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5. *Geological and Experimental Studies on Mechanism of Block Faulting.*

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Contents

1. Introduction

Block faulting is one of the most significant tectonic processes that deform the upper part of the crust and form characteristic geologic structures. Various kinds of structural relief, such as fault block mountains, are the geomorphological expressions of block faulting, and many earthquakes with varied magnitudes accompany block faulting. In the present paper several examples of block faulting in Japan which have been studied by the author are presented and the mechanisms of block faulting are discussed on the basis of the results of geological and experimental studies. Since block faulting occurs as a result of the activity of the faults which bound a fault block, it is important to study the character and the formative process of boundary faults. Hence, much effort has been expended for the study of boundary faults.

Before going into the main argument it is necessary to make clear what tectonic process the author means by "block faulting". Block faulting is the process by which fault blocks are formed and grow. A fault block in turn is defined as "a mass bounded on its sides, completely or in part, by faults" (REID et al., 1913). However this definition of a fault block seems too generalized. To speak of extremes, the fault blocks thus defined would involve blocks having a wide range of size from a fragment observed only under the microscope to a plate conceived in plate tectonics. It would be appropriate, therefore, to impose some restriction on the above definition, as described in the following paragraphs.

As horsts, grabens, and tilted fault blocks are considered to be typical fault blocks, the fault blocks will range in size from several hundred meters to a few hundred kilometers. Because block faulting is regarded as brittle deformation that occurs in the upper part of the crust, the boundary faults should reach virtually to the surface of the earth. Consequently, the upper surface of a fault block coincides with the earth's surface. In some cases, however, fault blocks may be covered by sediments after their formation.

There is a view that block faulting results exclusively from normal faulting. The present author does not agree with this view. It is not essential whether block faulting is brought about by normal faulting or high-angle reverse faulting. In some cases the boundary faults of a fault block change either laterally or vertically from normal faults to reverse faults. In other cases the boundary faults are a complex of faults of different kinds. Now the author thinks that faults bounding a fault block include not only high-angle reverse faults but also strike-slip faults in addition to normal faults. Certainly ideal strike-slip faulting will not generally produce a vertical dislocation of the earth's surface. It is not important, however, whether or not block faulting is accompanied by the development of a particular topographical relief, because a fault block is a geologic element, not necessarily a physiographic one. In some cases, the above-mentioned high-angle fault may change, in parts, into a low-angle fault or a flexure.

This paper is constituted from several sections as follows. In Sec. 2 to Sec. 6 examples of block faulting are presented, which have been studied by the author. In Sec. 7 experimental results are given which are concerned with the response of surface layers to faulting in the deeper portion. Several characteristic properties of block faulting obtained from the results of field observation and experimental and theoretical results are discussed in Sec. 8.

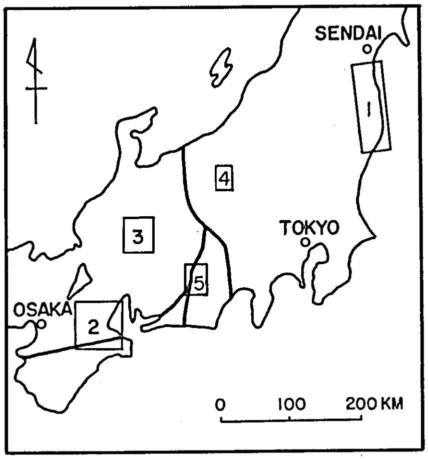

Fig. 1. Index map.
1. Abukuma range, 2. Southern area of Suzuka range, 3. Central area of Gifu Prefecture, 4. Matsushiro area, 5. Misakubo area.

Examples of block faulting given in Sec. 2 to Sec. 6 comprise the following areas as shown in Fig. 1. These areas are characterized by different tectonic history and geologic structures. The Abukuma range, described in Sec. 2, is one of the largest fault block mountains in Japan. In that area, four stages of block faulting are discernible, and the manners of block faulting at the individual stages are analyzed with special reference to the boundary faults. The southern area of the Suzuka range, described in Sec. 3, is located in the Inner Belt of Southwest Japan and occupies a part of the Kinki Triangle Area named by HUZITA (1962). In this area a number of fault blocks are disposed in an intricate manner. It is shown, however, that these fault blocks are divided into several groups according to their periods of activity so that each group of fault blocks shows a relatively simple pattern of block faulting. It is also shown that the boundary faults in this area are characterized by curved fault planes that become lower angle towards the earth's surface and higher angle towards the depth. In the central area of Gifu Prefecture described in Sec. 4, a pattern is displayed of an arrangement of fault blocks that occurred as a result of Quaternary strike-slip faulting. An earthquake occurred on one of the faults bounding these fault blocks in 1969. The relation between the earthquake and the fault is examined. The Matsushiro fault described in Sec. 5 was formed in company with the activity of a swarm earthquake in 1966. This fault is not a reactivated preexisting fault, but is an entirely, newly formed fault. Therefore, processes of birth of a new fault, or in other words, from a different point of view, the occurrence of new fault blocks bounded by the fault, were observed. In the Misakubo area described in Sec. 6 deep-seated structures are studied of a large strike-slip fault that had been formed before Miocene and submitted to subsequent denudation. Processes of formation of the fault are revealed by the results of structural analyses of the fracture zone around the fault.

Acknowledgments

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2. Abukuma Range

2-1. General Remarks

The Abukuma range, located on the Pacific Ocean side of Northeast Japan, has a parallelogram shape of 170 km long in a north-south direction and of 50 km wide in an east-west direction (Fig. 2). The geology of the range consists mainly of the metamorphic rocks, the Paleozoic strata and Jurassic strata which were subjected to the Late Mesozoic orogeny, and the extensive granitic rocks of Middle Cretaceous age (90–100 m.y.; KAWANO and UEDA, 1967). The Upper Cretaceous to Tertiary strata are distributed around various parts of the range. The thick Quaternary deposits occur in the Fukushima and Koriyama basins to the west of the range.

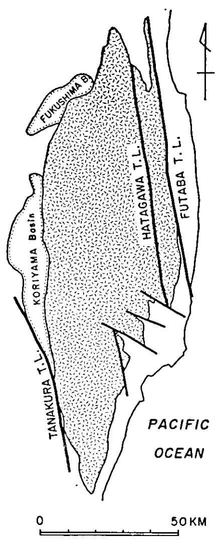


Fig. 2. Outline of Abukuma range and major tectonic lines.

There is the Futaba tectonic line along the eastern boundary of the range, and the Hatagawa tectonic line parallels about 10 km west of it. The range is bounded on the southwestern border by the Tanakura tectonic line. In addition to the above-mentioned major tectonic lines, there are several moderate-sized faults in the southeastern area of the range, as shown in Fig. 2.

Physiographical features of the Abukuma range are well displayed on the successive projected profiles (Fig. 3), drawn by KOIKE (1969). A low-relief land surface, with an altitude of 600–700 m, is developed extensively on the range, and a number of peaks, with an altitude of about 1000 m, rise as monadnocks above

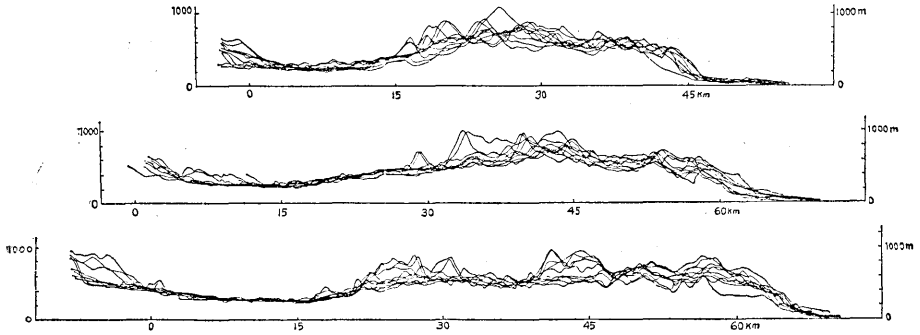


Fig. 3. Successive projected profiles of Abukuma range. The west is on left and the east is on right. The upper, middle and lower figures cross the northern, central and southern segments of the Futaba tectonic line, respectively (KOIKE, 1969).

the surface. A scarp is seen along the Futaba tectonic line, bordering the range on the eastern side. To the east of the scarp there extends a low hill land lower than 100 m in altitude. It seems that a low-relief land surface on the range is tilted westward, gently upwarping with a crest near the eastern border of the range. Present rivers are dissecting the range, especially in its marginal parts. Judging from the above-mentioned physiographical features, the Abukuma range is found to be a dissected peneplane and a fault block that is tilted westward.

Figure 4 shows the geologic outline of the area along the Futaba tectonic line trending N10°W. Basement rocks up to the Middle Cretaceous age occur on the western side of and within the tectonic line, whereas sedimentary covers, which are Upper Cretaceous to Pliocene in age, occur on the eastern side and a part of them lie in an area to the west of the tectonic line. These sedimentary covers of different ages facilitate the structural analyses of the Futaba tectonic line.

In the Soma area of the northeastern part of the Abukuma range, the basement rocks exhibit a peculiar mode of occurrence. They occur along the Futaba tectonic line and are separated by faults from the sedimentary covers that are distributed on both sides. This narrow mass of basement rocks is called "Wariyama horst" in this paper.

The sedimentary covers in the eastern margin of the Abukuma range consist of sandstones, siltstones, mudstones, and conglomerates of shallow marine to brackish or fresh water, including in part volcanic materials. Their total thickness is 2000 m. The sedimentary sequences are separated by several unconformities. In general the strata dip very gently toward the east, but they show steep dipping and, sometimes, are even overturned near the Futaba tectnic line.

Table 1 shows the succession of the sedimentary covers that occur in the eastern margin of the Abukuma range. The sequences of strata

Table 1. Succession.

GEOLOGIC AGE	(West) SOMA AREA	(East)		HIRONO-YOTSUKURA AREA
Recent				
Pleistocene	Landslide dep.			Sodetamayama f.
Pliocene		Tatsunokuchi f.		Taga G
		Kuboma f.		
Miocene				Shirado G
	Yoshigasawa f.	Hatsuno f.	Yunagaya G	Taira f.
	Hazama f.			Kamenoo f.
				Mizunoya f.
	Kaneyama f.			Goyasu f.
	Tenmyosan f.			Taki f.
	Shiode f.			
Paleogene			Shiramizu G	Shirasaka f.
				Asagai f.
				Iwaki f.
Cretaceous			Futaba G	Tamayama f.
				Kasamatsu f.
				Ashizawa f.
Jurassic to Paleozoic	Basement Rocks			

have been established by different authors (FUJITA and TSUJIKAWA, 1960; KITAMURA et al., 1955; IWAO and MATSUI, 1961) in the west, in the east of the Soma area, and in the Hirono-Yotsukura area. Although it is not easy to correlate the successions of the Neogene strata distributed in the above, separate, three areas, a tentative intercorrelation was tried as shown in Table 1 by referring to opinions of KITAMURA et al. (1955), KANNO (1955), FUJITA and TSUJIKAWA (1960), IWAO and MATSUI, 1961, HANZAWA (1964), IKEBE et al. (1973) and MITSUI et al. (1973).

The strata which are correlated to be Upper Miocene to Lower Pliocene in Figure 4 include the Taga group (Upper Miocene to Lower Pliocene) and the Tatsunokuchi formation (Lower Pliocene) listed in Table 1. They are developed extensively on the east of the Futaba tectonic line and cover the underlying strata. The distribution of the concealed formations has been revealed by EGUCHI and SUZUKI (1960), who carried out the detailed exami-

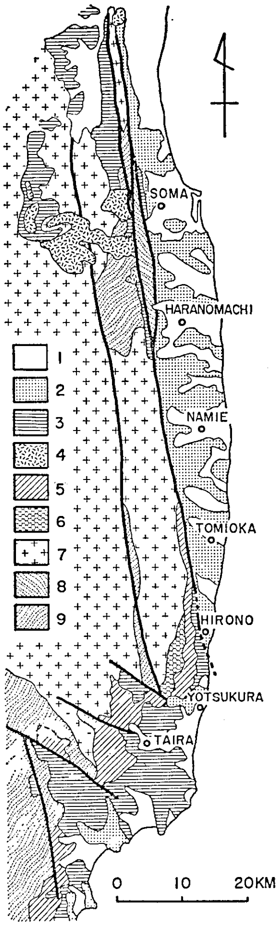


Fig. 4. Geologic outline of the eastern margin of Abukuma range.
1. Alluvium, 2. Upper Miocene to Lower Pliocene, 3. Lower to Middle Miocene, 4. Lower Miocene volcanics, 5. Paleogene, 6. Upper Cretaceous, 7. Granitic rocks, 8. Jurassic, 9. Paleozoic and metamorphics.

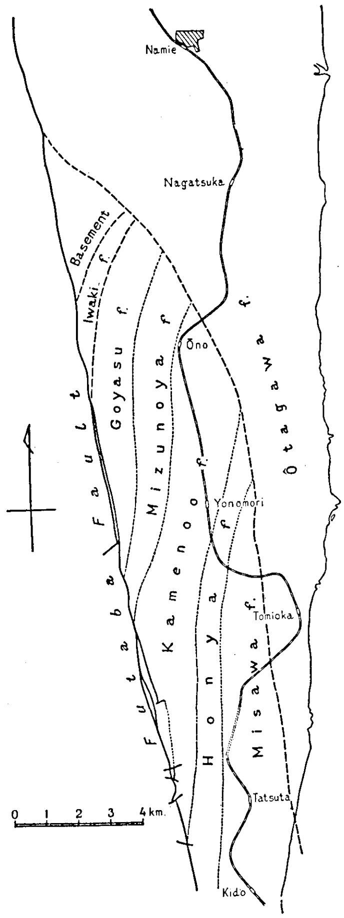
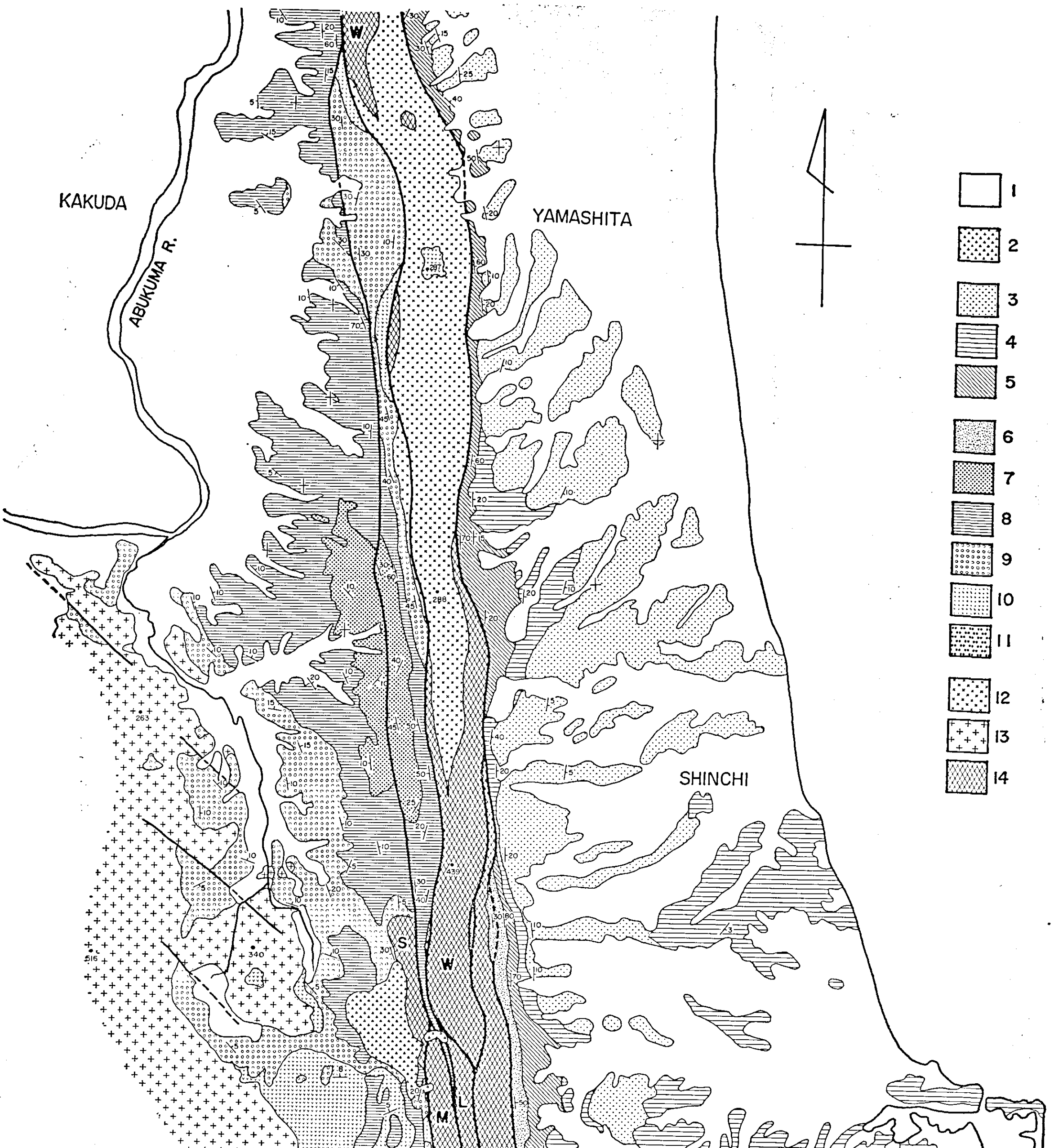


Fig. 5. Subsurface geology under the Tatsunokuchi formation and the Taga group (EGUCHI and SUZUKI, 1960).

nation of a number of drilling cores. Figure 5 shows that those formations of Iwaki (Paleogene) to Misawa (Miocene) gently dip toward ESE, whereas the Otagawa formation (the equivalent of the Pliocene Kuboma formation in Table 1) overlies them unconformably and extends northeasterly.

The geologic structure of the eastern margin of the Abukuma range is described in the following sections: Soma area (Sec. 2-2), Hirono area (Sec. 2-3) and Yotsukura area (Sec. 2-4). Then the fracture system of basement rocks and the stages of block faulting are summarized in Sec. 2-5 and Sec. 2-6, respectively.


KAKUDA
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SHINCHI
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2-2. Soma Area

The Soma area is located in the north of the Futaba tectonic line. In the central part of the area the Wariyama horst trends N10°W, and the Neogene sedimentary covers are distributed on both sides of it (Fig. 6). The Wariyama horst has a very narrow shape and rises within a zone between two major faults along the Futaba tectonic line. The zone is about 2 km in width and 50 km in length. Detailed geologic description of the Soma area will be reported in another paper (TSUNEISHI, 1979), and so only an outline of its geology is dealt with in this section.

Basement rock The basement rock, cropped out on the left side of Fig. 6, is a part of Mid-Cretaceous granite which constitutes the main body of the Abukuma range. It is overlain by the sedimentary cover unconformably. Another occurrence of basement rocks is seen in the Wariyama horst. The horst extends straight on the whole, but detailed inspection reveals that its east and west boundaries undulate slightly, and run nearly parallel to each other.

The Wariyama horst itself consists of five rock bodies that are separated by faults from each other. The block-J is the northern extension of the Jurassic Somanakamura group (MASATANI and TAMURA, 1959; MORI, 1963). It is composed of arkose, sandstone and shale. The block-L consists of white crystalline limestone with intercalations of shale and sandstone. This limestone is non-fossiliferous and apparently differs from the limestone contained in the Jurassic System. The former seems to be older than the latter, The block-M consists of metamorphic rocks including amphibolite, mica schist and green schist with a small intrusion of diorite. The block-S consists mainly of sandstone and of subsidiary limestone and shale. The limestone is similar to that of the block-L, whereas the sandstone to that of the block-W. The block-W is biggest in the Wariyama horst and consists of the unknown-aged Wariyama formation, which is intruded by granite. The Wariyama formation is composed of sandstone and shale. The age of the rocks in each block remains unknown except for the block-J. However, it is presumed that the blocks-S, L, W are of Late Paleozoic to Triassic and that the block-M is older, judging from the correlation with the geology of the surrounding area. The existence of another block-X is assumed to occur on the west of the Wariyama horst, but it is entirely masked by the sedimentary cover.

Fig. 6. Geologic map of Soma area.

1. Quaternary, 2. Landslide deposits, 3. Sandstone member of Tatsunokuchi formation, 4. Siltstone member of Tatsunokuchi formation, 5. Kuboma formation, 6. Hatsuno formation, 7. Yoshigasawa formation, 8. Hazama formation, 9. Kaneyama formation, 10. Tenmyosan formation, 11. Shiode formation, 12. Sheared granite, 13. Granite, 14. Basement rocks in Wariyama horst.

Sedimentary cover The Miocene strata with a total thickness of 700 m occur to the west of the Wariyama horst. They have been divided into the Shiode, Tenmyosan, Kaneyama, Hazama and Yoshigasawa formations in ascending order, as shown in Table 1. The Tenmyosan formation consists of andesitic or basaltic lavas and pyroclastics, and the others of marine or nonmarine clastic sediments. The Kaneyama formation interfingers with the Tenmyosan formation. Near the western border of the Wariyama horst, the Kaneyama formation contains a large quantity of angular fragments that were supplied from the horst. This suggests that the formation was deposited in the fault angle basin that occurred along the western border of the Wariyama horst.

On the other hand, the Miocene Hatsuno formation and the Pliocene Kuboma and Tatsunokuchi formations occur to the east of the Wariyama horst. The Hatsuno formation is composed of sandstone and conglomerate, and has a thickness of 180 m. It is correlative to the Yoshigasawa formation in the western basin on the basis of the similarity of lithofacies. The Kuboma formation consists of conglomerate, sandstone and mudstone with lignite seams and is 150 m in thickness. The formation overlies the Hatsuno formation with a conspicuous angular unconformity. The Tatsunokuchi formation in the Soma area is 150 m thick and overlies the Kuboma formation conformably. It comprises sandstone and siltstone members that interfinger with each other.

Also the Tertiary formations occur on the Wariyama horst in a limited extent. They include three formations; the basaltic lava of the Tenmyosan formation overling the granite in the north, a part of the Hazama formation inserted between block-L and block-M, and a part of the Hatsuno formation inserted between the block-W and block-J.

