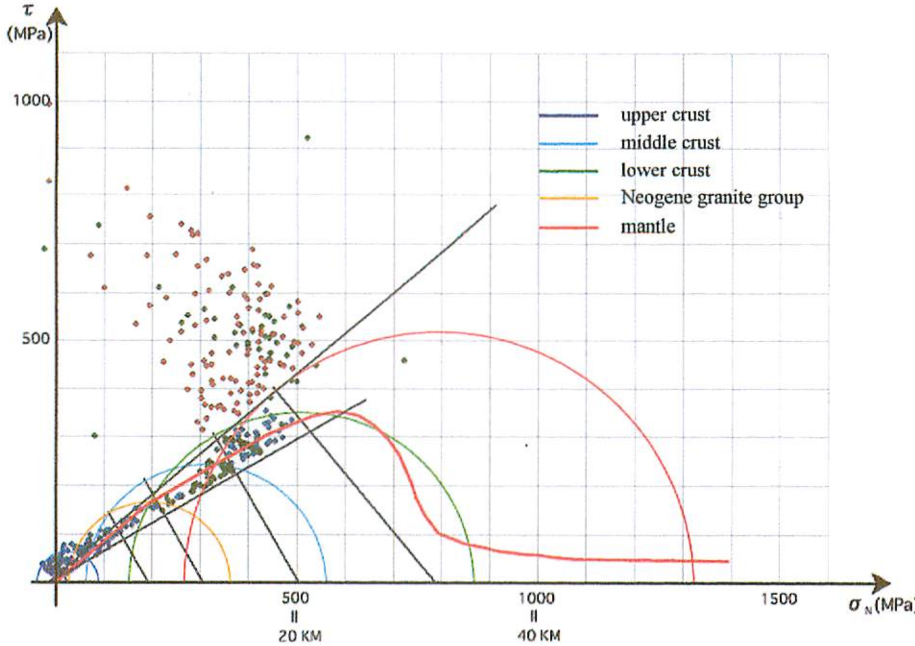


Fig.12 A distribution as shown in Fig.8 except for under the displacement 400m.