Geologic structure The rocks composing the Wariyama horst have been severely fractured. Especially, near the western margin of the horst, the rocks are most intensely crushed into fragments with a size of several centimeters or less. Mylonitized granites are observed in places near the western margin. Much elongated quartz grains and crushed feldspar grains are observed in the mylonites under the microscope. Slickensided surfaces occur from place to place in the horst. They have no appreciable fault clay and have horizontal striations carved on the solid rock surfaces. In addition, there occur such faults that have fault calys or fault breccias cemented with clay. The last type of faults has brought the sedimentary covers into contact with the basement rocks. The above-mentioned various types of rock deformation are presumed to have occurred not under the same conditions but under the varied confining pressures. It is probable that they may have been formed successively, in order of mylonitization, faulting with slickensides but without fault clays, fault-brecciation, and faulting with fault clays with decreasing, confining pressure resulting from uplift and denudation. Except for the last type of faulting, they occurred at least before the deposition of the Miocene formations, because the basal conglomerates of the Miocene formations overlie the crushed basement and contain clasts of the crushed bed rock.

Five blocks constituting the Wariyama horst are bounded by high-angle, essentially vertical faults (Fig. 7). In the case that the sedimentary cover is juxtaposed with the basement by these faults, the degree of fracturing around the faults conspicuously differs between the sedimentary cover and the basement rocks. The facturing of the sedimentary cover is much weaker than that of the basement. This means that these faults had been formed before deposition of the sedimentary covers and were reactivated afterward. As shown in Fig. 7, the traces of the faults branch off and again join smoothly. Such a pattern of fault traces suggests that these faults were formed as a single system on the whole. Left-lateral offsets of veins as well as horizontal fault striations were observed in places in shear zones around these faults. As described in Sec. 2-5, it seems that these faults were originally formed as left-lateral strike-slip faults during the Mid-Cretaceous time.

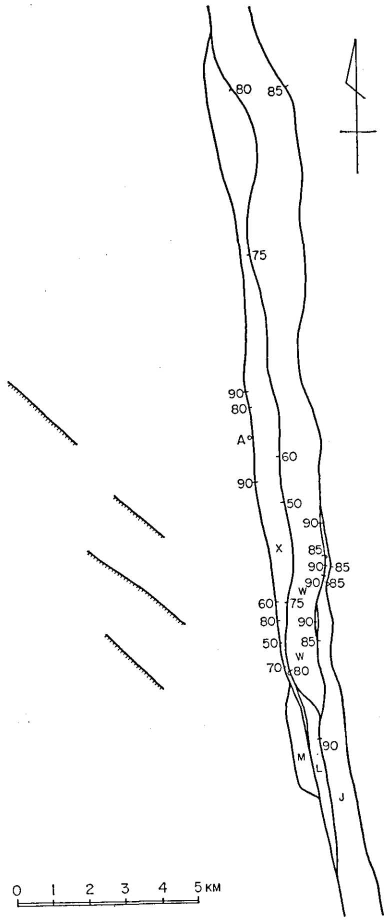


Fig. 7. Structural map of Soma area. Figures show dips of fault surfaces. Yoshigasawa fault passes near point A.

On the other hand, the structure of the sedimentary cover is much simple than that of the basement. Strata in the western basin have the appearance of an asymmetrical syncline with steep westward dipping in the eastern limb. However from the following reason it does not seem that the structure has resulted from the upward dragging of the sedimentary cover due to the uplifting of the Wariyama horst. There is a fault (the Yoshigasawa fault) along the axial part of the syncline. A fault block is defined by this fault and the western boundary fault of the Wariyama horst. Strata within the fault block show rather uniform west-

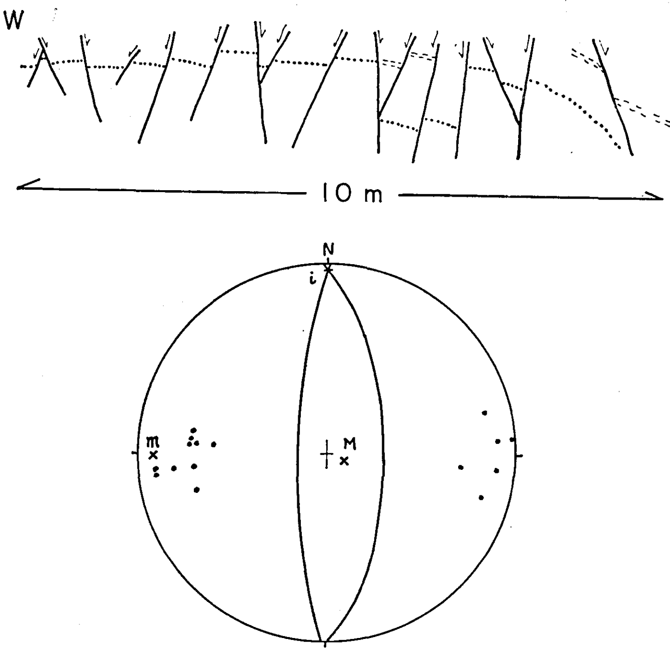


Fig. 8. Minor faults observed at point A of Fig. 7 and their stereographic projection (upper hemisphere of Wulf's net).

ward dipping except for steep dips in the vicinity of the fault, in other words, the dip-angles do not increase toward the Wariyama horst. This suggests that the synclinal structure probably resulted from the westward tilting of the fault block.

The Yoshigasawa fault is a vertical or high-angle normal fault, as shown in Fig. 7. In the central and southern part of the fault, the east side has moved down, whereas the west side has moved down in the northern part. Figure 8 shows a sketch of minor faults observed near the fault (at the point A in Fig. 7) and their stereographic projection. These minor faults show a conjugate set of north-trending normal faults. Considering that the minor faults are genetically related to the Yoshigasawa fault, the Yoshigasawa fault is found to be a dip-slip vertical or normal fault. Likewise the other faults that have displaced the sedimentary covers are also proved to have moved as dip-slip faults on the basis of the striations on their fault surfaces as well as nearby minor faults. That is to say, they originally formed as strike-slip faults and were reactivated as dip-slip faults after deposition of the sedimentary cover.

Figure 9 illustrates a schematic profile of the attitude of the sedimentary cover near the Yoshigasawa fault. It shows that the sedimentary cover within about 300 m east of the fault has been downbent toward the fault and formed a kind of reverse drag. This suggests that lateral extension across the fault occurred during faulting, at least, in the shallow level where the sedimentary cover lies. Within the Wariyama horst, slices of the sedimentary covers have dropped into the gaps between the blocks constituting the horst: between blocks S and W, M and L, or W and J. This also indicates that the lateral extension prevailed in the shallower depth within the horst.

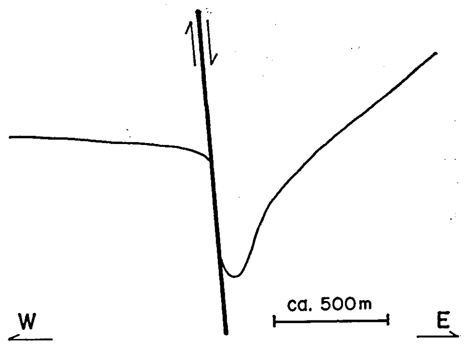


Fig. 9. Diagrammatic profile of Miocene formations in western basin.

The Miocene formations in the western basin adjoin the basement rocks of the Wariyama horst with a fault in most parts, and with an unconformity in some parts (Fig. 6). In the latter case the trace of the boundary between the Miocene formations and the basement runs to the west of the boundary fault of the horst.

The western boundary fault is a normal fault in the central and northern part, but it is a high-angle reverse fault in the southern part.

There are four NW-trending faults in the western margin of the western basin. Although fault planes themselves are not observable, these faults are presumed to be normal faults, because no appreciable drag is seen in the nearby sedimentary cover. The southwestern sides of these faults have consistently moved down and the blocks separated by the faults have tilted northwestward. This pattern of faulting is antithetic faulting. The center of upheaval of the Abukuma range is located to the southwest of the faults. The genetic relation between upheaval and formation of antithetic faulting is suggestive.

The sedimentary cover extending to the east of the Wariyama horst shows eastward gentle dipping in general, although near the horst it dips steeply to the east. The boundary between the horst and the sedimentary cover is a high-angle fault in most places and partly an unconformity. The Miocene Hatsuno formation dips more steeply than the Pliocene Kuboma and Tatsunokuchi formations near the eastern boundary fault of the Wariyama horst, and the former has been overlain by the latter with an angular unconformity. From the above facts, two periods of tectonic movement can be discerned: one after the deposition of the Hatsuno formation and before the deposition of the Kuboma formation, the other after the deposition of the Tatsunokuchi formation.

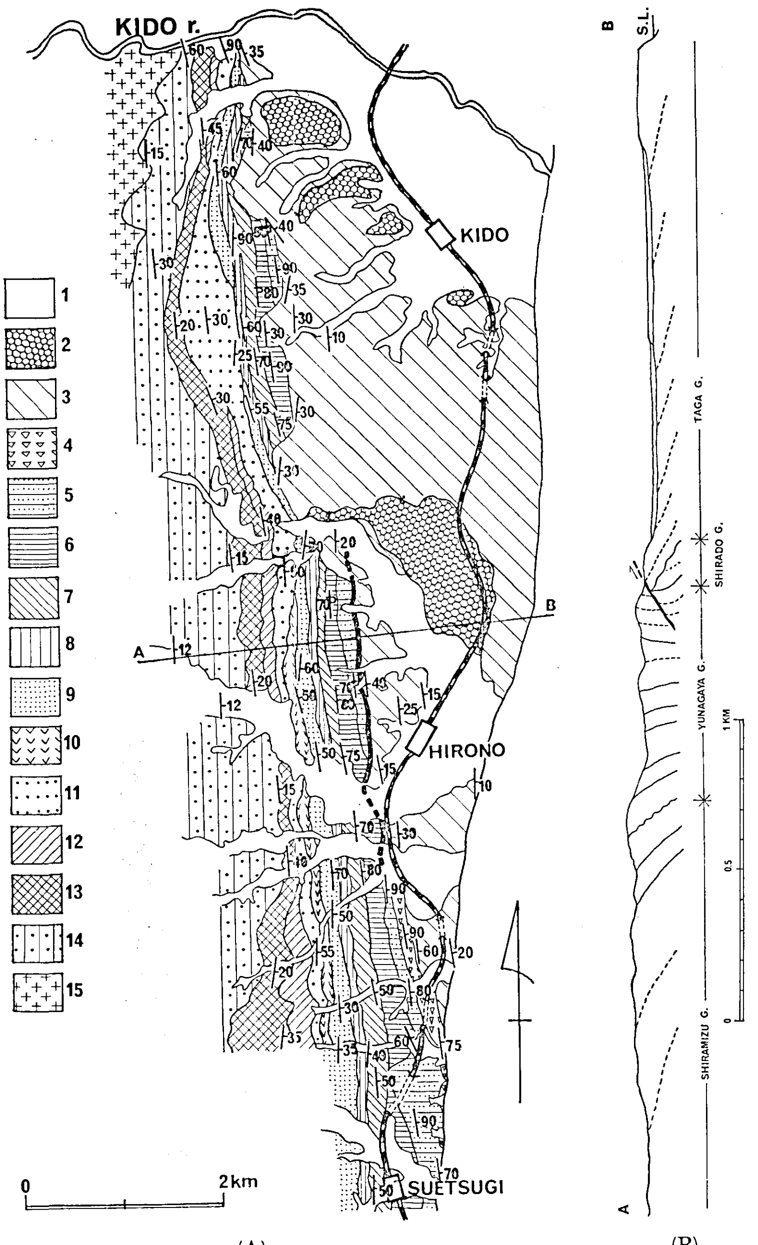
Uplift of the Wariyama horst Around the Wariyama horst the Miocene sedimentary cover, the pre-Tertiary basement, and the Pliocene sedimentary cover are disposed successively from the west to the east, although there is an exceptional occurrence of the Miocene Hatsuno formation, which resulted merely from a fault drag. This disposition has been produced by two different tectonic movements, viz., the uplifting of the Wariyama horst and the upheaval of the western Neogene basin relative to the eastern. Then the question is the sequence of the two tectonic movements. It is clarified from the geomorphological investigation.

In most places the Wariyama horst rises from the surroundings topographically as well as structurally. In this case, the sedimentary cover neighboring on the west of the horst is composed of non-volcanic sediments. On the other hand, to the west of Soma the horst does not rise from the western Neogene basin, where volcanic rocks of the Tenmysan formation occur. Therefore, the present topography involving the difference in altitude along the western border of the horst is found to be a product of erosion, not a direct expression of tectonism. The area covered extensively by the Tenmyosan formation has a low-relief surface such as developed on the area occupied by granitic rocks. The surface continues onto the Wariyama horst and is disrupted by the scarp extending along the eastern border of the horst. The above-mentioned physiographical features lead to the conclusion that the movement of the eastern boundary fault of the Wariyama horst occurred after the deposition of the Pliocene Tatsunokuchi formation. The Abukuma range, including the western basin in the Soma area, was uplifted by this faulting. On the other hand, the tectonic movement that is indicated by the angular unconformity between the Hatsuno formation and the Kuboma formation, as well as the faulting to which the Miocene formation in the western basin was subjected, is presumed to have occurred after the deposition of the Hatsuno or Yoshigasawa formation and before the deposition of the Kuboma formation. At that time, the Wariyama horst was uplifted as a horst in the strict sense of the word, because the uplift occurred in the company of faulting on both sides of the horst.

2-3. Hirono Area

The Hirono area is situated at the southern extremity of the Futaba tectonic line. As shown in Fig. 4, this area has been covered by the thickest sedimentary cover comprising the Upper Cretaceous, Paleogene and Neogene strata. Hence the Futaba tectonic line is expressed by deformations of the sedimentary cover. Since the results of the structural analysis of the area were already published (TSUNEISHI, 1966), only a brief summary is described here.

As listed in Table 1, the sedimentary cover is divided into the Upper



(A) (B)

Fig. 10. Geologic map and porfile of Hirono area (TSUNEISHI, 1966).
1. Alluvium, 2. Terrace deposit, 3. Taga group, 4. Shirado group, 5. Taira formation (Misawa member), 6. Taira formation (Honya member), 7. Kamenoo formation, 8. Mizunoya formation, 9. Goyasu formation, 10. Taki formation (rhyolitic tuff), 11. Taki formation (conglomerate), 12. Shirasaka formation, 13. Asagai formation, 14. Iwaki formation, 15. Basement.

Cretaceous Futaba group, the Paleogene Shiramizu group, the Miocene Yunagaya and Shirado groups, and the Mio-Pliocene Taga group. Their total thickness attains to 1900 m. They are mostly composed of sandstone, mudstones and conglomerates of shallow sea. There are unconformities between the groups. Above all the unconformity between the Shirado and Taga groups is a conspicuous angular unconformity.

Figure 10 shows the geological map of the area. A flexure zone with a width of about 2 km trends N10°W in the central part. In the flexure zone, beds dip steeply toward the east and they are even overturned in the most intensely deformed portions. On the other hand, the beds show gentle eastward dip of 10° or so outside the flexure zone. The Taga group overlies, with an angular unconformity, the underlying strata that dip steeply. The Taga group itself shows eastward dips of about 30° on the flexure zone. These facts suggest that the flexuring mostly occurred after the deposition of the Shirado group and before the deposition of the Taga group, and that it slightly progressed after the deposition of the Taga group.

Locally on the flexure zone there develops a fault across which the Taga group adjoins its underlying formations. It is a reverse fault whose fault plane dips 30° to the west and is called the Futaba reverse fault.

Many minor faults occur in the flexure zone. They have displace-

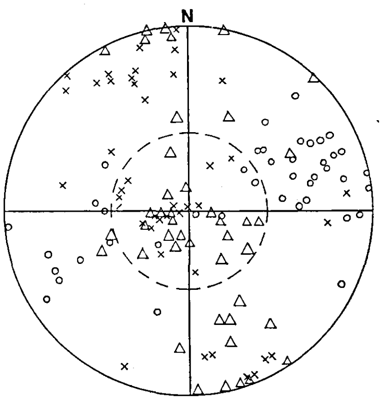


Fig. 11. Stereographic projection of stress systems determined from conjugate sets of minor faults (upper hemisphere of Wulf's net). Circles, triangles and crosses show axes of maximum, intermediate and minimum compressive principal stress, respectively (TSUNEISHI, 1966).

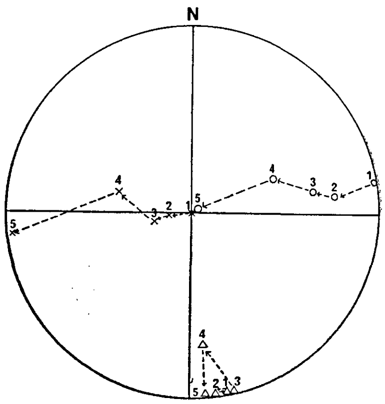


Fig. 12. Systematic change of stress system.
1. Futaba reverse fault, 2. Taira formation, 3. Kamenoo formation, 4. Goyasu formation, 5. Shirasaka formation (upper hemisphere of Wulf's net). Circles, triangles and crosses show axes of maximum, intermediate and minimum compressive principal stress, respectively (TSUNEISHI, 1966).

ments ranging from several millimeters to several meters. Some of them form conjugate sets. Figure 11 shows the stereographic projection of stress systems that were determined from the conjugate sets of minor faults. They were divided into two groups by the angles of plunge of the intermediate principal stress axes; one group whose intermediate axes plunge more than 45° (strike-slip stress system) and the other group whose intermediate axes plunge less than 45° (dip-slip stress system). The bearings of intermediate axes of the latter group trend about N10°W. The stress systems of the latter group were classified according to the formations in which the stress systems were determined: the Taira, Kamenoo, Goyasu and Shirasaka formations. Because these formations are arranged successively from the east to the west, we can examine the change of stress systems from the east to the west in the flexure zone. A systematic change of stress systems is shown in Fig. 12, in which the directions of σ_1 and σ_3 change gradually from the east to the west in the flexure zone and the direction of σ_2 is almost fixed. In Fig. 13 the disposition of stress systems is projected on the vertical section of E–W direction. The estimated stress system of the Futaba reverse fault is also illustrated. The disposition of stress systems determined by minor faults is consistent with that of the Futaba reverse fault.

As shown in Fig. 13, the maximum compressive principal stress is horizontal and the minimum one is vertical in the vicinity of the Futaba reverse fault. The disposition of stress systems is rotated counterclockwise as distance from the main fault increases. Eventually it shows a rotation up to 90° in the western part of the flexure zone, where normal faults occur.

It is inferred that such a stress distribution has resulted from a vertical differential movement of the basement along a nearly vertical fault. The formation of the flexure zone is also well explained by the movement. Whether a flexure is formed or a fault is developed is deter-

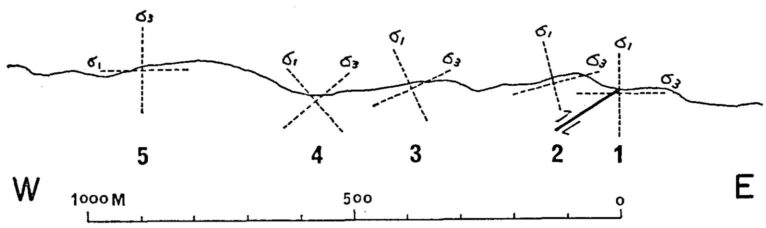


Fig. 13. Change of stress systems projected on vertical section of E–W direction. Points σ_1 and σ_3 show axes of minimum and maximum compressive principal stress (TSUNEISHI, 1966).
1. Futaba reverse fault, 2. Taira formation, 3. Kamenoo formation 4. Goyasu formation, 6. Shirasaka formation.

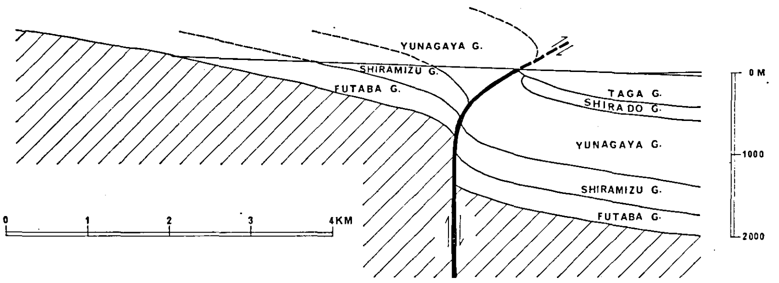


Fig. 14. Probable deep-seated structure (TSUNEISHI, 1966).

mined by the balance of physical properties of rocks and strain velocity. Hence the fact that faulting proceeded after flexuring might be attributed to the decrease of ductility of the sedimentary cover due to lithification and/or strain hardening.

There is no direct information about the movements of the basement under the sedimentary cover of the Hirono area. But in other areas, the Abukuma range is bounded by vertical faults and has been uplifted along them. Therefore it is reasonable to suppose that such a basement structure extends under the sedimentary cover of the Hirono area. Figure 14 shows a deep geologic section drawn on the basis of the above presumption. The Futaba reverse fault appears to have a curved fault plane whose dip is low-angle in the upper part and becomes high-angle or vertical in the lower part.

In summary, the Futaba tectonic line in the Hirono area is expressed by a combined structure of a flexure and a reverse fault that developed in the thick sedimentary cover. Block faulting occurred at two ages: one after the deposition of the Shirado group and before the deposition of the Taga group (Late Miocene), the other after the deposition of the Taga group (Late Pliocene to Pleistocene). The flexure was largely formed at the time of the former activity, whereas further growth of the flexure and development of the Futaba reverse fault occurred at the latter activity. These deformations are presumed to have essentially resulted from the vertical differential movement of the basement.

2-4. Yotsukura Area

The Yotsukawa area is characterized by WNW-trending faults, such as the Futatsuya, Akai and Yunotake faults, as shown in Fig. 2. As a result of the displacements of these faults the Abukuma range has lowered its altitude in this area, so that the sedimentary cover is extensively distributed, escaping denudation. Figure 15 is the geologic map around the Futatsuya fault. On the northeast of the fault, the basement rocks crop out. They have been overlain on the eastern part by the sedimentary cover comprising Upper Cretaceous and younger sediments. Gentle eastward inclination shown by the sedimentary cover indicates tilting of the basement due to upwarping. On the other hand, the Shiramizu, Yunagaya and Taga groups are distributed on the southwestern side of the Futatsuya fault.