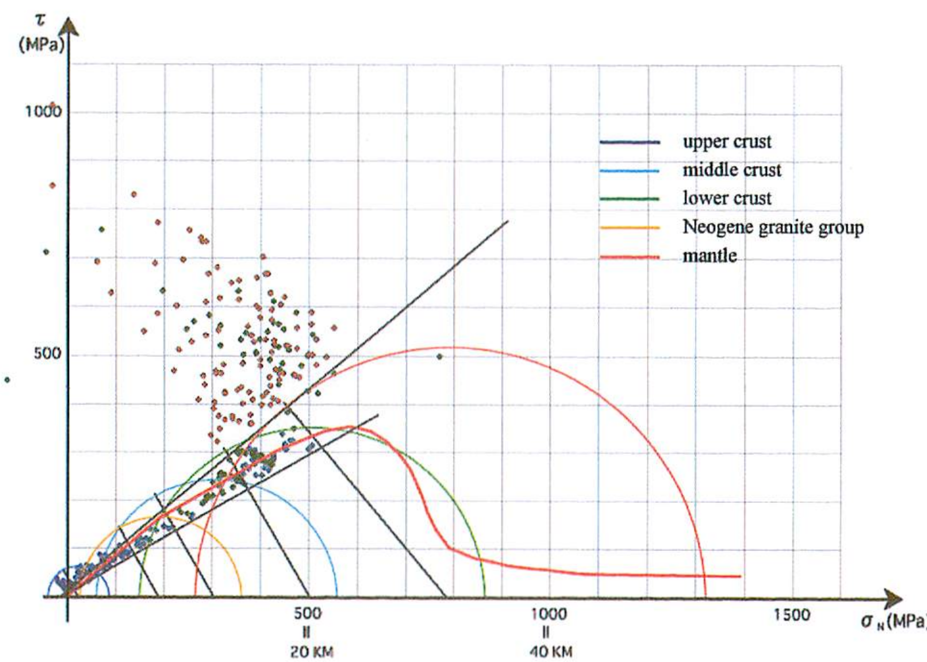


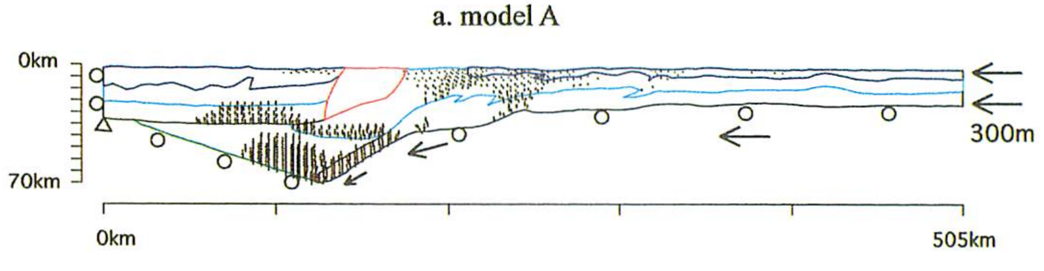
Fig.13 A distribution as shown in Fig.8 except for under the displacement 500m.

Plastic deformation overcomes brittle deformation in deep crust of high temperature and pressure, and rock starts to flow.

A number of coloured points indicate (σ, τ) values of the failured element within mantle (red), lower crust (green), middle crust (light blue), upper crust (blue) and Neogene granites (light brown). Five large coloured circles are drawn as the representative Mohr's circle which touch their failure lines. The Mohr's circle lay their σ_1 point at their average depth, that is, 1350MPa for mantle, 850MPa for lower crust, 560MPa for middle crust, 360MPa for Neogene granites and 90MPa for upper crust.

Since we consider a number of red and green failured points within the black full circke are not failure from the geological view point, the failue line (black) for mantle must be changed into the flow law line (red) as shown in Fig.8. This means the brittle failure of the changing to the flow during the depth 20km to 30km.

If the distribution of failured elements of our simulation coincides with the distribution of actual earthquake, we can say that the values of cohesion used in our study are realistic. We compared the distribution of the failured elements under the 300m displacement of model A (Fig.15a) and those under the 100m displacement of model B (Fig.15b) with the hypocenter distribution (Fig.14).



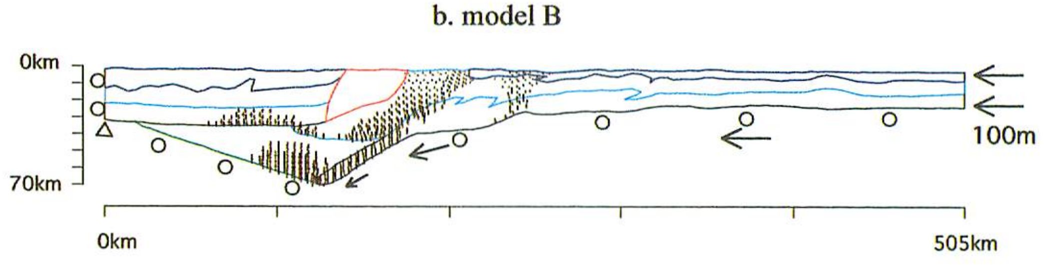


Fig.15 Simulated failured elements distribution which is compared with the distribution of earthquakes (Ishida, 1992). Upper figure shows distribution under the displacement 300m of model A. Lower figure shows distribution under the displacement 100m of model B.