The unconformity observed at the base of the Yunagaya group is worthy of note. In the eastern part of the Yotsukura area, the Taki formation of the Yunagaya group overlies the Shirasaka formation of the Shiramizu group, as is the case with the Hirono area. In the central part, the Taki formation lacks its lower conglomerate member, and the upper tuff member covers the Shirasaka formation. In the western part, where the whole Taki formation is lacking, the overlying Goyasu formation covers successively the Shirasaka formation, the Iwaki formation and the basement rocks toward the west. The above-mentioned stratigraphic relation indicates that transgression progressed westward during early Miocene when the Yunagaya group was deposited. Moreover, this indicates that the Yotsukura area as a whole has tilted slightly eastward before the deposition of the Yunagaya group.

Figure 16 is the tectonic map of the Yotsukawa area. Faults are divided into a WNW-trending group and an ENE-trending group. These faults have not displaced the Taga group, whereas the groups older than the Taga group were displaced. Hence, the age of the faulting is presumed to be Late Miocene. The faults are nearly vertical faults when the basement rocks juxtapose the sedimentary cover across them. On the other hand, they appear as normal faults when they pass through the sedimentary cover. It is assumed, therefore, that these faults are vertical faults in the basement and change into normal faults in the sedimentary cover. These faults are also presumed to be dip-slip faults, judging from the associated minor faults. There is a regularity about the sense of slip of the faults and the direction of tilt of the fault blocks. As for the WNW-trending faults, the southern sides have moved down and the intervening blocks have tilted northward. As for the ENE-trending faults, the northern sides have moved down and the intervening blocks have tilted southward. That is to say, these faults are two sets of antithetic faults. The regularity is also recognizable in the area adjacent to the south of the Yotsukura area, as shown in Fig. 17, that was originally produced by SUGAI et al. (1957).

Minor faults that developed in the Yotsukura area are of the normal fault type. The arrows of Fig. 16 show the directions of the minimum compressive principal stress axes determined by conjugate sets of the minor faults. They trend NNE and NNW except for those developed in

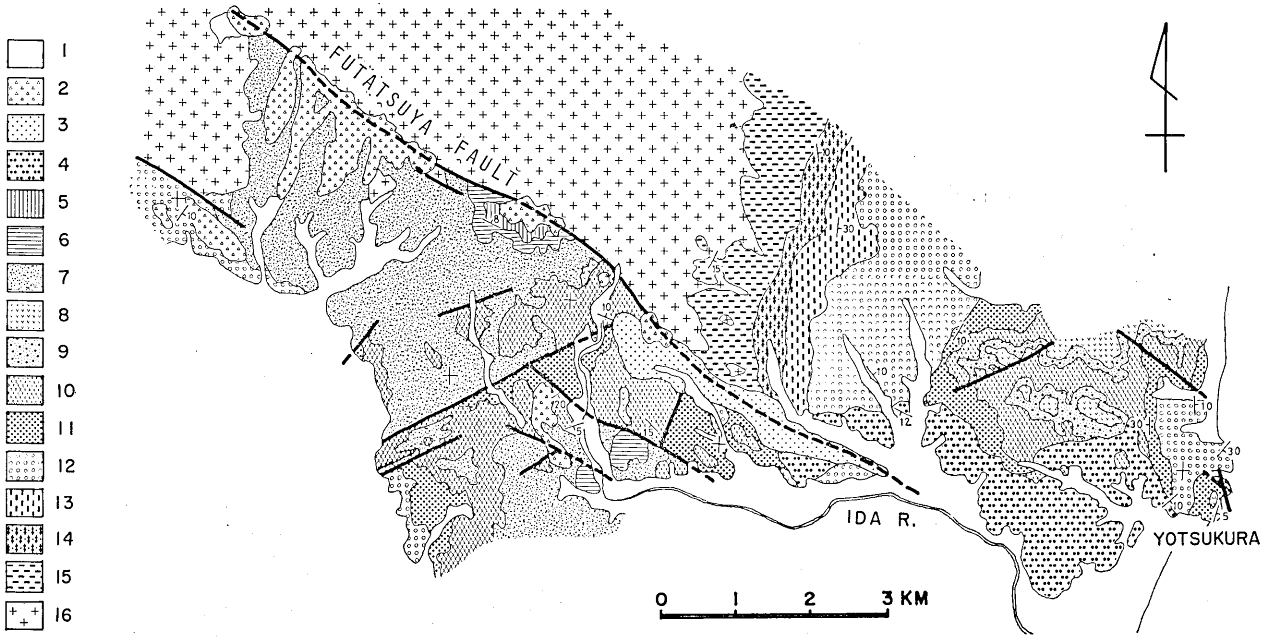


Fig. 15. Geologic map of Yotsukura area (TSUNEISHI, 1964 MS).
1. Alluvium, 2. Terrace deposits, 3. Sodetamayama formation, 4. Taga group, 5. Kamenoo formation, 6. Mizunoya formation, 7. Goyasu formation, 8. Rhyolitic tuff member of Taki formation, 9. Conglomerate member of Taki formation, 10. Shirasaka formation, 11. Asagai formation, 12. Iwaki formation, 13. Tamayama formation, 14. Kasamatsu formation, 15. Ashizawa formation, 16. Basement rocks.

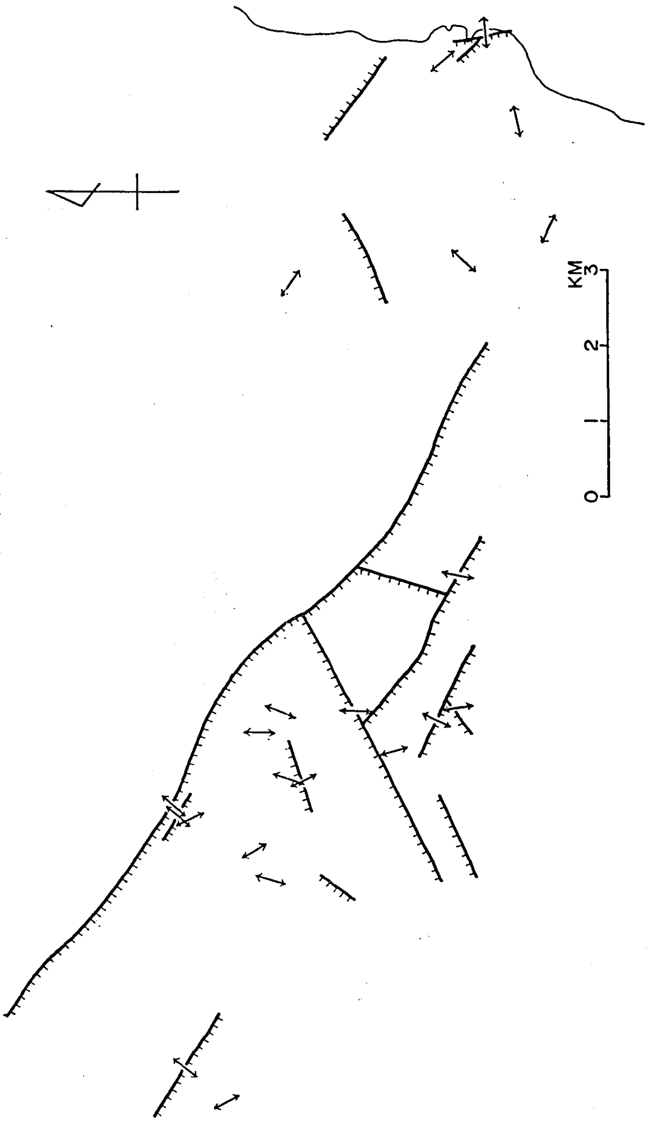


Fig. 16. Structural map of Yotsukura area. Arrows show direction of axes of minimum compressive principal stress.

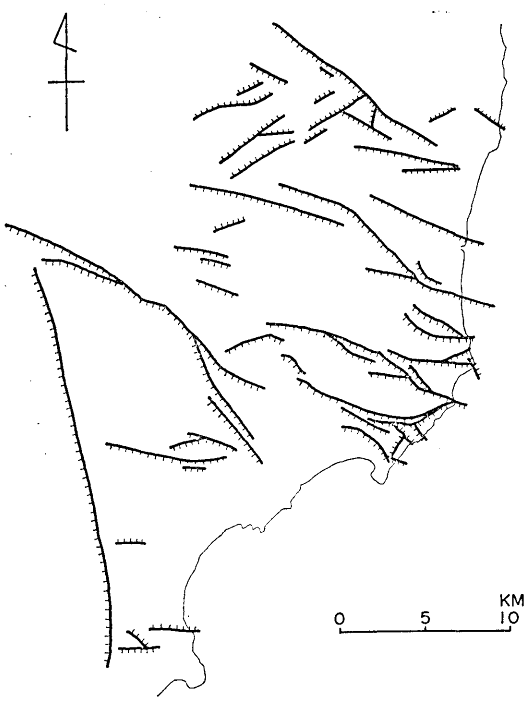


Fig. 17. Normal fault systems in Yotsukura area and its southern extension (SUGAI et al., 1957).

the eastern part of the area that may have been under the influence of the Futaba tectonic line. MITSUI (1969) investigated the minor faults developing in the area adjacent to the south of the Yotsukura area. Figure 18 shows the attitudes of minor faults and the stress systems determined by the minor faults, which were studied by him. The minor faults are grouped into two sets; an ENE-trending one and a WNW-trending one. The minor faults must therefore have been intimately related to the two sets of major faults illustrated in Fig. 17.

The tectonic features of the Yotsukura area are summarized as follows. The area was subjected to block faulting in Late Miocene. It is presumed that the faults related to the block faulting are dip-slip vertical faults in the basement and change into normal faults in the sedimentary cover. The faults and associated minor faults are divided into a WNW-trending set and an ENE-trending set. Each set of faults shows a regularity with respect to the sense of slip and the direction of the tilt of the intervening blocks, and so seems to be a product of antithetic faulting.

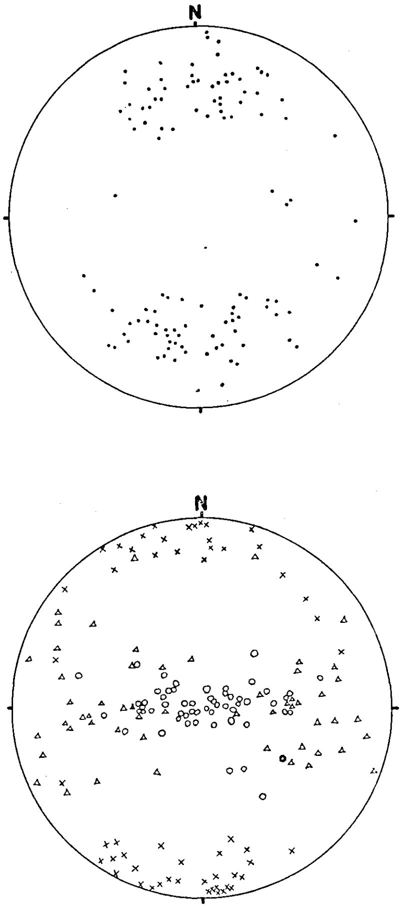


Fig. 18. Stereographic projection of minor faults and stress systems determined by them (upper hemisphere of Schmidt's net). Circles, triangles and crosses show axes of maximum, intermediate and minimum compressive principal stress respectively (MITSUI, 1969).

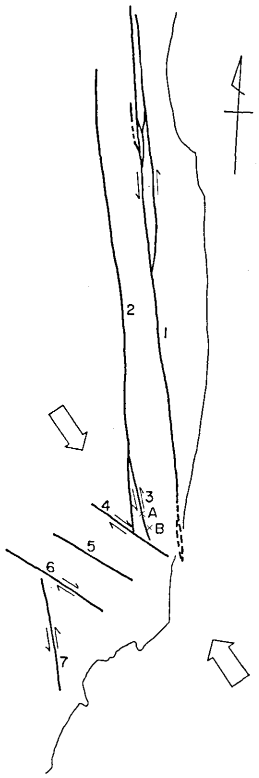


Fig. 19. Fracture systems of basement.
1. Futaba tectonic line, 2. Hatagawa tectonic line, 3. Yaguki fault, 4. Futatsuya fault, 5. Akai fault, 6. Yunotake fault, 7. Idosawa fault.

2-5. Fracture Systems of the Basement

In the eastern margin of the Abukuma range, faulting that occurred after the deposition of the sedimentary cover, occurred in many cases as reactivation of the faults that had formed in the basement before the deposition of the cover. Hence it is important to elucidate how and when these old fracture systems were produced in the basement. To put it briefly, it is concluded that they were formed by strike-slip faulting in the Middle Cretaceous time (after emplacement of the granite and before deposition of the Futaba group). In the following are cited several lines of evidence leading to the conclusion.

Figure 19 shows the principal fracture system that developed in the basement. The following features are recognized: faults trend comparatively straight; they consist of a north-trending system and a west-northwest-trending system; the fault planes dip vertically. These features suggest the former system and the latter system were probably formed by left-lateral and right-lateral faulting, respectively. The field observations confirm the high probability of the scheme, as follows.

In the Soma area, as already described in Sec. 2-2, the Wariyama horst consists of several different rock bodies of lenticular shapes that are mutually jointed by vertical faults. Within the horst, the minor

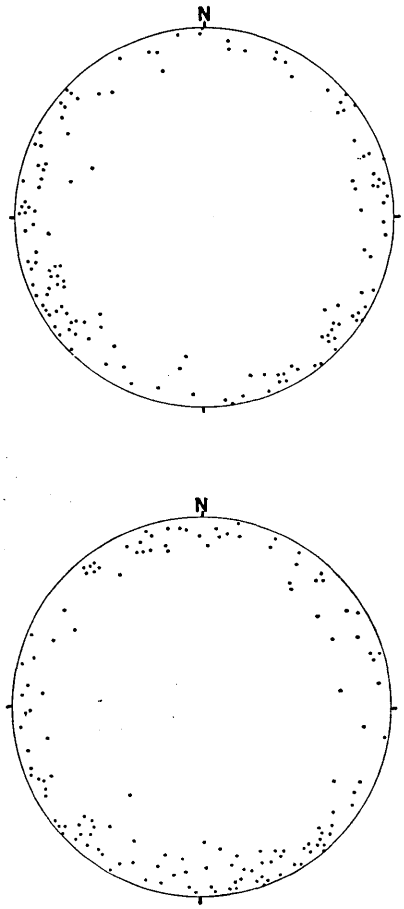


Fig. 20. Minor faults (upper) and striations (lower) observed at point A of Fig. 19 within crush zone of Yaguki fault (upper hemisphere of Schmidt's net).

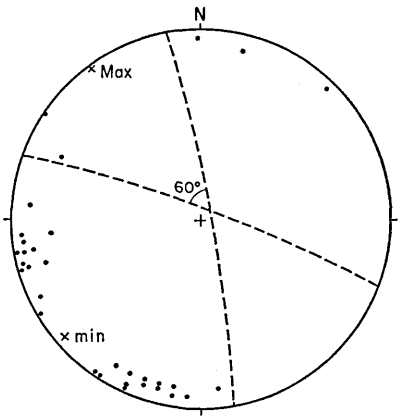


Fig. 21. Shear fractures developed in granite at point B of Fig. 19 (upper hemisphere of Wulf's net).

faults with horizontal striations, as well as the left-lateral offsets of veins along north-trending minor faults, occur occasionally. These occurrences support the hypothesis of left-lateral strike-slip fault origin of the Futaba tectonic line. The lens-like structure observed in the Wariyama horst is considered to represent the structure of the fault zone that formed due to the strike-slip faulting of the tectonic line.

To the west of the Futaba tectonic line, and parallel to it, there extends the Hatagawa tectonic line. The Hatagawa tectonic line has not displaced the Upper Cretaceous and younger sedimentary covers. The Yaguki fault, as shown in Fig. 19, is a branch of the Hatagawa tectonic line on its southern extremity. Numerous minor faults with horizontal striations occur in the granite along the Yaguki fault. Figure 20 shows the stereographic projection of those minor faults and the striations that were measured at point A of Fig. 19. The minor faults display a preferred orientation parallel to the Yaguki fault with a trend of NNW, and the striations are predominantly horizontal. Hence the Yaguki fault is found to have formed at least as a strike-slip fault, although its sense of slip is not known.

In addition to this, similar minor faults with horizontal striations are observable in the granite at the point B, somewhat apart from the Yaguki fault. As shown in Fig. 21 they have two separate trends of NNW and WNW. Since the surface features of the fault planes are similar to each other in both groups, they are presumed to form a conjugate fault set. If so, it is concluded that the NNW-trending and the WNW-trending faults are left-lateral and right-lateral strike-slip faults respectively on the basis of the shear angle. The minor faults at point B thus display a clear pattern of conjugate set, whereas those at point A show a predominant clustering around the trend parallel to the Yaguki fault. The difference may be explained by the distance from the main fault (Point A is nearer to it than point B). Such a manner of development of minor faults has been also ascertained along the Komyo fault in the Misakubo area (TSUNEISHI et al., 1975).

IWAO and MATSUI (1961) noted that the folding axes of metamorphic rocks were dragged clockwise near the WNW-trending Futatsuya and Yunotake faults, shown in Fig. 19, and concluded that the two faults were originally formed as right-lateral strike-slip faults. Moreover, the present author observed that many minor faults with horizontal striations were developed in the metamorphic rocks along the NNW-trending Idosawa fault.

The above-mentioned various lines of field evidence lead to the conclusion that NNW-trending and WNW-trending fractures in the basement have formed, respectively, as left-lateral and right-lateral strike-slip faults that are conjugate with each other.

2-6. Block Faulting in the Eastern Margin of the Abukuma Range

At least four different periods of block faulting are discernible in the eastern margin of the Abukuma range. They are assigned to the Middle Cretaceous, Early Miocene, Late Miocene and Late Pliocene to Pleistocene ages. Each block faulting was not the repetition of the same tectonic process, but was characterized by different crustal deformations. Hence it is probable that the regional tectonic forces, which caused the different block faulting, were also different from each other. On the other hand, we can point out a common feature that the second and later block faultings occurred, utilizing the fracture systems in the basement, which had been produced by the first block faulting.

The first block faulting was, as described in Sec. 2-5, strike-slip faulting. By this tectonic movement, north-trending fractures and west-northwest-trending fractures occurred. Therefore, the tectonic force that resulted in the faulting is presumed to have been a NW-trending compression, as designated by arrows in Fig. 19. Since the type of the faulting is of the strike-slip kind, it is presumed that a NE-trending extension should have prevailed at the same time.

During the second block faulting, the western boundary fault of the Wariyama horst was activated in the Soma area, and the Miocene sedimentary basin occurred on the west of the fault. At that time, the Abukuma range lay in a low altitude and the sea partly invaded the inland of the range. This is substantiated by the unconformities at the base of the Miocene Yunagaya group in the Yotsukura area and the Shiode formation in the southwest of the Soma area. Although there is no definite evidence, it is presumed that an EW-trending tension had persisted as a regional tectonic force throughout the Abukuma range and that the normal faulting occurred along the western boundary of the Wariyama horst.

During the third block faulting, various kinds of tectonic phenomena were recorded in the eastern margin of the Abukuma range. In the Soma area, the uplift of the Wariyama horst as well as probably the NW-trending normal faults in the western part of the area occurred. In the Hirono area, the flexuring occurred along the Futaba tectonic line. In the Yotsukura area, WNW-trending and ENE-trending normal faults were formed.

Among them, the flexuring in the Hirono area directly indicates the upheaval of the Abukuma range. TSUNEISHI (1966) estimated the total amount of vertical displacement along the Futaba tectonic line to be 1000 m. The amount of 700 m from the 1000 m is attributed to the third block fulting. Since it is presumed that the upwarping of the range accompanied the upheaval of the range, the amount of upheaval in the central part of the Abukuma range might have been larger than 700 m. Incidently, the amount of displacement along the Futatsuya fault in the

Yotsukura area has been estimated to be more than 500 m (TSUNEISHI, 1964 MS).

In the northern part of the Abukuma range, the western side of the Futaba tectonic line has not risen so greatly, relative to the eastern side, as in the Hirono area. This is indicated by the fact that rather thin Miocene strata have been preserved on both sides of the tectonic line. Moreover, the amount of displacement that is presently shown by the Miocene strata on both sides of the Wariyama horst is mostly attributed to the following fourth block faulting. However, the Wariyama horst was uplifted within a zone along the Futaba tectonic line during the third block faulting. The amount of uplifting is estimated to be a few hundred meters by means of the correlation of the basaltic lavas lying on the horst as a remnant to the Tenmyosan formation.

A group of normal faults in the western part of the Soma area and two groups of normal faults with different trends in the Yotsukura area show systematic senses of fault slip. They are assumed to have been formed by an antithetic faulting related to the upwarping of the Abukuma range. If the hypothesis holds true, we can decide the center of upheaval, conversely. The Abukuma range is assumed to have risen with two centers of upheaval which are situated in the central parts of the northern half and southern half of the range respectively. That is to say, a group of normal faults in the western part of the Soma area and a group of ENE-trending normal faults in the Yotsukura area are related to the upheaval of the northern half of the Abukuma range, whereas another group of WNW-trending normal faults in the Yotsukura area is related to that of the southern half.

As already described in Sec. 2-2, narrow slices of the Tertiary sedimentary cover are inserted between blocks constituting the Wariyama

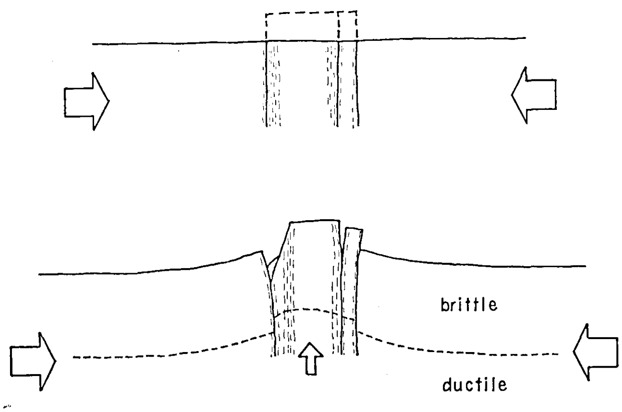


Fig. 22. Uplifting mechanism of Wariyama horst.

horst. This phenomenon was interpreted as the result of an EW-extension exerted on the shallow portion of the horst. However, the EW-extension could not promote the uplifting of the horst. On the contrary, an EW-trending compressional tectonic force would be an alternative driving force. As shown in Fig. 22, we assume that the Wariyama horst was submitted to lateral compression. Since inner parts of the horst had been crushed and brecciated severely, rocks within the horst would be more easily deformed and shortened in width under the compression than the lesser crushed rocks extending outside the horst. Rocks in the root of the horst, which are relatively ductile due to an increased confining pressure, will be also shortened in width and thickened, so that a pushing-up force is exerted on the horst.

The Abukuma range is presumed to have risen under an EW-trending compression that is inferred from the uplifting mechanism of the Wariyama horst during the third period of block faulting. The manner of upheaval includes upwarping with two centers of upheaval and faulting.

In the fourth block faulting, the eastern boundary fault of the Wariyama horst was displaced and the western side of the fault moved up in the Soma area. The amount of displacement is estimated to be about 300 m. In the Hirono area, there occurred further progress of flexuring and faulting along the Futaba reverse fault in the sedimentary cover. The amount of vertical displacement along the basement fault is estimated to be 300 m. However, no faulting occurred in the Yotsukura area. The present topography of the Abukuma range is mostly a product of the fourth block faulting. Hence the deformational figure of the range is able to be inferred from it. The Abukuma range was upwarped, with a north-trending axis near the eastern margin, and tilted westward as a whole. The tectonic force that was exerted on the range is presumed to have been an EW-trending compression in the same manner as that of the third block faulting.

3. Southern Area of the Suzuka Range

In the southern area of the Suzuka range, dip-slip faulting occurred repeatedly during the Late Cenozoic time, so that rocks of the area were faulted into numerous fault blocks. The area is geotectonically situated in the Inner Belt of Southwest Japan, and founded by metamorphic rocks and granite that are related to the Late Mesozoic orogeny. The Miocene Isshi group, and Plio-Pleistocene Agé and Kobiwako group overlie the basement as sedimentary covers.

Figures 23 and 24 show the geologic map and the geologic sections, respectively, of the Matsuzaka area that occupies a part of the southern

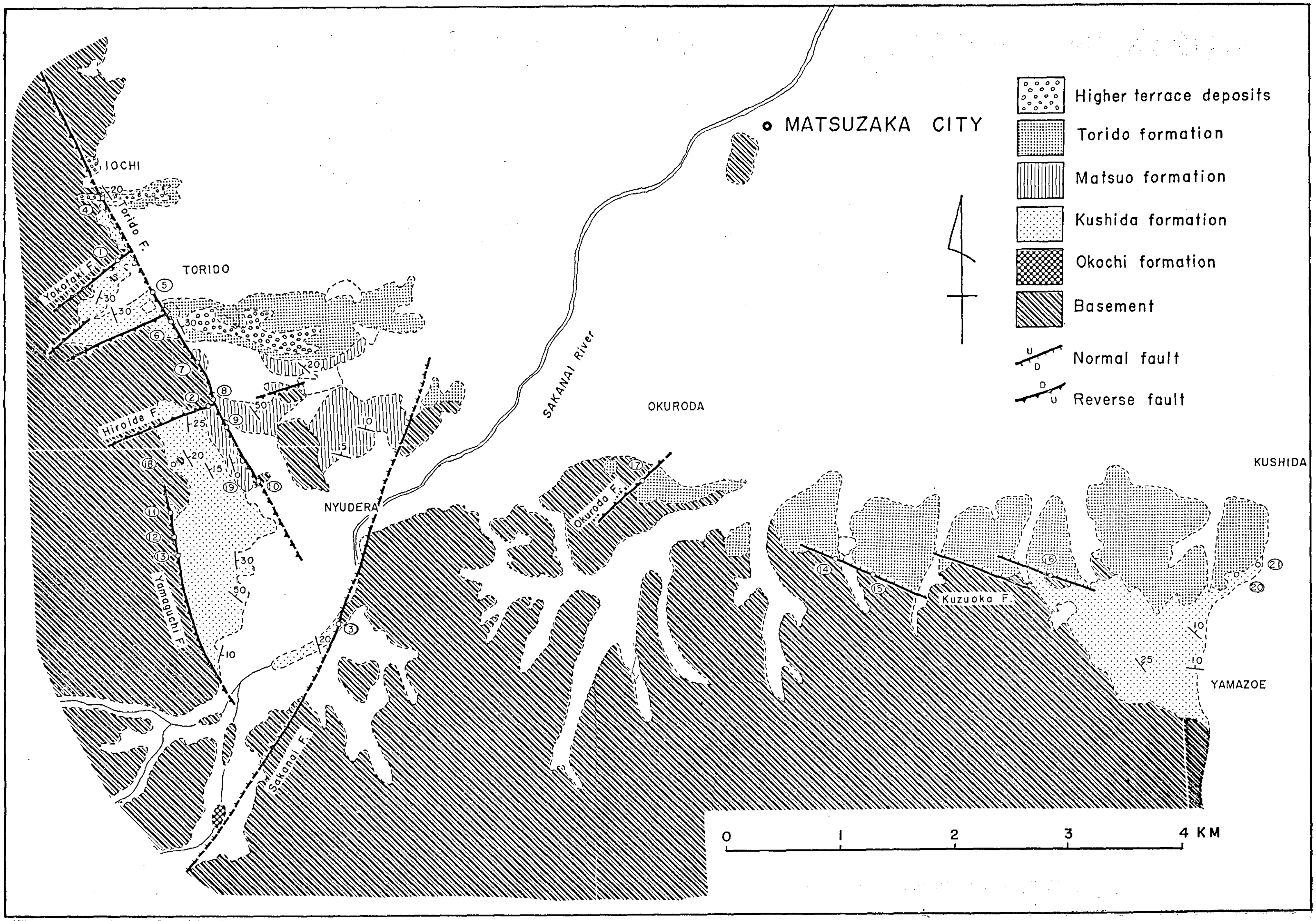


Fig. 23. Geologic map of Matsuzaka area (TSUNEISHI, 1970).

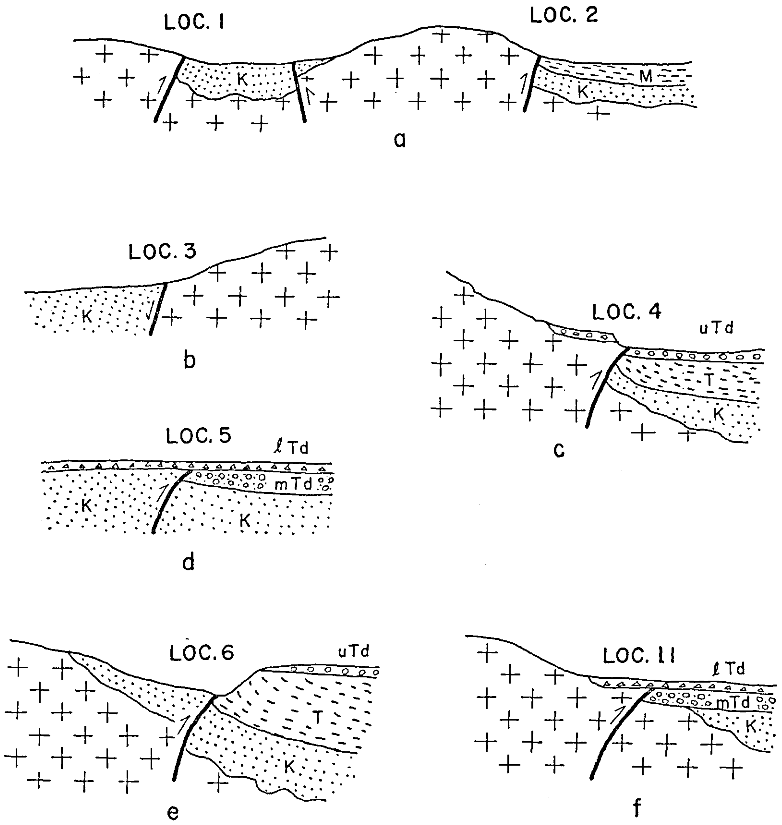


Fig. 24. Geologic profile of Matsuzaka area (TSUNEISHI, 1970).
K: Kushida formation of Isshi group, M: Matsuo formation of Isshi group, T: Torido formation of Agé group, uTd: Upper terrace deposits, mTd: Middle terrace deposits, lTd: Lower terrace deposits.

area of the Suzuka range. The Matsuzaka area has been divided into small blocks in a mosaic pattern by variously trending normal and reverse faults. TSUNEISHI (1970) grouped these faults into several sets on the basis of the periods of activity, the strikes and the types of displacement. The Yokotaki and Hiroide faults are ENE-trending high-angle reverse faults, and were formed by the block faulting that first occurred after the deposition of the Miocene Isshi formation. The trend nearly parallel to the trend of the gneissose texture of the basement rocks. The Sakanai fault is a NE-trending normal fault that occurred after the deposition of the Isshi group and before the deposition of the Plio-Pleistocene Agé group. The northwestern side of the fault has moved up, and the blocks on both sides of it have been tilted southeastward. The Torido and Yamaguchi faults are NNW-trending reverse faults that occurred after the deposition of the Agé group. Both faults are arranged en-échelon. The

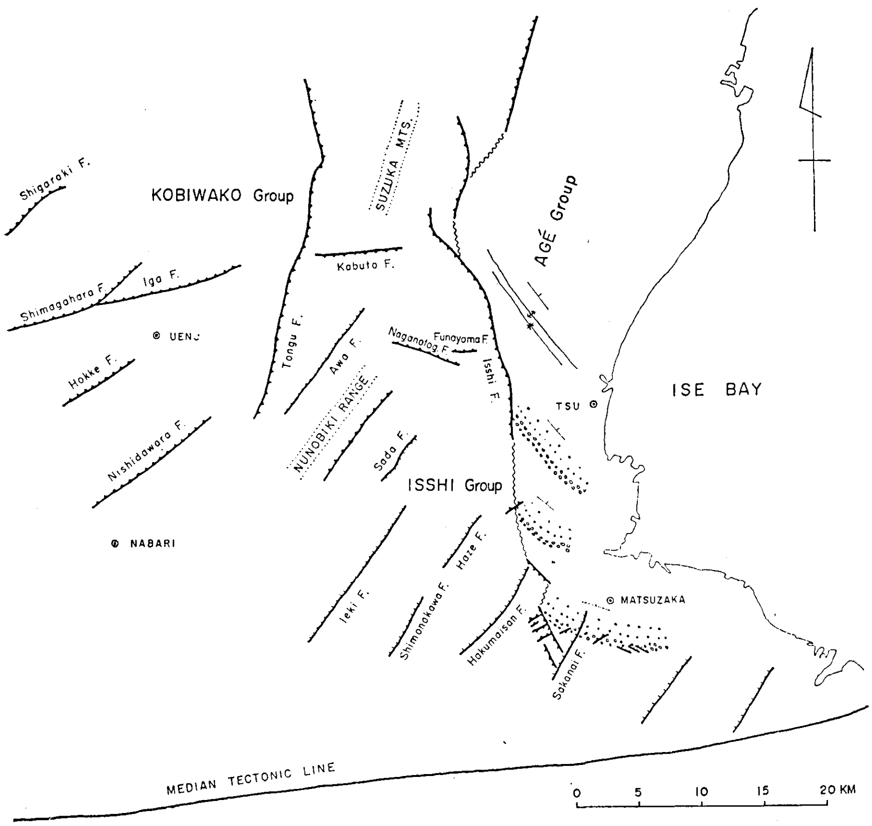


Fig. 25. Fault systems in southern area of Suzuka range (TSUNEISHI, 1970).

western sides of these faults have moved up. They were reactivated later and displaced deposits of the higher and middle terraces. The above-mentioned grouping of faults is applicable to the whole southern area of the Suzuka range.

Figure 25 shows the tectonic map of the southern area of the Suzuka range. Numerous faults have divided the area into blocks. These faults were grouped in the same manner as in the Matsuzaka area (Fig. 26). Faultings of stage-I and stage-II occurred after the deposition of the Isshi group and before the deposition of the Agé group. The faulting of stage-I is expressed by the activity of EW-trending high-angle reverse faults including the Yokotaki and Hiroide faults of the Matsuzaka area. These faults are named the Yokotaki fault system. The faulting of stage-II is expressed by the activity of NE-trending normal or high-angle reverse faults including the Sakanai fault of the Matsuzaka area. These faults are arranged at nearly equal intervals. Along these faults, with the exception of the Soda fault, the northwestern sides have moved down,

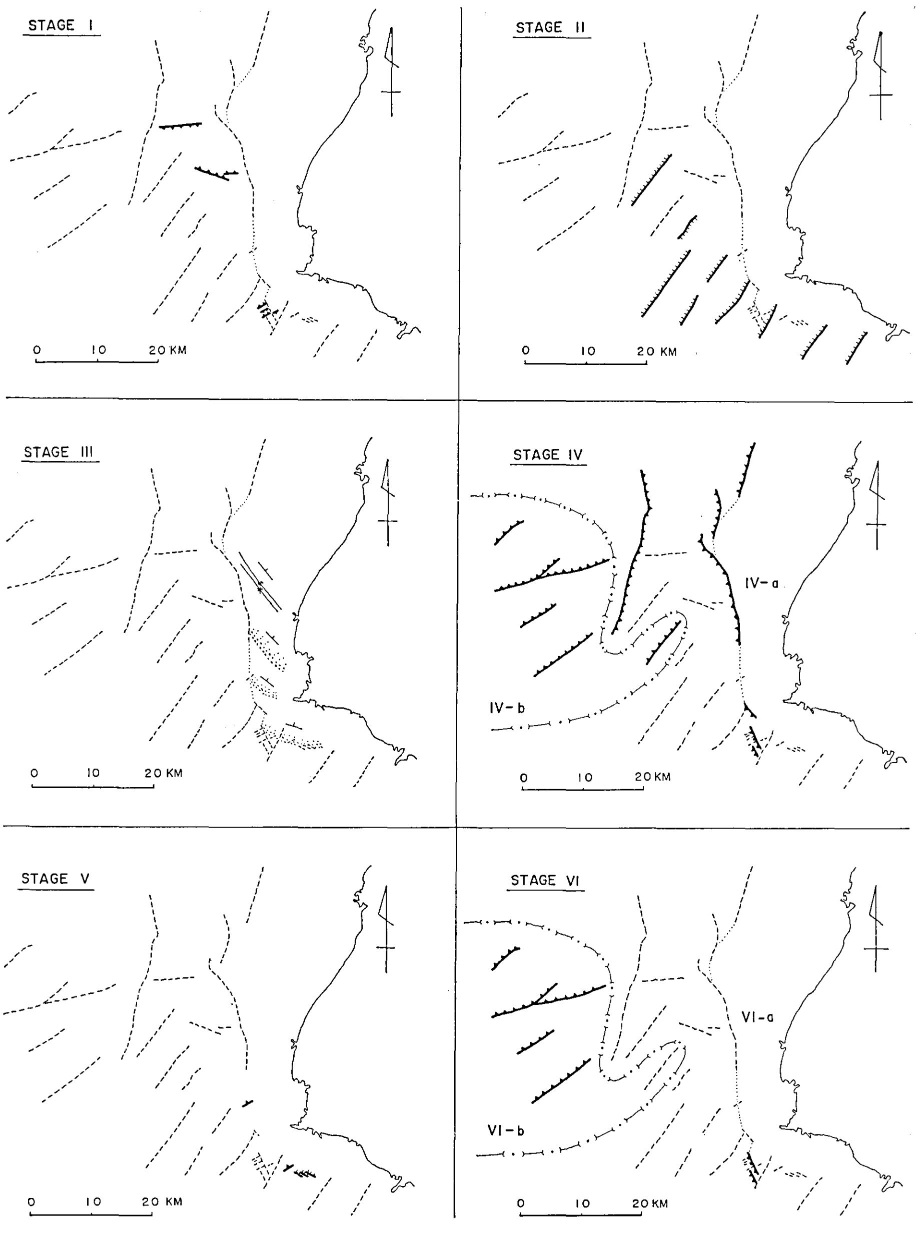


Fig. 26. Stages of block faulting in southern area of Suzuka range (TSUNEISHI, 1970).

and the intervening fault blocks have been tilted to the southeast. This group of faults is named the Sakanai fault system.

The faultings of stages-III, IV, V occurred after the deposition of the Agé group and the Kobiwako group. The activity of stage-III is expressed by step-like flexures developed in the Agé group. Northeastern limbs of the flexures are gentle and southwestern limbs are steep. This structural feature of the sedimentary cover probably reflects a series of tilt blocks of the basement. The faulting of stage-IV-a is expressed by the activity of those faults that bound the Suzuka range on the eastern and western borders. The Suzuka range was uplifted as a horst by the faulting, These faults are high-angle reverse faults. Among them the faults that bound the range on the eastern border are called the Isshi fault system as a whole. The Isshi fault system consists of a set of en-échelon arranged reverse faults and flexures connecting these faults. The Torido and Yamaguchi faults in the Matsuzaka area belong to the fault system at the southern extremity. The fault that bounds the Suzuka range on the western border is a reverse fault called the Tongu fault. This fault is also arranged en-échelon with other faults beyond an extent of Fig. 25. Faulting of stage-IV-b occurred in the area extending to the west of the Suzuka range, and produced a group of tilt blocks. These blocks were bounded by reverse faults and uniformly tilted northwestward. These reverse faults are called the Iga fault system. The faulting of stage-V is expressed by the activity of WNW-trending small-sized normal faults and NE-trending small-sized reverse faults. The faulting of stage-VI occurred as a reactivation of several faults that belong to the Iga and Isshi fault systems.

As a result of the above-mentioned grouping of the faults, individual fault systems show a simple pattern of block faulting. Both the Isshi fault system and the Tongu fault of stage-IV-a, which uplifted the Suzuka range as a horst, are synthetic faults. On the other hand, the Sakanai fault system of stage-II, the step-like flexures of the Agé group of stage-III and the Iga fault system of stage-IV-b display antithetic fault patterns in the sense that the down thrown side of a fault is opposite to the direction of the tilt of the blocks on both sides of the fault.

The most deeply subsided portion of the sedimentary basin of the Kobiwako group is located in Lake Biwa to the west of the area that is occupied by the Iga fault system, and the individual blocks bounded by the faults belonging to the Iga fault system have been tilted toward Lake Biwa. Furthermore, the center of subsidence of the sedimentary basin of the Agé group is located to the northeast of the area that is occupied by the step-like flexures of the Agé group, and individual blocks have been tilted toward the center of subsidence. Therefore, these antithetic faults are thought to have occurred in relation to a large-scale warping of the crust. The age of the activity of the Sakanai fault system is old, and therefore the paleogeography at that time is not clearly known. However, the center of upwarping is presumed to have been located to the northwest, because

Table 2. Dip of fault surface.

Stage	Fault System	Strike	Range	Mean	Observed Value
I	Yokotaki	E-W	70°-90° Rev.	83° Rev.	70°N, 90°N, 90°N
II	Iga	NE	60° Norm.-70° Rev.	78° Norm.	60°W, 60°W, 60°W 70°W, 70°W, 70°W 70°W, 80°W, 90°W 85°E, 80°E, 70°E
III	Agé G.	NW	—	—	—
IV-a	Isshi	NNW	65°-82° Rev.	70° Rev.	65°W, 80°W, 82°W
IV-a	Tongu	NNE	50°-80° Rev.		50°E, 50°E, 70°E 75°E, 80°E, 80°E
IV-b	Iga	NE	40°-80° Rev.	67° Rev.	40°N, 50°N, 60°N 60°N, 70°N, 70°N 75°N, 80°N, 80°N 80°N
V	Oguroda	NE	30°-50° Rev.	40° Rev.	30°W, 50°W
V	Kuzuoka	WNW	60-70° Norm.	63° Norm.	60°N, 60°N, 70°N
VI-a	Isshi	NNW	25°-55° Rev.	39° Rev.	25°W, 30°W, 30°W 30°W, 35°W, 40°W 40°W, 40°W, 45°W 50°W, 50°W, 55°W
VI-b	Iga	NE	—	—	—

Norm: normal dipping, Rev: reverse dipping.

each fault block has been tilted toward the southeast. HUZITA (1968) has noted in his study of the Late Cenozoic crustal deformation that crustal undulations with a wavelength of 80-100 km prevail in Southwest Japan. On the other hand, the fault blocks produced by the Sakanai and Iga fault systems and the step-like flexures of the Agé group have a size of about 10 km. Hence these block faultings are regarded as a tectonism of the secondary order which is governed by the large-scale crustal undulation.

The following characteristics are deduced from the observation of faults bounding individual fault blocks. Table 2 shows the dips of faults that have been reported by many geologists. The dips of faults were divided according to the fault system, and the average value was calculated. The faults belonging to the Sakanai fault system of stage-II include reverse faults in addition to normal faults. However, the measured values of the dips continuously range from a normal fault dipping 60° to a reverse fault dipping 70° without any appreciable gap between the two types of faults. Then, in the calculation of average a reverse fault with a dip of 80°, for example, was dealt with as a normal fault with a dip of 100°.

As shown in Table 2, the average value of the dips of the reverse faults increases from 39° to 83°, as the ages of faulting become older. Likewise, the average dip of the normal faults changes from 63° to 78°, although there are only two examples. The areal distribution of the fault systems of each stage does not give a possibility that the steep dips of the older fault planes have resulted from the tilting of fault blocks associated with the younger faulting. Therefore, the steepening of dips of fault planes is well interpreted as follows. The faults of the older stages have been submitted to long-term erosion and profound denudation in general. Those portions of the faults that we presently observe at the surface of the earth had formed at a deeper level. It is propable, therefore, that the faults distributed in the southern area of the Suzuka range are characterized by such curved fault surfaces that dip gently near the earth's surface and steeply at it's depth.