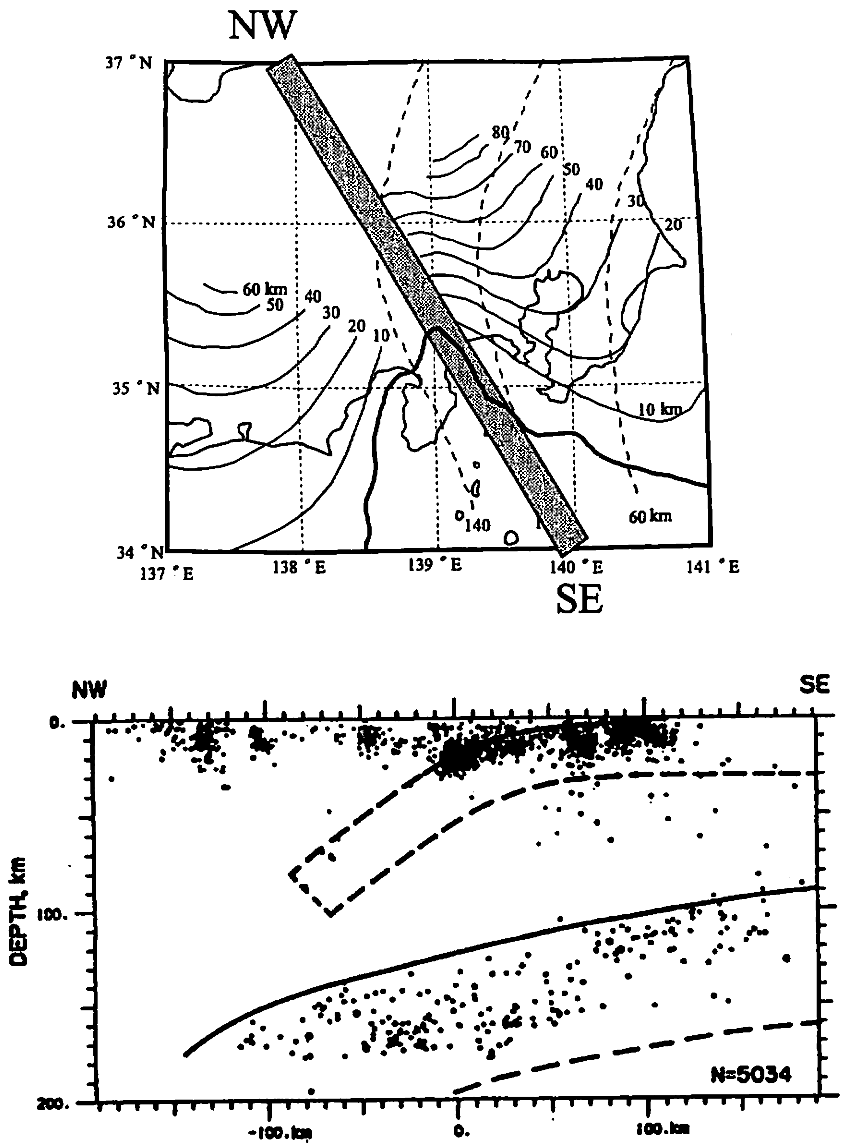


Fig.14 Rectangle of upper figure indicates the cross section line of the lower figure of earthquake distribution (Ishida, 1992).

In the study area, the Philippine Sea plate has subducted under the Eurasian plate, at the same time the Pacific plate has subducted under the Philippine Sea plate as shown in Fig.16. Examination of the data of focal mechanism in Fig.17 shows thrust and strike-slip faults, which do not coincide the normal fault calculated from our simulation.