4. Central Area of Gifu Prefecture

In the central area of Gifu Prefecture, strike-slip faulting has actively prevailed in the Quaternary time, so that we can well study the character of block faulting by the strike-slip faults in recent geologic time. The rocks of this area consist mainly of the Paleozoic formations, the Nohi rhyolites and the younger volcanics. The Nohi rhyolites, a product of Late Cretaceous acid volcanism, are composed mainly of welded tuffs, and overlie folded Paleozoic formations with an angular unconformity. They occur most extensively and thickly in the area. The younger volcanics are composed of the Plio-Pleistocene andesitic lavas and pyroclastics and occur in the northern part of the area (GEOLOGICAL SURVEY, 1961).

Figure 27 shows the distribution of Quaternary strike-slip faults studied by TSUNEISHI (1976). The NW-trending fault have left-lateral strike-slip displacements and the NE-trending faults have right-lateral displacements. Fault planes or fault crush zones are observable at the points-1, 3, 4, 5, 7, 9, and 11 of Fig. 27. The dips of these faults are vertical. It is certain that these faults have been active during the Quaternary time judging from offset river courses and displaced Quaternary deposits.

These faults are divided into two groups: faults that were newly formed in the Quaternary time and faults that had been formed before and reactivated during the Quaternary time. When the geologically estimated displacement along a fault coincides in magnitude with the topographically estimated displacement, the fault is proved to have been formed for the first time in the Quaternary time. Along the Atera fault, for example,

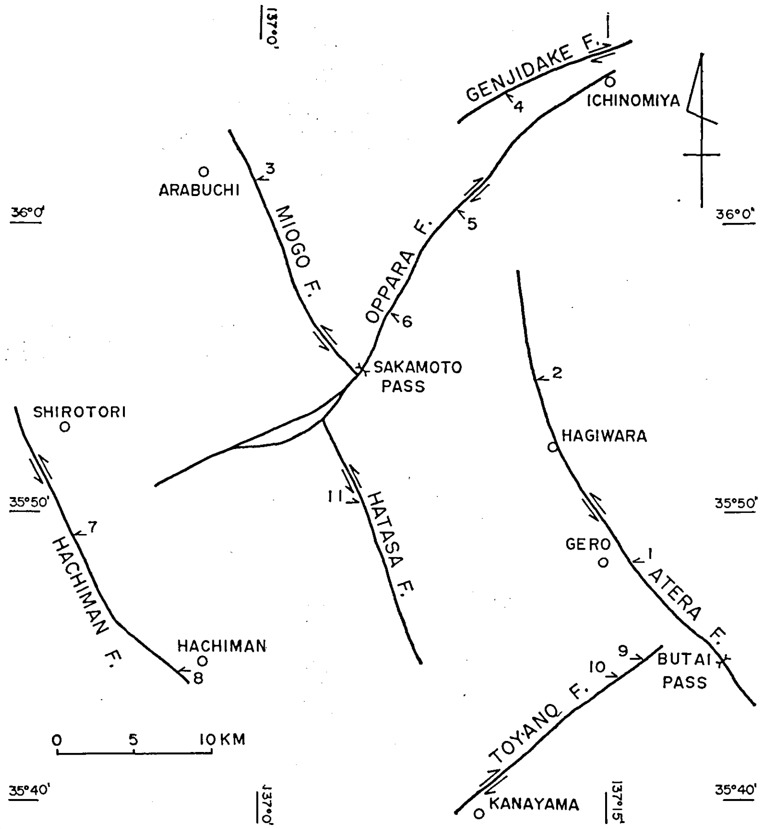


Fig. 27. Quaternary fault system in central area of Gifu Prefecture (TSUNEISHI, 1976).

the amount of displacement estimated by a geological method is 8–12 km (NISHINA, 1973) and that estimated by a topographical method is 8 km (SUGIMURA, 1967). Along the Oppara fault, the former amount is about 3 km (YOSHIDA, 1972) and the latter amount is 3–4 km (TSUNEISHI, 1976). Hence the Atera and Oppara faults are proved to have been formed for the first time in the Quaternary time.

The above-mentioned two groups of faults are characterized by different manners of rock fracturing due to faulting. Particular minor fault surfaces occur in the fracture zone along the faults that had been formed before the Quaternary time. The minor fault surfaces have been ornamented with parallel striations indicative of shearing directions. These striations have been carved directly on hard rock surfaces, not on fault clays. On the contrary, such a manner of minor faulting is not observable along the faults that have formed for the first time during the Quaternary time. Furthermore, the systematic lens-like shearing is observable in the fracture zones of the former group of faults, whereas the rocks in the fracture zones of the latter group of faults have been merely fractured into irregular, polygonal fragments. Thus, the old faults display the features of rock deformation produced at deeper level, whereas the young faults show the deformational features at shallow level. These features are comprehensible by taking the period of time needed for uplift and denudation into consideration.

In conclusion, the Miogo, Hatasa and Hachiman faults were formed before the Quaternary time and reactivated later, whereas the Atera, Genjidake, Oppara and Toyano faults were formed for the first time in the Quaternary time.

These strike-slip faults have developed as a conjugate fault system during the Quaternary time. The individual faults may have been activated sporadically, and have many times repeated their fault slippage to attain the present amounts of displacement. In the long run, however, the activities can be regarded as having been steady through the Quaternary time. These faults have divided the central area of Gifu Prefecture into fault blocks with a size of 15–25 km across. Because the size of these fault blocks has persisted during the Quaternary time, the size of individual fault blocks is considered to represent a minimum unit of block faulting characteristic of this area.

A group of fault blocks shown in Fig. 27, as a whole, is comprised by a larger fault-block, which had been formed by large-scale Quaternary faults in Central Japan, such as the Atera, Neo-valley, Yanagase and Atotsugawa faults. These large-scale faults are about 80 km in length, whereas the small-scale faults shown in Fig. 27 are 20 km in length. Such a composite structure of block faulting developed in Central Japan is analogous to the relation between the individual faults and the fault systems that have been recognized in the southern area of the Suzuka range.

Occurrences of shallow earthquakes are mostly regarded as an expression of recent block faulting. A large earthquake, such as the Nobi earthquake of 1891 (M=8.4), occurred along the Neo-valley fault bounding large-scale fault-blocks. On the other hand, moderate-sized earthquakes, such as the Hachiman earthquake of 1934 (M=6.2) and the Gifuken-chubu earthquake of 1969 (M=6.6), occurred, respectively along the Hachiman and Hatasa faults shown in Fig. 27.

The relation between the Gifuken-chubu earthquake of 1969 and the Hatasa fault gives information on the deep-seated structures of the fault. A seismological study on the earthquake and a geological study on the fault have been reported by WATANABE and KUROISO (1970) and TSUNEISHI (1976) respectively. Figure 28 shows the surface trace of the Hatasa

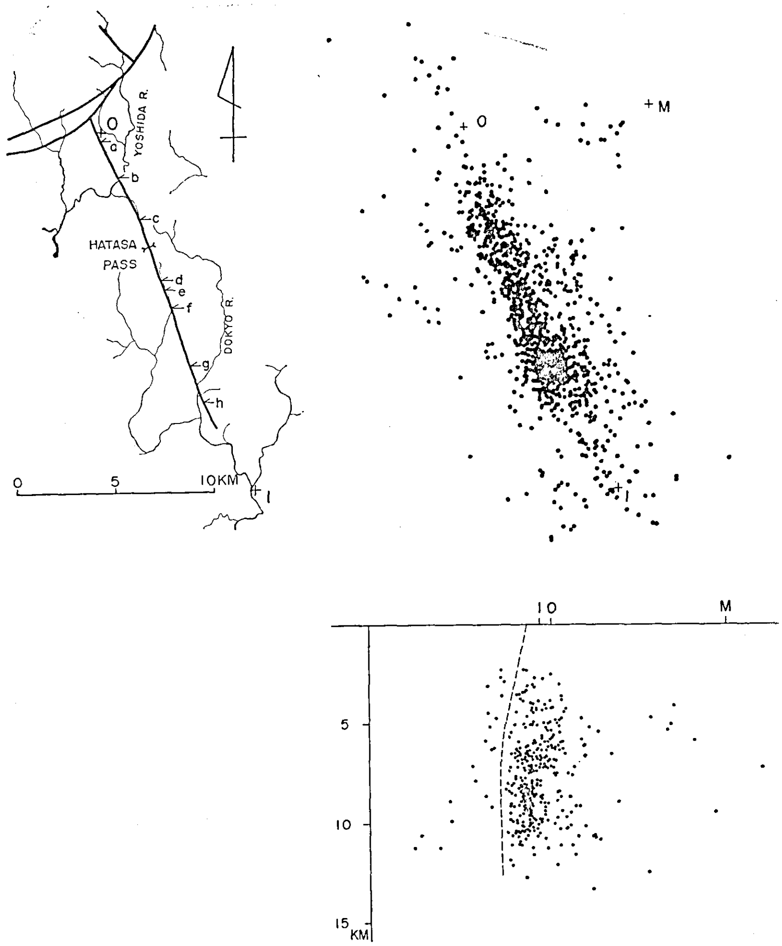


Fig. 28. (a): Surface trace of Hatasa fault (TSUNEISHI, 1976), (b): Epicentral distribution of aftershocks (WATANABE and KUROISO, 1970), (c): Vertical distribution of aftershocks (WATANABE and KUROISO).

fault and the distribution of observed aftershocks. WATANABE and KUROISO (1970) noticed a narrow aseismic zone along the western border of the most densely clustering belt of aftershocks and related the aseismic zone to the main slip plane of the fault. The seismologically presumed slip plane apparently does not coincide with the geologically observed trace of the Hatasa fault on the surface; the former parallels the latter 1.5 km to the west. However, since the Hatasa fault dips 80° westward at point C of Fig. 28, the seismologically presumed slip-plane and the Hatasa fault will possibly coincide with each other under the ground. Fig. 28(c) shows the vertical distribution of aftershocks projected on the vertical cross section perpendicular to the fault trace. This figure was personally presented from

Watanabe and Kuroiso. The vertical trace of the Hatasa fault is estimated as the broken line.

The fact that the supposed main slip plane is quite devoid of aftershock occurrences will be ascribed to the severely crushed character of rocks within a narrow zone surrounding the main slip plane. On the contrary, many aftershocks occurred in a belt of about 2 km wide to the east of the main slip plane at a depth ranging from 2 km to 12 km. Hence, it is presumed that many minor faults newly formed under the ground within the belt, indicated by the occurrence of aftershocks. The fact that most of the aftershocks occurred on the east side of the main slip plane is explained by the difference in rock types under the ground on opposite sides of the Hatasa fault (TSUNEISHI, 1976). From the geological data the deep-seated rocks are presumed to be granite on the east side of the fault and crystalline schists on the west side. When granite and crystalline schists, abutting each other across a fault, are subjected to a certain amount of strain, granite is more likely to be broken down in a brittle manner, whereas crystalline schists in a ductile manner.

5. Matsushiro Area

The Matsushiro area, which was the site of the conspicuous swarm earthquake in 1965–66, is situated in the northern part of the Fossa Magna belt (Fig. 1). Figure 29 shows the outline of geology of the region surrounding the Matsushiro area. Subsidence of the northern Fossa Magna began in the Early Miocene period, accompanied by submarine volcanism. In the Middle to Late Miocene, intrusion of diorite and porphyrite occurred in a belt crossing the sedimentary basin in a NE-SW direction. Since then, the belt has become comparatively rigid and has become an uplifted block. The belt is named the Central Belt of Uplift (IIJIMA, 1962). In the sedimentary basin to the northwest of the belt the deposition of thick marine sediments continued through Miocene to Pliocene, whereas in the basin to the southeast of the Belt non-marine Pliocene sediments accumulated. The strata in the northwestern basin have been later folded and faulted. The folding is considered to be still active, as is indicated by Late Quaternary folded terraces and by the results of precise levelling (MORIMOTO et al., 1966). Sedimentation still continues in the Nagano basin, which lies between the northwestern basin and the Central Belt of Uplift.

As shown in Fig. 30, the crustal structure of the Matsushiro area, by a explosion seismic method, reveals a striking structural contrast between the Central Belt of Uplift and the sedimentary basins on both sides of the Belt (ASANO and YOSHII, 1973). The profile is crossing the Central

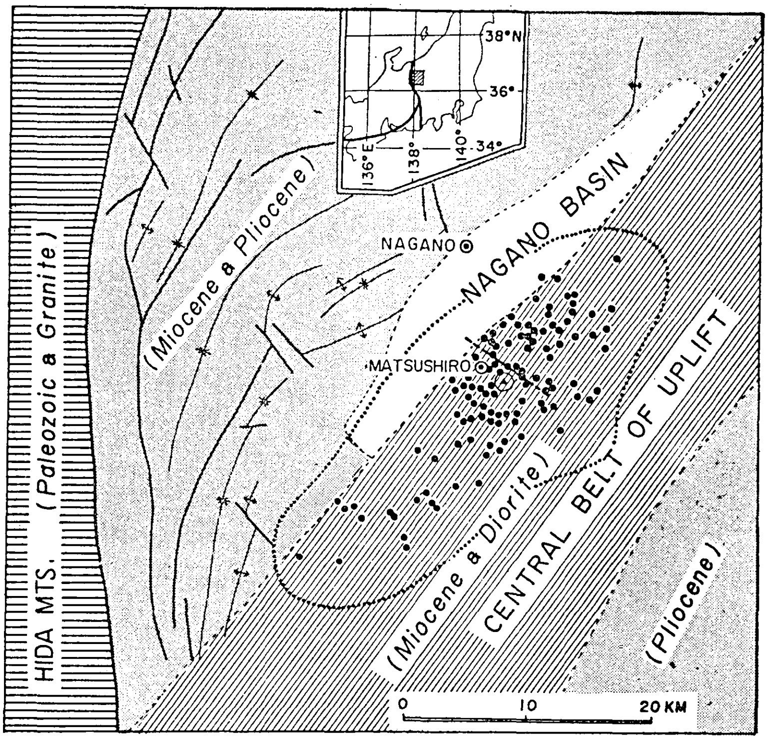


Fig. 29. Simplified tectonic map around Matsushiro area, including epicentral distribution of major shocks and realm of ultra-micro earthquakes (TSUNEISHI and NAKAMURA, 1970).

Belt of Uplift in a NNW direction. A sharp dislocation of the upper surface of the layer with a velocity of 6.0 km/s occurs beneath the boundary between the Central Belt of Uplift and the basin to the northwest of it, indicating the existence of a fault. The fault is covered by thick sediments of the Nagano basin and is not observable on the surface except for a subsidiary fault. Thus the Central Belt of Uplift is safely regarded as a NE-trending fault block.

The Matsushiro swarm earthquake began to occur in 1965 under Matsushiro Town which is situated near the northwestern margin of the Central Belt of Uplift. The seismic area gradually enlarged to the northeast and to the southwest and finally became an ellipse with a long axis of 34 km (HAGIWARA and IWATA, 1968). As shown in Fig. 29, the enlargement of the seismic area is clearly controlled by the Central Belt of Uplift. In 1966, ground cracks suggesting underground faulting appeared in the Matsushiro area. The inferred fault trends N55°W, crossing the Central Belt of Uplift. This implies that the single fault block of the

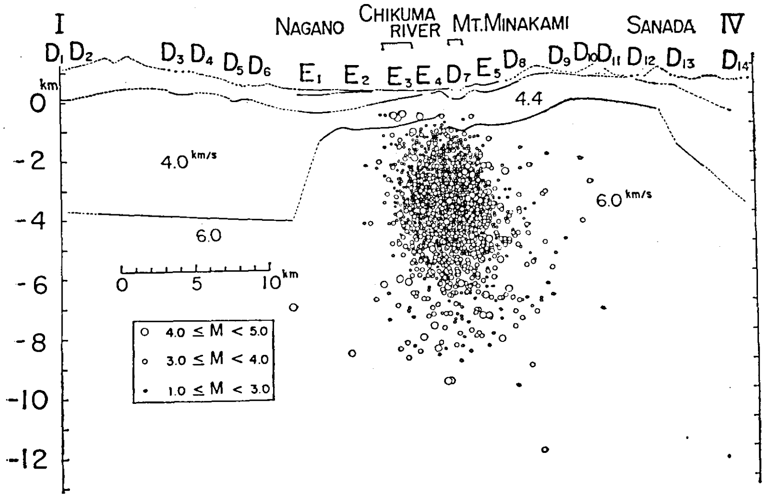


Fig. 30. Crustal structure determined by explosion seismic method and hypocentral distribution of felt Matsushiro swarm earthquakes (ASANO and YOSHII, 1973). Left side trends N25°W.

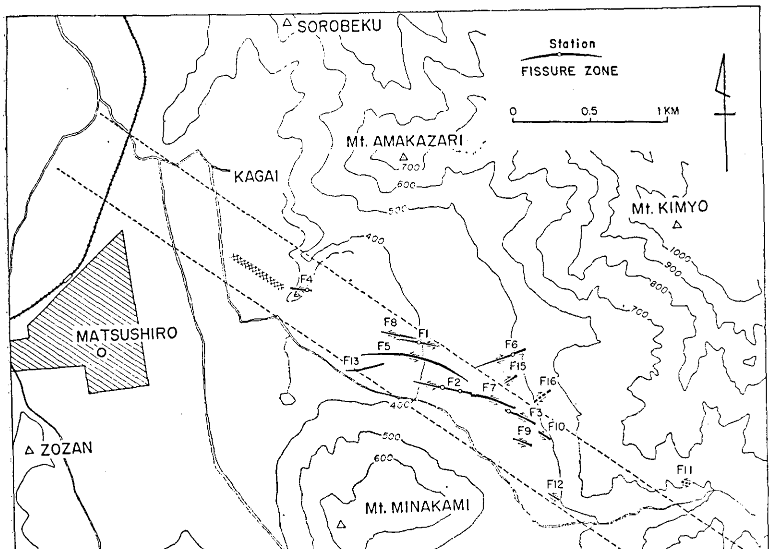


Fig. 31. Surface expression of Matsushiro earthquake fault (TSUNEISHI and NAKAMURA, 1970).

Central Belt of Uplift began to be divided into two fault blocks.

This fault named the Matsushiro earthquake fault was not a reactivated preexisting fault but a newly formed fault. Therefore, we can get information on formative processes of a fault in its early stage from the observation of the Matsushiro earthquake fault. Because detailed studies of the Matsushiro earthquake fault have been reported by NAKAMURA and TSUNEISHI (1966, 1967), and by TSUNEISHI and NAKAMURA (1970), only a brief outline of it will be described in the following.

The manner of the surface expression of faulting is greatly controlled by the surficial geology. Ground cracks occur on the alluvial fans and bedrock hills, whereas they do not occur on the low plains composed of fine, soft sediments. In the latter case, the buried fault is recognized by systematic deformation of long man-made structures such as concrete dikes of rice-fields, road-side ditches, underground water pipes, and railway tracks.

Figure 31 shows the distribution of ground cracks and deformed man-made structures. Each ground crack is composed of en-échelon arranged simple cracks up to several meters long, which are regarded as being formed essentially by tension fracture. Therefore, the ground crack is here called a fissure zone in distinction from the elementary crack. There are right-lateral and left-lateral fissure zones in the sense of horizontal displacement, which is indicated by the mode of en-échelon arrangement and by the sense of their displacement. The left-lateral fissure zones are distributed en-échelon in a belt with a width of 500 m. Various deformed man-made structures are also distributed in the belt. The Matsushiro earthquake fault is inferred to exist below this belt. The amount of left-lateral displacement of the fault was estimated to be 50 cm by TSUNEISHI and NAKAMURA (1970) on the basis of field and instrumental observations.

As shown in Fig. 29, the Matsushiro earthquake fault is situated in the central part of the seismic area. However, because the long axis of the seismic area is nearly perpendicular to the trend of the fault, the displacement of the fault is considered to be ascribable to only a small proportion of the earthquakes. Instrumental observations on displacements of several fissure zones revealed two different time modes of displacement: one is a gradual increase and the other is an abrupt jump. The epicenters of earthquakes that caused jumps in surface displacements are distributed within a belt of 2 km width enclosing the fissured belt. The epicenters of these earthquakes seem to show a somewhat larger scattering than that expected from the accuracy of the observation. This suggests that the Matsushiro earthquake fault is made up of a group of en-échelon arranged shear planes, instead of a single fault plane, at depth as well as on the surface. Taking account of the fact that this fault is a newly formed fault, the above-supposed subsurface features of the fault might be generally characteristic of the early stage of formation of a fault. That is to say, it is suggested that a fault is composed of a group of en-échelon arranged minor faults at its initial stage and then, as displacement increases, the minor faults are connected with each other to form a single fault plane.

6. Misakubo Area

The Misakubo area is situated on the northern segment of the Komyo fault. The Komyo fault is a large left-lateral strike-slip fault along the western margin of the Akaishi range in Central Japan (Figs. 1 and 32). The main period of activity of the fault is thought to be Late Oligocene to Early Miocene. The present Komyo fault has exposed its deeper portions on the surface as a result of uplift and succeeding denudation. Hence we can study here the deep-seated structures of a fault in contrast with the Matsushiro area where surficial features of faulting were dealt with.

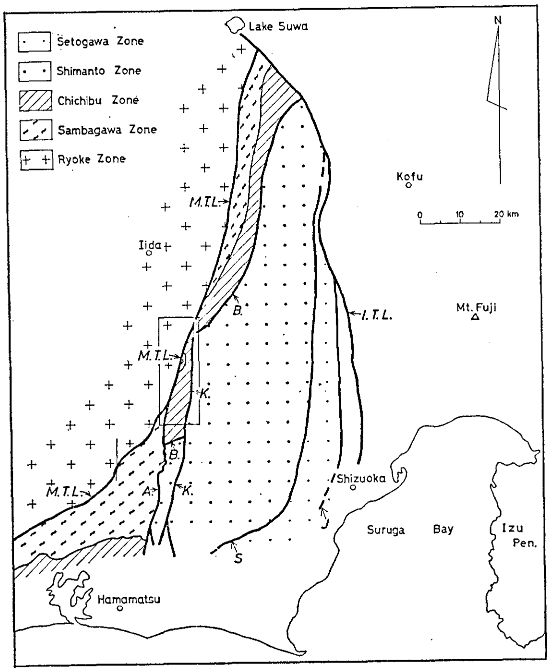


Fig. 32. Major geologic elements around Komyo fault.
A: Akaishi fault, B: Butsuzo tectonic line, I.T.L.: Itoigawa-Shizuoka tectonic line, J: Jumaiyama tectonic line, K: Komyo fault, M.T.L.: Median tectonic line, S: Sasayama tectonic line (TSUNEISHI et al., 1975).