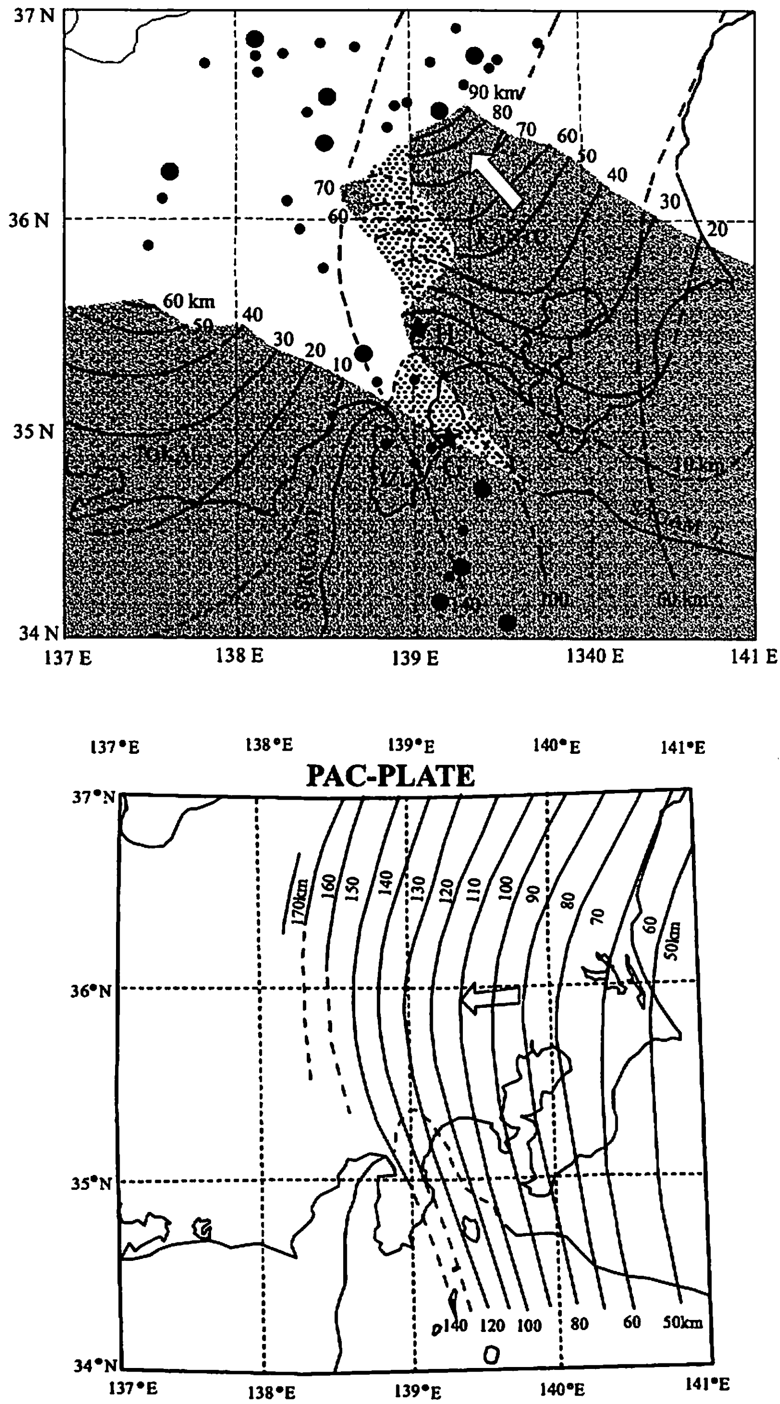


Fig.16 Upper figure shows the subduction of Philippine Sea plate. Lower figure shows the subduction of Pacific plate (Ishida, 1992).