TSUNEISHI et al. (1975) have analyzed the mode of rock deformation in the fracture zone of the Komyo fault and elucidated the formative processes of the fault. Because knowledge of the formative processes of a fault is indispensable for the study of block faulting, the outline of the results will be mentioned in the following.

Figure 32 shows a large-scale geologic structure of the region stretching around the Komyo fault. The Komyo fault displaced the Butsuzo tectonic line about 25 km left-laterally. In result, the Komyo fault is the boundary between the Chichibu terrain on the west and the Shimanto terrain on the east along the northern segment of the fault. The study was carried out near the northern segment of the Komyo fault in the Misakubo area.

In the Misakubo area, many minor faults with a size of one to ten meters occur on the western side of the Komyo fault in the "Paleozoic" and Paleogene strata. The surfaces of the minor faults are often ornamented with many densely spaced parallel striations indicative of a direction of fault-slippage. These minor faults with striations were systematically measured.

Figure 33 shows the stereographic projection of measured minor faults and the histogram of them in ten-degree increments of azimuth. The fault-plane strikes have two peaks; a higher one at N15°W, and a lower one at N75°W. The angle between the two peaks is 60°. The striations plunge essentially horizontally. This suggests that minor faults were formed as strike-slip faults. The sense of slip determined by the displacement of key layers or by the shape of striations on the fault surfaces is consistent with the suggestion. Thus, the two groups of minor faults in Fig. 33 trending about N15°W and N75°W, respectively, probably make

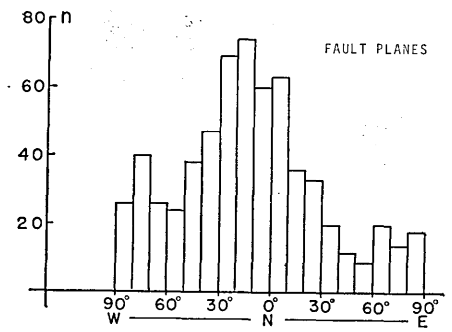


Fig. 33. Attitudes of minor faults measured and a histogram of them counted in ten-degree increments of azimuth (TSUNEISHI et al., 1975). Upper hemisphere of Schmidt's net.

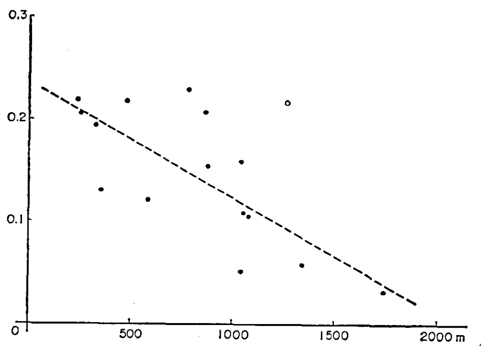


Fig. 34. Frequency distribution of minor faults with regard to an axis perpendicular to main Komyo fault (TSUNEISHI et al., 1975).

a conjugate set of left-lateral and right-lateral strike-slip faults.

Because all minor faults with striations that crop out in the range from foot level to 2 m high were recorded along the segments of good exposure on the outcops of roadside cliffs, the areal distribution of the frequency of minor faults can be examined. The surveyed routes were divided into sixteen sections, and the frequency per one meter of route was calculated. In Fig. 34 the frequency of minor faults is represented as a function of the distance from the Komyo fault. The frequency of minor faults shows a systematic change: the minor faults occur mostly within a zone 2000 m wide adjacent to the main fault, and the frequency of minor faults clearly increases toward the main fault.

Figure 35 shows the change of attitudes of minor faults with the distance from the main Komyo fault. The minor faults were divided into three groups according to the distance of their occurrence from the main fault. The strikes of the conjugate fault surfaces change their directions counterclockwise up to a maximum of about 20°, as they approach the main fault. That is to say, left-lateral minor faults have a strike of N20°W, in the neighborhood of the main fault, whereas they are nearly parallel to the main fault with a N-S trend in areas distant from it. This characteristic is interpreted as follows. Most of the minor faults were formed at the earlier stage in the history of the structural developments along the Komyo fault. Succeeding left-lateral displacements along the Komyo fault were probably accompanied by the counterclockwise rotational movements, bending the strata and causing drag of the strata near the fault. Therefore, the strikes of present-day minor faults change direction counterclockwise as they approach the main fault.

Figure 35 shows another characteristic: the ratio of left-lateral minor faults, subparallel to the main fault, to right-lateral minor faults becomes larger as they approach the main fault. A physical interpretation on the

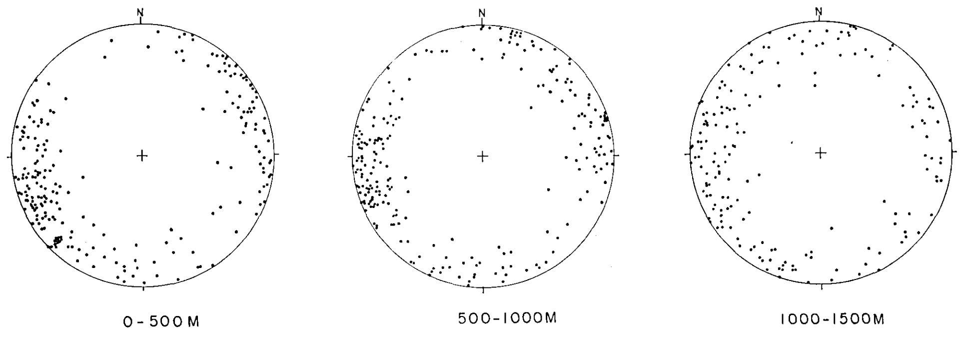


Fig. 35. Attitudes of minor faults grouped with regard to distance from Komyo fault (TSUNEISHI et al., 1975). Upper hemisphere of Schmidt's net.

characteristic was given by TSUNEISHI et al. (1975). Further extended discussion of the formative process of a fault will be given in Sec. 8.

7. Model Experiment

Sedimentary covers give a valid clue to the knowledge of the mechanisms of block faulting. For example, the age of block faulting can be fixed by the age of the sedimentary cover; simplicity of deformation of the sedimentary cover makes it easy to discern the character of block faulting. On the other hand, the sedimentary cover, as a matter of course, conceals structures of the underlying basement. Several lines of speculation are inevitable to draw a conclusion about the displacement of the block-faulted basement which underlies the sedimentary cover, when available data by drilling and geophysical probing is incomplete. Such speculation will come to have validity when a systematic relation between the manners of deformation of the sedimentary cover and the underlying

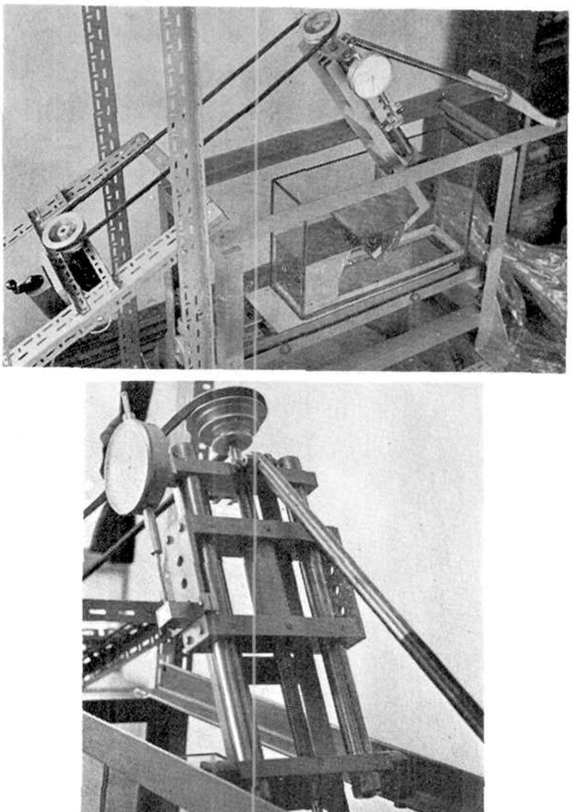


Fig. 36. Photographs of apparatus used.

besement at block faulting is obtained.

In order to know systematic relations of deformational behaviors between the sedimentary cover and the underlying basement, various kinds of experiments including theoretical treatment, model experiments and photoelastic experiments have already been carried out by HAFNER (1951),

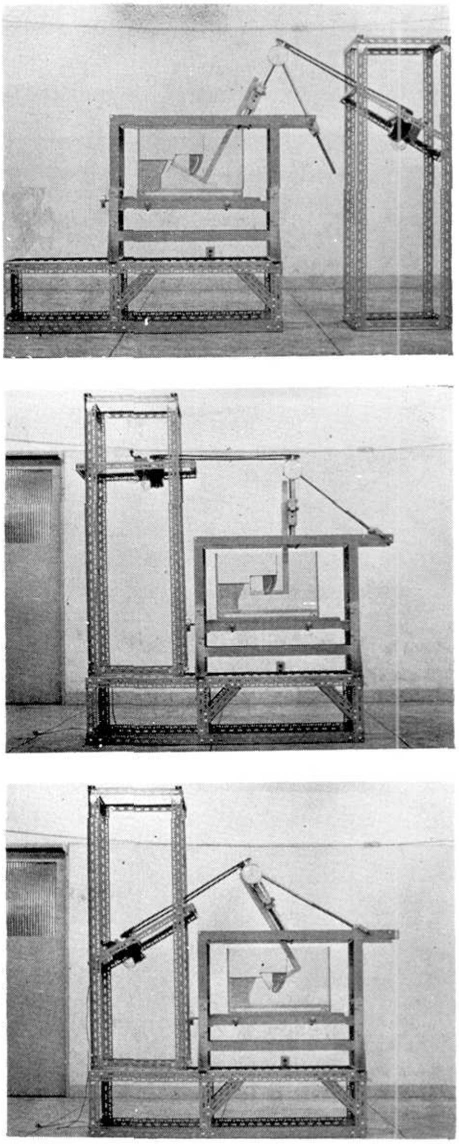


Fig. 37. Examples of setting of apparatus: normal fault dipping 60° (upper), vertical fault (middle), reverse fault dipping 60°.

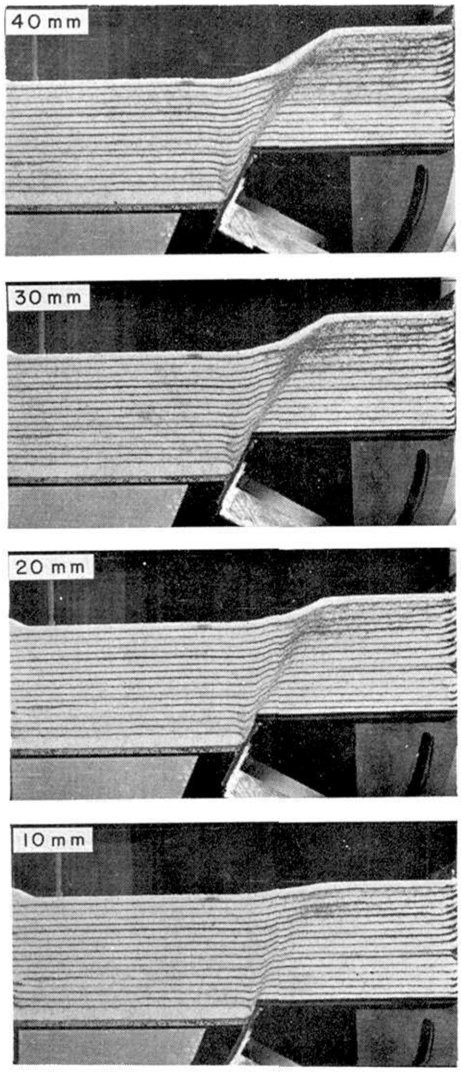


Fig. 38. Experimental result using medium sand. Normal fault dipping 60°.

SANFORD (1959), BELOUSSOV and GZOVSKY (1965), KINUGASA (1974), etc. . . For the manner of movement of basements, these experiments adopted such a model as involves displacement along a vertical fault plane. Model experiments for displacement along non-vertical faults, normal faults or reverse faults, which develop in basements, have not been carried out yet. The author devised an elaborate apparatus for the purpose of clarifying the mechanism in cases of normal, vertical, and reverse faulting. Although full experiments by the apparatus have not been accomplished yet, several notable results will be mentioned in the following. The author is

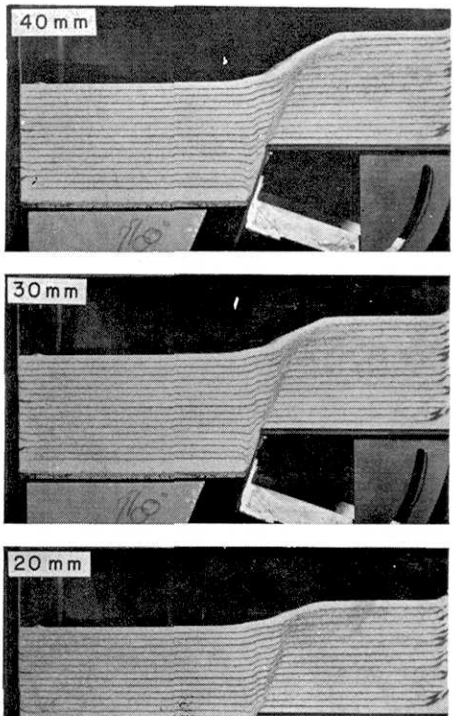


Fig. 39. Experimental result using medium sand. Normal fault dipping 70°.

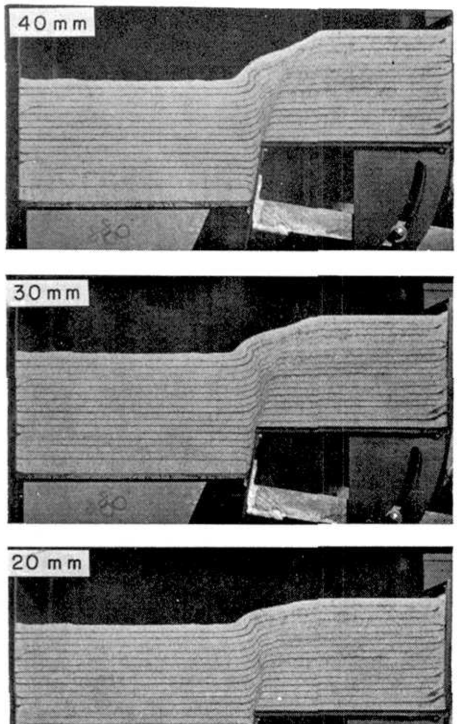


Fig. 40. Experimental result using medium sand. Normal fault dipping 80°.

greatly indebted to the staff of the technical section of the Earthquake Research Institute for making the apparatus.

Figure 36 shows a photograph of the apparatus. A box made of glass plates of 1 cm thick with a size of 57 cm × 17 cm × 36 cm (H) is seen in the central part of the upper photograph. Two benches are horizontally placed side by side in the box, one is fixed to the box, and the other is mobile. The mobile bench can smoothly slide upward without making any gap between both benches, and between the mobile bench and the two inner sides of the box. The uplift of the mobile bench is accomplished by turning

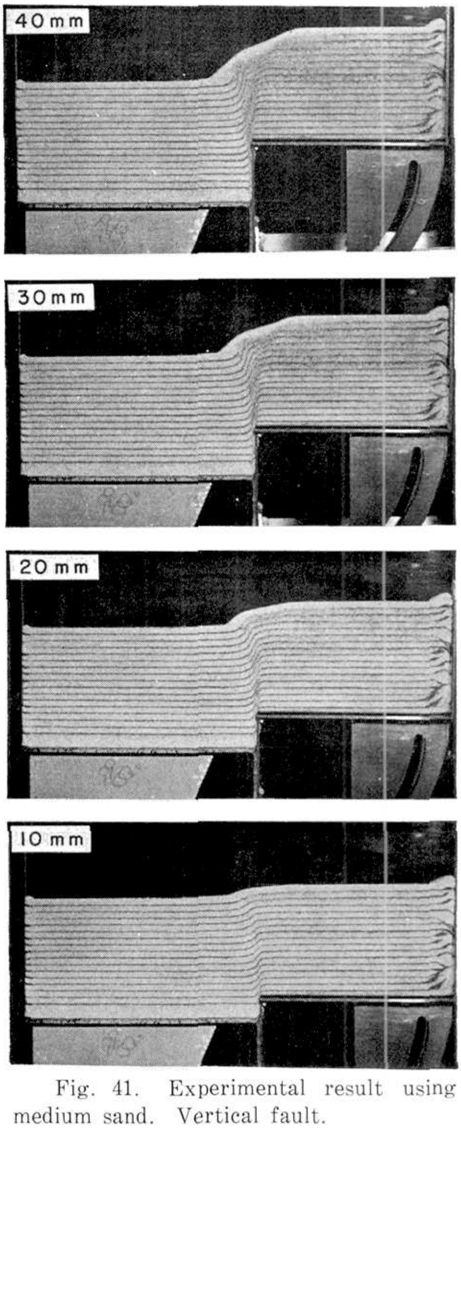


Fig. 41. Experimental result using medium sand. Vertical fault.

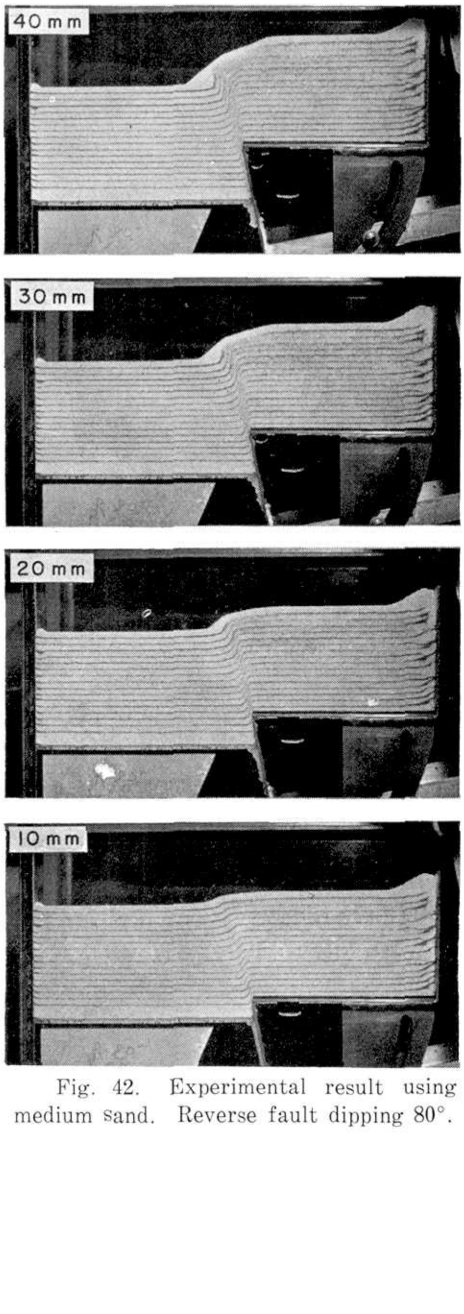


Fig. 42. Experimental result using medium sand. Reverse fault dipping 80°.

a screw shaft of 2 mm-pitch which passes through the frame supported by two guide-rails. The speed of uplift is variable by operating the gear-box attached to the motor or by changing the size of the pulleys. The experiments shown in the following have been carried out under the speed of 2 mm/min. Angles of inclination of the basement fault are optionally variable from a normal fault dipping 60° through a vertical fault to a reverse fault dipping 60°, as shown in Fig. 37. Sand or sand mixed clay, which is used as model material, is placed about 9 cm thick on the two benches lying side by side at the same level. The sand body in the box

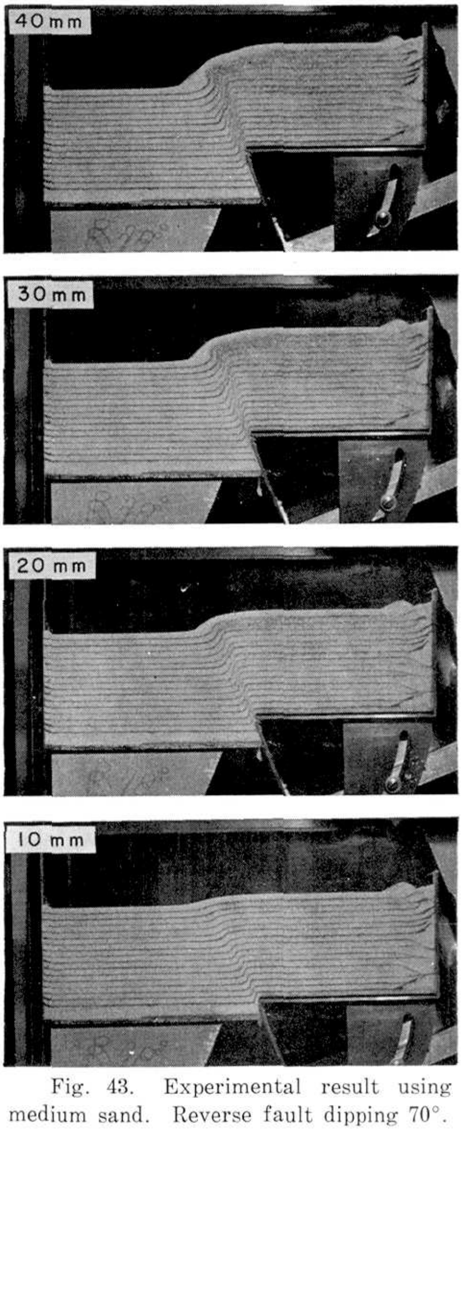


Fig. 43. Experimental result using medium sand. Reverse fault dipping 70°.

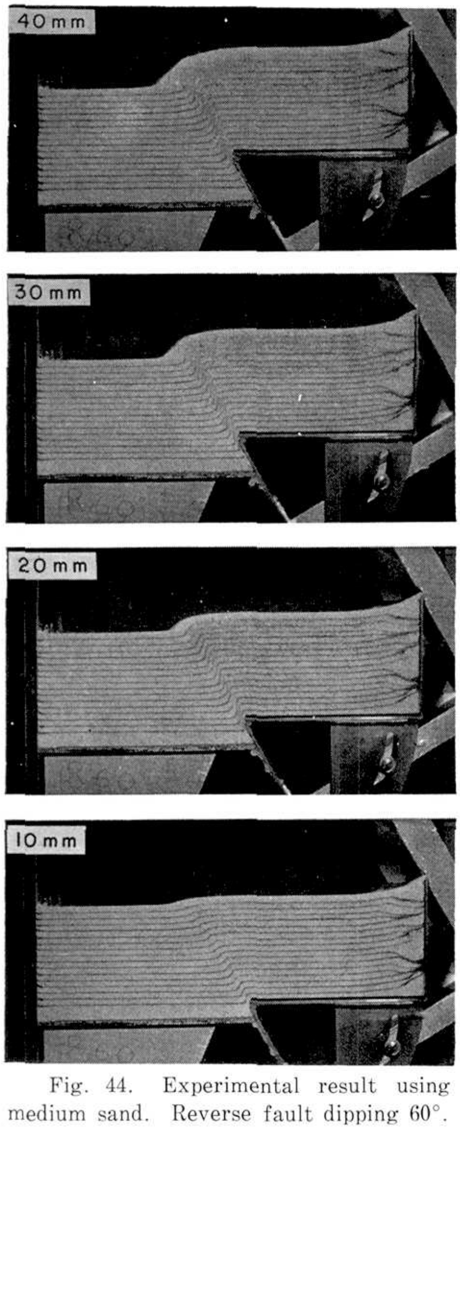


Fig. 44. Experimental result using medium sand. Reverse fault dipping 60°.

simulating the sedimentary cover is 33 cm × 17 cm × 9 cm (H) large. Deformation was observed from the side or from the top with the naked eye as well as by photography. Photographs were taken from the side with every 1 mm increment of displacement. Thin seams of colored resin powder as passive markers were placed every 5 mm near only one side of the glass box. Hence the model material is not a layered body but isotropic homogeneous one. The present experiments have been done by using dry material, and experiments using water-steeped material will be carried out in future. The friction between the glass surface and the material is slight and did not bring about any trouble, as having already been mentioned by SANFORD (1959).

In Figs. 38–44, the results of the experiments are shown in which well-sorted medium sand for industrial casting has been used. In this case no apparent faults appeared, but a flexure was formed. Since the well-sorted medium sand has little cohesion, the experiments have resulted in a manner of plastic deformation in appearance. A more detailed process of deformation has been traced, based on the experiments of Figs. 38–44, and is shown in Fig. 45.

In the following are mentioned characteristic deformational features of sedimentary covers which are produced as basement faults changing from a normal fault dipping 60° through a vertical fault to a reverse fault dipping 60°.

Normal 60°-fault (*Normal fault dipping 60°*) In the photograph of Fig. 38, a flexure zone fans out upward from the basement fault, when the displacement of the basement amounts to 10 mm. Dips of the sedimentary cover in the flexure zone change in a step-like manner; the cover dips steeply at the front margin (left in the figure) and back margin (right in the figure) of the flexure zone, and forms two steps. The two steeply dipping parts are regarded as a kind of fault, and are called faults in the following. The fault at the front margin is a normal fault in its lower part and a reverse fault in its upper part, forming a curved fault. On the other hand, the fault at the back margin is a normal fault. When the basement has been displaced more than 10 mm, the front curved fault stops growing and only the back normal fault continues to grow. Together with growth of the normal fault, the sedimentary cover in front of the fault is dragged and gets to dip more steeply.

Another remarkable deformation is the sagging in front of the flexure zone. The sagging begins at the early stage of deformation and grows as the basement displacement increases. The sag is wide at the upper and narrow at the lower, whereas it subsides more deeply at the lower than at the upper. The sag is regarded as a kind of reverse drag. The sag is considered to occur in order to compensate for the loss of material

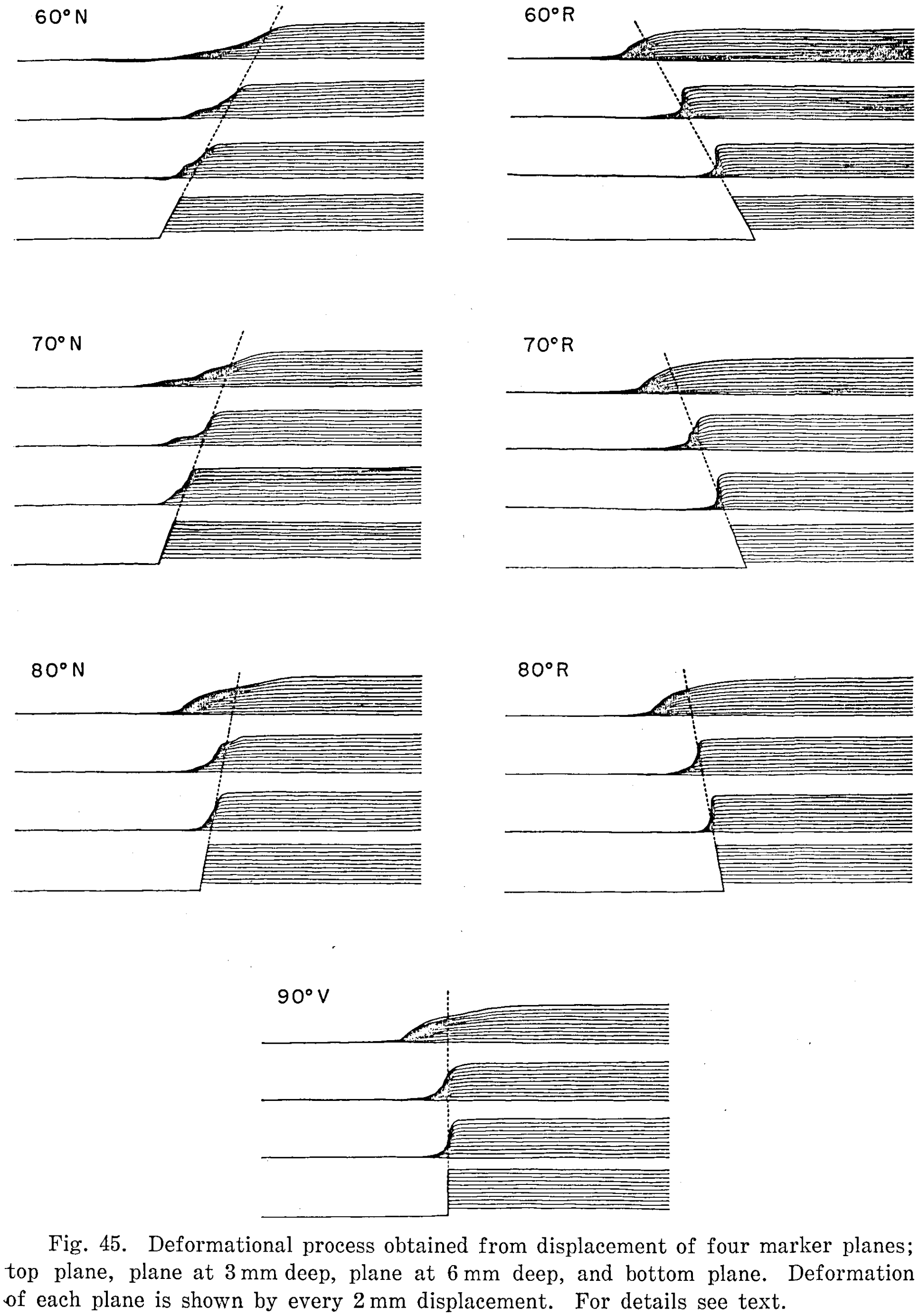


Fig. 45. Deformational process obtained from displacement of four marker planes; top plane, plane at 3 mm deep, plane at 6 mm deep, and bottom plane. Deformation of each plane is shown by every 2 mm displacement. For details see text.

which has been caused by the lateral pulling apart of the sedimentary cover in the vicinity of the faults.

Normal 70°-fault The deformational feature, when the basement fault is a normal fault dipping 70°, is principally the same as that of the normal 60°-fault, although there is minor difference between them as follows. Comparing with each other, at 10 mm displacement of the basement, in the case of the 60°-fault, the back normal fault develops more conspicuously than the front cylindrical fault, whereas the latter develops more conspicuously than the former in the case of the 70°-fault, although the former grows afterward as well. The sag is not so intense as that of the 60°-fault, although the reverse drag is clear at the lower.

Normal 80°-fault Only the front cylindrical fault appears at the 10 mm displacement of the basement. At 20 mm displacement the back normal fault begins to grow for the first time and continues to grow with further displacement. The cylindrical fault continues to grow successively together with the progress of the drag. Strata rotate at the upper part until they are reversed through vertical. In this manner, in case of the 80°-fault, the drag in front of the cylindrical fault is more conspicuous than those in the case of the 60°- and 70°-faults, whereas the reverse drag develops weakly only at the lower part.

Vertical fault A curved fault, vertical at the lower and reverse at the upper, forms at 10 mm and 20 mm displacements of the basement, as well as a flexure around the curved fault. The back normal fault begings to grow at 30 mm dislocation. The steep part within the flexure zone is wider than that of the 80°-fault. No reverse drag appears.

Reverse 80°-fault Single curved reverse fault forms steeper at the lower and gentler at the upper, and no normal fault appears. The steep part within the flexure zone is rather narrow.

Reverse 70°-fault The principal deformational features are the same as those of the reverse 80°-fault except for the somewhat complicated flexuring in the flexure zone, which has been caused by backward shifting of the center of flexuring during deformation. The manner of shifting is well expressed in the deformation of the second horizon from the top in Fig. 45.

Reverse 60°-fault A flexure zone has been formed along the extension of the basement fault, although the uppermost part of the flexure leans forward slightly. The flexure becomes intense as deformation progresses, and the center of the flexure changes into a fault without changing the location of the deformation zone.

In Fig. 45, the process of deformation of the four key layers (the top plane, plane at 3 cm deep, plane at 6 cm deep, and the bottom plane) has been drawn successively with every 2 mm displacement of the base-

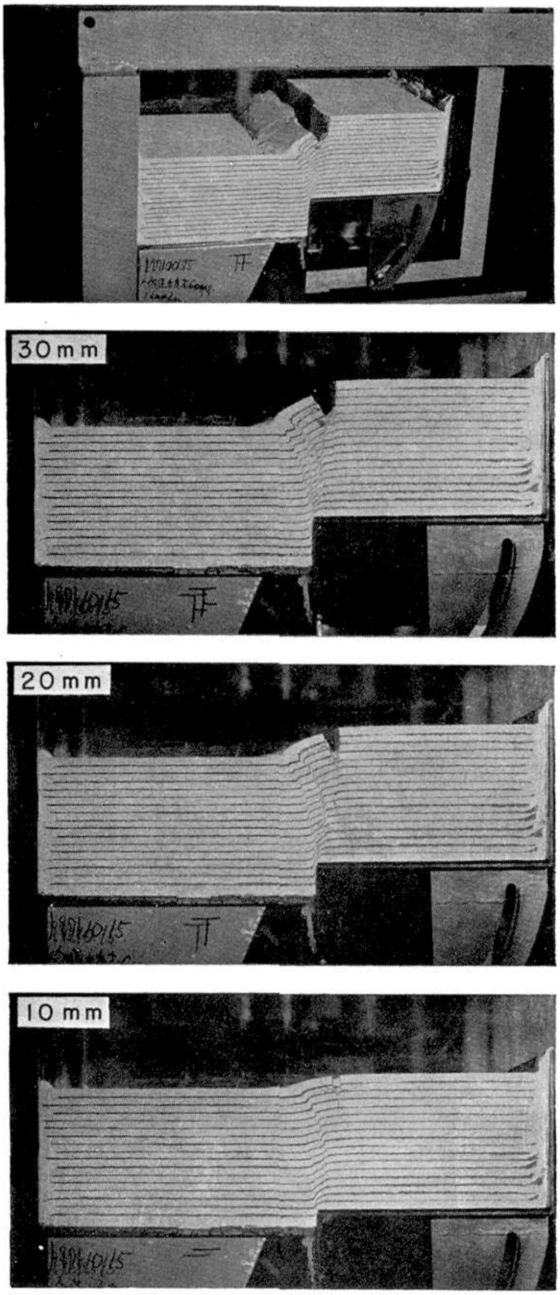


Fig. 46. Experimental result using a mixture of sand and kaolin clay (15 wt%) as model material. Vertical fault in the basement.

ment (bench) until the total amount of displacement attains to 2 cm. From the displacement process of four key layers for each case shown in Fig. 45, several characteristics as a whole are recognized as follows. The flexure zone becomes narrower as the basement fault changes its attitude from a normal 60°-fault through a vertical fault to a reverse 60°-fault. As a result, the inclination of layers within the flexure zone for a unit displacement increases. When the basement fault is a normal fault, the flexure zone developed in the sedimentary cover is located on the back of the basement fault (the uplifted side, or the right side of each figure). On the contrary, when the basement fault is a reverse fault, the flexure zone in the sedimentary cover is located on the front of the basement fault. Moreover, referring to the disposition of the flexure zone against the extension line of the basement fault (dotted lines in the figure), the flexure zone changes its location backward from the extension line (toward the right of each figure) as the basement fault changes from a normal 60°-fault to a reverse 60°-fault.

The experiments shown in Figs. 38–44 have been carried out by using well-sorted medium sand. As for these kind of experiments, the principal deformational pattern will be kept unchanged even if the experimental materials are changed. Detailed deformational features will change, however, depending on the experimental materials. Figure 46 shows the result of an experiment which was done with a mixture of well-sorted fine sand (by weight 85 percent) and kaolin clay (15%). In contrast with the relatively smooth flexures that were formed in the former experiments, a deformational feature of a sharp-cut, step-like manner has appeared in this experiment. For the purpose of studying the configuration of faults which are formed in the flexure zone, the latter experiment is more convenient than the former. However, one difficulty arising is that a crevasse occurs at a place where a normal fault is expected to form. In Fig. 46, a crevasse with a depth of 3 cm occurred at the upper part of the sedimentary cover of 9 cm thick. If this applies to nature, it comes that a crevasse of 700 m deep forms in a sedimentary cover of 2000 m thick. This is not actual. This discrepancy is ascribed to the fact that the similarity is not held between the model material and

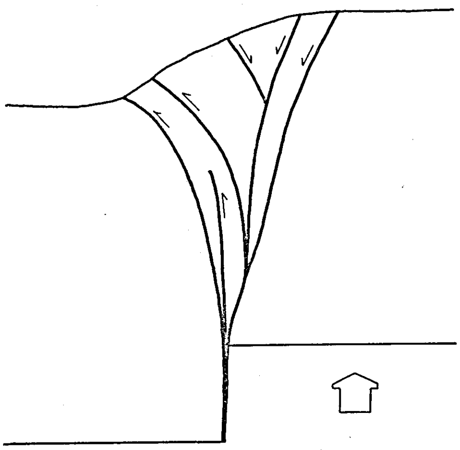


Fig. 47. Faults in sedimentary cover produced by displacement of vertical fault at basement.

natural rocks with regard to shear strength and tension strength. The model material (fine sand with kaolin matrix) in the latter experiments has larger cohesion than that (medium sand without matrix) of the former experiments. Experiments that use water-immersed materials so as to reduce cohesion are one possible method to remove this trouble.

Figure 47 shows the faults which have been traced from the photograph of Fig. 46, although the normal faults have been inferred from the crevasse distribution. The mode of occurrence of the faults is much similar to that presented by SANFORD (1959). Moreover, this result bears a close resemblance to the flexure and minor fault distribution in the flexure zone of the Hirono area in the Abukuma range described in Sec. 2.

8. Discussion

Examples of block faulting studied in several areas have been presented in Secs. 2 to 6. Studied block faulting differs from each other with respect to tectonic history of block-faulted areas, time of activity, type of faulting, spatial extent of block faulting and now observable depth where faulting occurred before. Although some restriction is inevitable due to these difference on discussing a general rule of block faulting, several subjects can be referred to as common features related to block faulting. In the following, they are discussed on the basis of the results of geological and experimental studies.

(*1*) *Manner of fracturing of rocks due to faulting*

The manners of rock deformation are considered to depend on the specific mechanical properties of rocks, the confining pressure, the differential stress, the strain rate and the temperature under which the rocks are subjected to deformation. In fact, it has been observed along the Futaba tectonic line of the Abukuma range that weak, non-indurate rocks of sedimentary cover were predominantly flexured, whereas hard, indurate rocks in the basement were faulted as a rigid body.

Some examples that show the effect of confining pressure on fracturing are given as follows. In the Wariyama horst of the Soma area, various types of rock deformation were observed in basement rocks, mostly in granite. Among them, mylonitization seems to represent deformation at the deepest level, because quartz crystals in granite show an intensive flow structure. Hence the depth of occurrence of mylonization is roughly estimated to be more than 10 km. Minor faults having striations carved on their hard surfaces are presumed to have been formed at a moderate depth. This type of shear fracture can be seen extensively in the vicinity of the Komyo fault whose period of main activity is from Late Oligocene to Early Miocene, and in the Wariyama horst. Such a shear fracture is also observed along the faults that had formed before Quaternary time in the central area of Gifu Prefecture. Aftershocks, accompanying present-day shallow earthquakes, are probably generated by faulting along these type of minor faults. Therefore the minor faults with striations are supposed to have formed at an approximate depth ranging from 2 km to 10 km. Brecciation or fragmentation of basement rocks extensively observed in the Wariyama horst is analogous to a manner of rock deformation known as "extension fracture" or "wedge fracture" in rock mechanics. Hence it is probable that such a type of fracturing occurs at low confining pressure or at a shallow depth.

(2) *Fault-forming process*

A fault having a large amount of displacement will not occur by faulting one time. Instead it is considered that a fault progresses through many steps. This problem has been discussed by TSUNEISHI et al. (1975).

The process of development of the Matsushiro earthquake fault was described in Sec. 5 as an example of the birth of a fault in a virgin area. This fault does not have a single fault plane on the ground surface but is composed of en-échelon arranged fissures essentially of the tension fracture kind that are distributed within a belt of 500 m width. It was suggested on the basis of seismological data that the fault might be made up of a group of en-échelon arranged shear planes at a depth as well. The observed amount of displacement of the fault is 50 cm in a left-lateral strike-slip component (TSUNEISHI and NAKAMURA, 1970). On the other hand, the relative movement of two triangulation points which are located on the opposite sides of the fault was estimated to be 98 cm in component parallel to the trend of the fault by the geodetic method (GEOGRAPHICAL SURVEY INSTITUTE, 1966). Because the two points are located about 1 km away from the fault, the amount of 98 cm should comprise both the elastic and non-elastic deformation of the area around the fault, in addition to the amount of the fault displacement of 50 cm. Results of repeated electro-optical measurements (KASAHARA et al., 1968) suggest that the amount of elastic deformation is small and that non-elastic deformation preceded and accompanied the surface faulting. It is supposed that the non-elastic deformation results in the flexuring of the area around the fault.

These facts obtained from the study of the Matsushiro earthquake fault are generalized as follows. Flexuring occurs before a main fault begins to develop. Next, an embryonic form of a main fault develops concurrently with flexuring. In this stage, the fault does not have a single fault plane but is composed of a group of en-échelon arranged shear

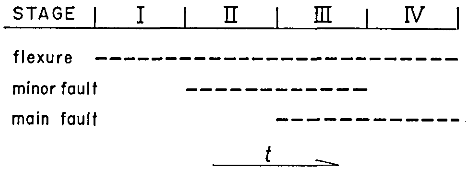


Fig. 48. Stage of fault-forming process (TSUNEISHI et al., 1975).

planes.

As described in Sec. 6, in the vicinity of the Komyo fault the frequency of minor faults having the same sense of slip with that of the main fault conspicuously increases toward the main fault. This suggests that a main fault develops as a result of the proliferation of minor faults. The relation between the Matsushiro earthquake fault and the swarm earthquake and the relation between the Futaba reverse fault and the associated minor faults in the Hirono area of the Abukuma range support the supposition.

The Gifuken-chubu earthquake of 1969 described in Sec. 4 suggests the next stage of the fault-forming process. Generation of minor faults shown by an aftershock series concurrently accompanied a slippage of the main fault which has a single fault plane.

On the other hand, it has been shown in Sec. 6 that minor faults in the vicinity of the Komyo fault were rotated by the displacement of the main fault. This indicates that displacements along the main faults still continue after the formation of minor faults. The Parkfield-Cholame earthquake of 1966 that occurred along the San Andreas fault presents a good example of faulting at this stage. In this case, the hypocenters of aftershocks are distributed within a very narrow zone, virtually on a single slip plane on which the main slippage occurred (EATON et al., 1970). The aftershock activity was not observable in the area outside the fault.

On the basis of the above-metioned discussion the fault-forming process is divided into four stages as shown in Fig. 48: the first stage in which only flexuring occurs, the second stage in which minor faults begin to occur, the third stage in which a main fault occurs and grows with minor faults, and the fourth stage in which formation of minor faults declines and displacements along the main fault proceeds with flexuring. MOGI (1968) has deduced a similar process from an experimental study.

(3) *Repetition of block faulting*

Because a fault displacement associated with one large earthquake amounts to several meters at most, commonly observed faults with much large displacements are considered to be a product of repeated displacements.

On the other hand, besides the repetition of faulting along a fault, we can recognize the repetition of periods of faulting on a larger time scale. For example, in the Abukuma range described in Sec. 2, four repetitions of block faulting are discernible. In this case, the second and later block faultings were repeated by utilizing, essentially, the same faults which had been formed during the first block faulting. On the contrary, in the southern area of the Suzuka range described in Sec. 3, six stages of block faulting were discernible. In this case, the block faulting was repeated without utilizing the same faults with one exception. And new fault systems were successively formed. Block faulting during the Quaternary time in the central area of Gifu Prefecture shows an intermediate feature: some faults were reactivated along the preexisting faults, whereas the other faults were newly formed.