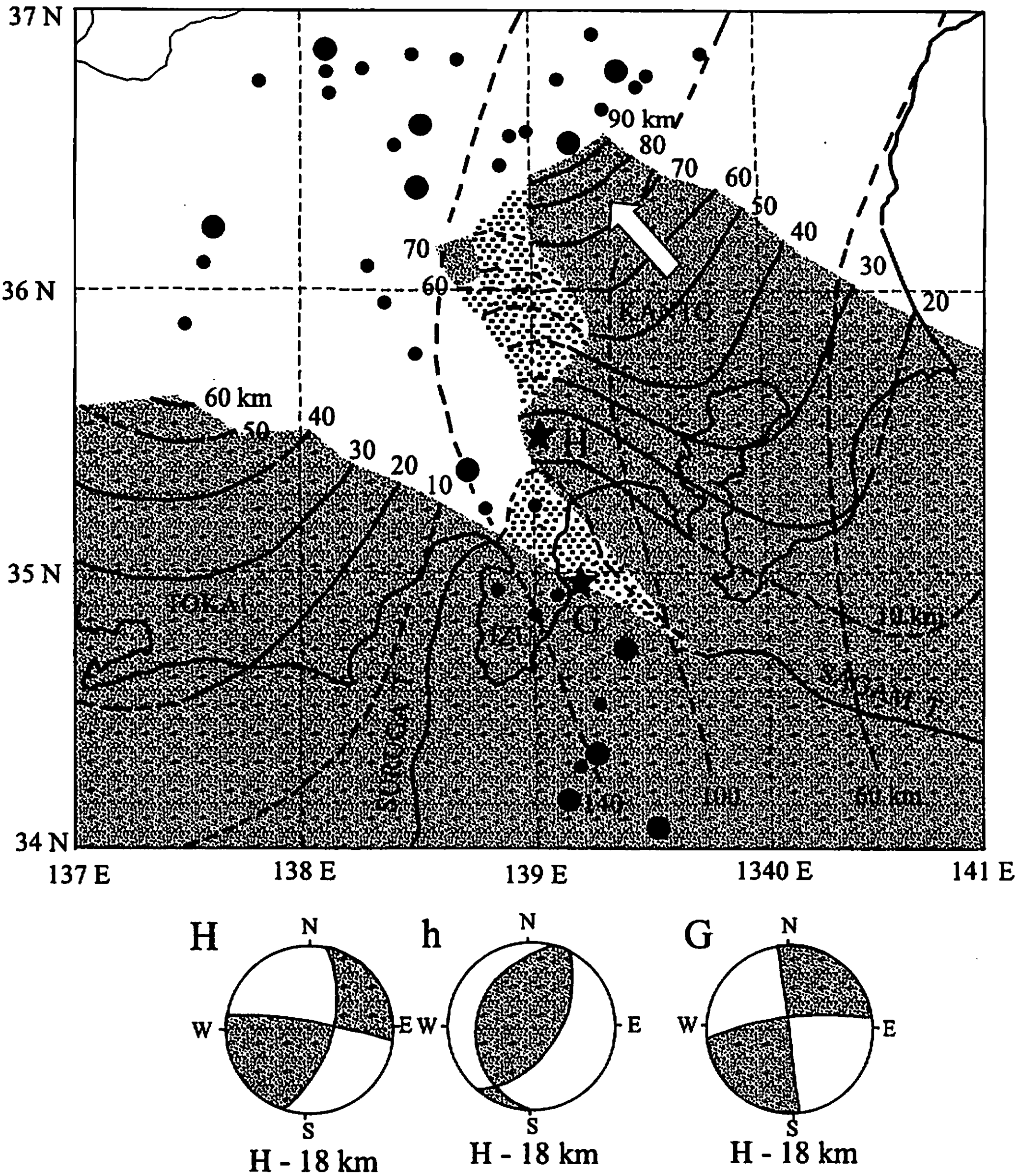


Fig.17 Focal mechanism around Izu peninsula, G: 1980, earthquake at offshore of east Izu peninsula (magnitude 6.8), H: 1983, earthquake at eastern Yamanashi (magnitude 6.0), h: aftershock of H, shadow zone: PHS plate, solid line: depth contour line of PHS, dashed line: depth contour line of PAC plate, ●: Quaternary volcanoes (Ishida, 1992).

Conclusion

If the value of boundary displacement increases, the numbers of failured elements decrease.

Rock behaves from brittle to plastic and to flow as depth is increasing.

Simulated fault type, normal fault, does not coincide with the fault types which are derived from the focal mechanism data.

References

Amano, K., 1986, Southern Fossa Magna as the multi collision zone, Monthly Earth (Gekkan Chikyu), 8, No.10, 581-585 (in Japanese).

Aoike, H. Soh, W. Tokuyama, E. and Taira, T., 2001, Izu collision zone tectonics and material circulation, Monthly Earth (Gekkan Chikyu), extra, No. 32, 181-190 (in Japanese).

Ishida, M., 1992, Geometry and relative motion of Philippine sea plate and Pacific plate beneath the Kanto-Tokai district, Japan, JGR, 97, No. B1, 489-513.

Karino, K. and Murata, A., 1999, Structural gelogy, Asakura, pp298 (in Japanese).

Seno, T., 2001, Elementary plate tectonics, Asakura, pp.190 (in Japanese).