Generally speaking, in case that block faulting occurs under a given regional tectonic force, if there exists previous faults that are likely to be displaced by that tectonic force, the faults will be activated; on the other hand, if they do not exist, new faults will be formed. However, the repetition of block faulting does not necessarily imply the repetition of a similar type of regional tectonic force. In the Abukuma range, the first block faulting occurred as strike-slip faulting under a NW-trending regional compression, whereas the second and later block faultings occurred as dip-slip faulting under an EW-trending regional compression, as described in Sec. 2.

(4) *Faulting in sedimentary cover due to faulting in basement*

The manner of response of the sedimentary cover to faulting in the basement was best shown in the Hirono and Yotsukura areas of the Abukuma range, where thick sediments cover the basement, as described in Sec. 2. The results of model experiments that were concerned with this subject were given in Sec. 7.

In the sedimentary cover, a flexure and a reverse fault were developed in the Hirono area, while normal faults occurred in the Yotsukura area. Nevertheless, in both areas faulting in the basement was supposed to be of a dip-slip type along virtually vertical fault planes, on the basis of the study of geologic structures in the surrounding area. It is necessary, therefore, to explain why different types of faults occurred in the sedimentary cover due to essentially the same vertical faulting in the basement.

Experiments show that the manner of deformation of the sedimentary cover is seriously dependent on the dip and the sense of displacement of the basement fault, as shown in Sec. 7. When the basement is displaced along a high-angle reverse fault plane dipping 80°, only one reverse fault develops in the sedimentary cover in addition to an intense flexure. When the basement is displaced along a vertical fault plane, a set of normal and reverse faults as well as an intense flexure develops in the sedimentary cover. When the basement is displaced along a high-angle normal fault

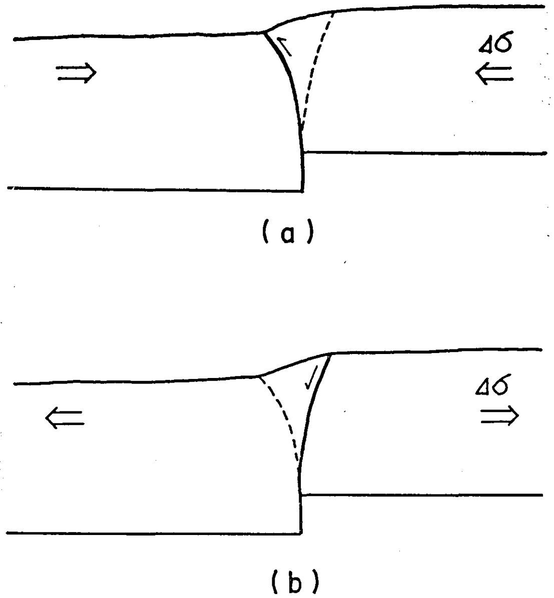


Fig. 49. Relation between sense of additional horizontal stress and type of resulting main fault.

plane dipping 80°, a normal fault distinctly develops, and a reverse fault and a flexure become less clear in the sedimentary cover. When the basement is displaced along a normal fault plane dipping 70°, only a normal fault develops, and no intense flexure and no reverse fault develop in the sedimentary cover. These sensitive responses of deformation of the sedimentary cover to the dip and the sense of displacement of the basement fault are supposed to be caused by a horizontal component of stress which is produced by the displacement along the basement fault.

Figure 49 illustrates a model in which the basement is displaced along a vertical fault plane and an additional stress is horizontally exerted on the sedimentary cover. When the additional stress is compressional, a reverse fault in the sedimentary cover will be promoted to develop, whereas a normal fault will be restricted to develop. On the contrary, when the additional stress is tensional, a reverse fault will be restricted to develop, whereas a normal fault will be promoted to develop.

The additional horizontal stress is superimposed on the stress resulting from displacement along the basement fault as follows. Because in experiments, basement blocks behave as a complete rigid body, an additional horizontal stress could not be generated by deformation of basement blocks themselves without an opening across the basement fault. However, the natural basement blocks are not rigid bodies and are able to deform in an elastic or non-elastic manner, especially as a result of the opening or closing of various kinds of fractures developed in the basement.

Thus, when the basement is displaced along a vertical fault plane under a regional tectonic force of horizontal extension, the basement will become somewhat lengthened in a direction perpendicular to the fault plane and eventually will exert an additional horizontal tensional stress on the sedimentary cover. Consequently a normal fault develops in the sedimentary cover. If the regional tectonic force is horizontally compressional, a quite opposite process will progress, and consequently a reverse fault develops in the sedimentary cover.

From the above-mentioned reasoning, we may conclude that block faultings in the Hirono and Yotsukura areas occurred, respectively, under compression in an E-W direction and tension in a N-S direction as a horizontal component of the regional tectonic force. The results do not conflict with other facts concerning the block faulting of the Abukuma range.

(5) *Verticality of boundary fault and size of fault blocks*

Attitudes of fault planes are mainly controlled by those of stress systems. Because the atomosphere cannot keep a shear stress, the attitudes of stress systems are restricted near the surface of the earth: an axis of three principal stress axes is vertical and the other two are horizontal. Consequently a normal fault dipping about 60°, a reverse fault dipping about 30° or a strike-slip fault dipping 90° will be developed when rocks with mechanically isotropic and homogeneous strength are faulted near the earth's surface. In fact, the Futaba reverse fault, which is a product of the latest block faulting of the Abukuma range, dips 30° on the present surface. However, in the Soma area, dip-slip faulting in the same period occurred along a vertical fault plane, because the fault plane was inherited from a preexisting fault. In the southern area of the Suzuka range as well, the latest faulting occurred as a low-angle reverse fault (refer to Table 2). In the central area of Gifu Prefecture, Quaternary strike-slip faults dip about 90°.

Such a restriction imposed on the disposition of a stress system near the surface is not applied to the deeper portions of the crust. For example, the above-mentioned Futaba reverse fault, which dips 30° near the present surface, is supposed to become steeper donward and ultimately vertical. In the southern area of the Suzuka range, the dips of faults become steeper as their ages of activity become older, whether the faults are normal or reverse, as shown in Table 2. This was interpreted as follows. Older faults are likely to be subjected to longer periods of denudation and consequently are likely to expose their deeper segments. Therefore, the faults in the area are presumed to have been formed originally as those faults whose fault planes become steeper downward and ultimately vertical.

In the central area of Gifu Prefecture where strike-slip faults are extensively distributed, it is probable that the dips of fault planes and the plunge of the intermediate principal stress axis are vertical at a deeper level as well as at a shallower level. This was proved by the hypocentral distribution of aftershocks accompanying the Gifuken-chubu earthquake of 1969 (Fig. 28).

It was shown in Sec. 2 that the faults bounding the Abukuma range are essentially vertical. The verticality of the boundary faults is ascribed to the fact that these faults originally occurred as strike-slip faults. Thereafter these faults were reactivated as dip-slip faults three times. This shows that the verticality of the faults did not hinder dip-slip faulting along the faults. Therefore, even though the faults bounding the Abukuma range originally occurred as dip-slip faults, the dips of the faults would not have been so different from those of the present faults.

All of the faults which were dealt with in this study were essentially vertical. This verticality of the boundary faults may be one of the attributes that block faulting assumes. In the following paragraphs it is theoretically considered why dips of boundary faults are essentially vertical.

Block faulting is regarded as a brittle fracturing in the upper portion of the crust. Rocks in the basement generally deform in a brittle manner at a shallow level and in a ductile manner at a deeper level, because the mechanical property of rocks changes from brittle to ductile with increasing confining pressure as shown by the result of the study of rock mechanics. However, the manner of deformation of rocks may show an abrupt change when the kind of rocks composing the crust changes at a certain depth.

KIMURA (1968) revealed that the folding styles change in the order of flexure folds, shear or lens folds, and flow folds from a shallow level to a deep level. Flow folds are characteristic of metamorphic rocks and result from ductile deformation of the material. He estimated the depth of occurrence of flow folds to be about 10 km by the stratigraphic method. SCHOLZ et al. (1969) noticed that the earthquakes in California did not occur below the level of 15 km, and estimated the thickness of the brittle layer to be 15 km. The depth of the boundary between the brittle layer and the ductile layer first depends on the definition of ductility. Moreover, even if a strict definition of ductility is given, the depth of the boundary will change by the kind of constituent rocks and the geothermal gradient. However, for the present, assuming that a brittle layer of 10–15 km thickness overlies a ductile layer, the following discussion is continued.

According to the Rittinger's theory of crushing, the energy needed for crushing is in proportion to the surface-area increment that results from the crushing of the material. Assuming that the energy for fracturing is gradually supplied to a body by an external force, the body will be fractured successively along the surface with the minimum cross-sectional area. When the body has the shape of a plate with a certain thickness and is set horizontally, vertical fractures are expected to occur, because the vertical sections have the minimum cross-sectional areas. Thus the brittle layer occupying the upper part of the crust will be most naturally fractured along vertical planes.

As the supply of energy to the brittle layer continues, the number of the vertical fractures will successively increase until the distance between the individual vertical fractures becomes equal to the thickness of the brittle layer. At this stage, further progress of the hitherto continued fracturing process is interrupted for a while, because the vertical section is no longer the only surface that has the minimum cross-sectional area. It is supposed that the minimum size of fault blocks is thus determined.

In the Yotsukura area and its southern extension, the size of the fault blocks bounded by the relatively large faults is about 10 km (Fig. 17). In the southern area of the Suzuka range, the size of the fault blocks bounded by the faults belonging to the Sakanai and Iga fault systems is 5–10 km (Fig. 25). In the central area of Gifu Prefecture, the size of the fault blocks bounded by strike-slip faults is 15–25 km (Fig. 27).

The above-mentioned groups of fault blocks with a comparatively well-sorted size have continued to be activated for at least several hundred thousand or several million years in each area. These block faultings in the individual areas may be regarded as having been steady during their periods of activity. Consequently the size of the fault blocks in each area is regarded as representing the minimum unit size of fault blocks characteristic of the area. If the above-mentioned fault block-forming hypothesis is accepted, the size of fault blocks as a minimum unit will be indicative of the thickness of the brittle layer in the area.

The Abukuma range as a whole, the Suzuka range, or the large-scale fault blocks bounded by large strike-slip faults, such as the Atera, Neo-valley and Atotsugawa faults in Central Japan, have a larger size than the above-mentioned fault blocks. The sizes of them are roughly 100 km across. The formation of these larger fault blocks can not be explained by the above-mentioned fault block-forming hypothesis. Possibly these larger fault blocks may have resulted from the deformation of the layer with a larger thickness which is rooted at a deeper level in the crust or mantle.

9. Summary

Several block-faulted areas in Japan were surveyed and the mechanisms of block faulting were discussed on the basis of geological and

experimental studies. The faults that bound individual fault blocks include normal, high-angle reverse, and strike-slip faults.

The Abukuma range records four different periods of block faulting, assigned to Middle Cretaceous, Early Miocene, Late Miocene and Late Pleistocene. The first block faulting was of strike-slip faulting. By this faulting, the N-trending fractures, such as the Futaba and Hatagawa tectonic lines and the Idosawa fault, and the WNW-trending fractures, such as the Futatsuya, Akai, Yunotake faults, were formed as left-lateral and right-lateral strike-slip faults respectively. The second and later block faultings occurred as dip-slip faulting by utilizing essentially the same faults which had formed during the first block faulting. The structural analysis of the Abukuma range was carried out in the Soma, Hirono and Yotsukura areas.

In the Soma area, the Wariyama horst composed of basement rocks rises within the fault zone along the Futaba tectonic line, and the Neogene sedimentary covers are distributed on both sides of it. The following structural features are revealed in this area: the Wariyama horst consists of five rock bodies that are separated by faults from each other; most of the faults have vertical fault surfaces.

In the Hirono area, the Futaba tectonic line is expressed by the combined structure of a flexure and a reverse fault that developed in the thick sedimentary cover. A reverse fault occurred after the deposition of Miocene to Lower Pliocene strata. These deformations are concluded as having resulted from the vertical differential movement of the underlying basement along a vertical fault.

The Yotsukura area was subjected to block faulting in the Late Miocene time as well as in the Middle Cretaceous time. It is presumed that the faults related to the block faulting in the Late Miocene time were dip-slip vertical faults in the basement and nomal faults in the sedimentary cover. The faults and associated minor faults are divided into two sets of faults trending WNW and ENE respectively. Each set of faults shows a regularity with respect to the sense of slip and the direction of tilt of the intervening blocks, and produces a set of antithetic faults.

In the southern area of the Suzuka range, dip-slip faulting occurred repeatedly during the Late Cenozoic time, so that rocks of the area were displaced into numerous fault blocks. These faults were grouped into several fault systems on the basis of the periods of activity, the strikes and the types of displacements. Some of the fault systems are sets of antithetic faults. The dips of faults become steeper as their ages of activity become older, whether the faults are normal or reverse. Therefore, the faults in the area are presumed to have been formed originally as those faults whose fault surfaces become steeper downward and ultimately vertial.

In the central area of Gifu Prefecture, strike-slip faulting has actively prevailed in the Quaternary time. The faults are divided into two groups: faults that were newly formed in the Quaternary time and faults that had been formed before and were reactivated during the Quaternary time. These strike-slip faults have developed as a conjugate fault system during the Quaternary time and have divided the area into fault blocks with a size of 15–25 km across. Since the activity of these faults is regarded as having been steady through the Quaternary time, the size of individual fault blocks is considered to represent a minimum unit of block faulting. The relation between the occurrence of present-day earthquakes and the faults was examined.

In the Matsushiro area, the formative process was studied of the Matsushiro earthquake fault that was newly formed in association with the Matsushiro swarm earthquake of 1965–66. The fault was about to divide a single fault block known as the Central Belt of Uplift into two fault blocks. The surface trace of the fault is recognized as an assemblage of minute ground cracks arranged in a double échelon and by a number of deformed man-made structures. These surficial expressions of faulting occurred within the zone of 500 m width. Instrumental observations on displacements of the fault and seismological observations on the earthquakes related to the faulting suggest that the Matsushiro earthquake fault is made up of a group of en-échelon arranged shear planes at depth as well as on the surface.

In the Misakubo area, the deep-seated structures of the Komyo fault, a large left-lateral strike-slip fault, were studied. Many minor faults with striations on their fault surfaces were systematically measured in the vicinity of the Komyo fault. The minor faults occur mostly within a zone 2000 m wide adjacent to the main fault, and their frequency clearly increases toward the main fault. Left-lateral minor faults have a strike of N20°W in the neighborhood of the main fault, whereas they are nearly parallel to the main fault with a trend of N-S in the areas distant from it. This deficiency of parallelism was interpreted by the counterclockwise rotational movement of strata due to the left-lateral strike-slip faulting of the Komyo fault.

In Sec. 7 the results were shown of the model experiments concerning the deformational manner of the sedimentary cover and the underlying basement at block faulting. The dip of the basement fault in the apparatus is variable from a normal fault dipping 60° through a vertical fault to a reverse fault dipping 60°. Sand or sand mixed with clay was used as model material. The experimental results show that the manner of deformation of the sedimentary cover is seriously dependent on the dip and the sense of displacement of the basement fault. When the basement is displaced along a high-angle reverse fault plane dipping 80°, only one reverse fault in addition to an intense flexure develops in the sedimentary cover. When the basement is displaced along a vertical fault plane, a set of normal and reverse faults as well as an intense flexure develops in the sedimentary cover. When the basement is displaced along a high-angle normal fault plane dipping 80°, a normal fault plane distinctly develops, and a reverse fault and a flexure become less clear in the sedimentary cover. When the basement is displaced along a normal fault plane dipping 70°, only a normal fault develops, and no intense flexure and no reverse fault develop in the sedimentary cover.

In Sec. 8 were discussed several common features related to block faulting on the basis of geological and experimental studies. First, as for the manner of fracturing of rocks due to faulting, mylonitization, formation of minor faults with clear striations and brecciation of rocks were considered to occur successively with decreasing confining pressure. Secondly, the fault-forming process was discussed on the basis of the studies of the Matsushiro and Misakubo areas. The process is divided into four stages; the first stage in which only flexuring occurs, the second stage in which minor faults begin to occur, the third stage in which a main fault occurs and grows with minor faults, and the fourth stage in which formation of minor faults declines and displacements along the main fault proceeds with flexuring. Thirdly, the repetition of block faulting was discussed. Block faulting occurred four times by using essentially the same faults in the Abukuma range, whereas it occurred repeatedly by forming successively new faults in the southern area of the Suzuka range. Fourthly, the manner of deformation of the sedimentary cover due to faulting in the basement was examined. As shown in the Hirono and Yotsukura areas, even if the basement underwent dip-slip displacements along the virtually vertical fault planes, different types of faults developed in the sedimentary cover: a reverse fault occurred in the former area and a normal fault occurred in the latter area. This difference was explained by supposing an additional horizontal stress exerted on the sedimentary cover. Fifthly, the dip of boundary faults was examined on the basis of several lines of field evidence, and a hypothesis that the dips of boundary faults are essentially vertical was presented. A model in which a brittle crustal layer overlies a ductile crustal layer was introduced in order to explain the mechanism of block faulting. The verticality of boundary faults is deduced from the model by considering energy needed for fracturing. In addition, the size of fault blocks as a minimum unit is deduced from the model. The minimum size is comparable to the thickness of the brittle layer.

References

ASANO, S. and T. YOSHII, 1973, The structure of crust and upper mantle around Japan as revealed by explosion seismic method, *Publ. 50th Ann. Great Kanto Earthq.*, 227-238, *Earthq. Res. Inst.. (in Japanese with English abstract).*

BELOUSSOV, V. V. and M. V. GZOVSKY, 1965, Experimental tectonics, *Phys. and Chem. Earth*, **6**, 409-498, *Pergamon.*

EATON, J. P., M. E. O'NEILL and J. N. MURDOCK, 1970, Aftershocks of the 1966 Parkfield-Cholame, California, earthquake: A detailed study, *Bull. Seism. Soc. Amer.*, **60**, 1151-1197.

EGUCHI, M., S. SUZUKI, 1960, Subsurface geology in the northern part of the Futaba district (Tomioka and its environs), Joban coal-field, *Sci Rep. Tohoku Univ. 2nd ser. Spec. vol.*, **4**, 424-436. *(in Japanese with English abstract).*

FUJITA, Y. and N. TSUJIKAWA, 1960, Some problems on the Miocene series in the western environs of Soma City, Fukushima Prefecture, Japan, *Jour. Geol. Soc. Japan*, **66**, 363-370. *(in Japanese with English abstract).*

GEOGRAPHICAL SURVEY INSTITUTE, 1967, Geodetic surveys in the area of Matsushiro earthquake swarm, *Bull. GSI*, **12** (2), 20-25.

GEOLOGICAL SURVEY, 1961, Geological map of Japan, Iida-sheet (1:200,000).

HAFNER, W., 1961, Stress distributions and faulting, *Geol, Soc. Amer., Bull.*, **62**, 373-398.

HAGIWARA, T. and T. IWATA, 1968, Summary of the seismographic observation of Matsushiro swarm earthquakes, *Bull. Earthq. Res. Inst.*, **46**, 485-515.

HANZAWA, S., 1964, Regional geology of Japan: Tohoku-chiho, *Asakura Shoten* 4th ed., 368 p. *(in Japanese).*

HUZITA, K., 1962, Tectonic development of the Median Zone (Setouchi) of Southwest Japan, since the Miocene with special reference to the characteristic structure of Central Kinki Area, *Jour. Geosci., Osaka City Univ.*, **6**, 103-144.

HUZITA, K., 1968, Rokko movements and its appearance—Interesting structural pattern of Southwest Japan and Quaternary crustal movements—, *Quaternary Res.*, **7**, 248-260. *(in Japanese with English abstract).*

IIJIMA, N., 1962, Volcanostratigraphy and petrology of the northeastern part of Fossa Magna (1), *Bull. Fac. Education, Shinshu Univ.*, **12**, 1-48. *(in Japanese).*

IKEBE, N., Y. TAKAYANAGI, M. CHIJI, K. CHINZEI, Y. IKEBE, K. NAKASEKO and K. SHIBATA, Inter-basinal correlation of the Japanese Neogene, *Mem. Geol. Soc. Japan*, **8**, 215-219. *(in Japanese with English abstract).*

IWAO, S. and H. MATSUI, 1961, Explanation text of the geological map, Taira and Kawamae, *Geological Survey of Japan.*

KASAHARA, K., A. OKADA, M. SHIBANO, K. SASAKI, S. MATSUMOTO and M. HIRAI, 1968, Electro-optical measurement of horizontal strains accumulating in the swarm earthquake area (4), *Bull. Earthq. Res. Inst.*, **46**, 651-661.

KANNO, S., 1955, Geology of the environs of Kaneyama-machi, Igu-gun, Miyagi Prefecture, *Res. Bull. Geol. Miner. Inst. Tokyo Univ. Education*, **4**, 11-23. *(in Japanese with English abstract).*

KAWANO, Y. and Y. UEDA, 1967, Periods of the igneous activities of the granitic rocks in Japan by K-A dating method, *Tectonophys.*, **4**, 523-530.

KIMURA, T., 1968, Some folded structures and their distribution in Japan, *Japanese Jour. Geol. Geogr.*, **39**, 1-26.

KINUGASA, Y., 1974, Photoelastic experiments of the transverse bending, *Rep. Geol. Surv. Japan*, **250** (2), 159-174. *(in Japanese with English abstract).*

KITAMURA, N., T. SHIBATA and A. UEDA, 1955, Geolgy of the neighbouring area of Matsukawa-Ura, *Contr. Inst. Geol. Paleont. Tohoku Univ.*, **45**, 84-96. *(in Japanese with*

English abstract).

KOIKE, K., 1969, Geomorphological development of the Abukuma mountains and its surroundings, Northeast Japan, *Japanese Jour. Geol. Geogr.*, **40**, 1-24.

MASATANI, K., M. TAMURA, 1959, A stratigraphic study on the Jurassic Soma group on the eastern foot of the Abukuma mountains, Northeast Japan, *Japanese Jour. Geol. Geogr.*, **30**, 245-257.

MITSUI, S., 1969, Analysis of minor faults in the area between Taira and Onahama, *Tohoku Univ. Inst. Geol. Pal. Contr.*, **67**, 99-117. (*in Japanese with English abstract*).

MITSUI, S., K. OUCHI and S. ENDO, 1973, Stratigraphy and geological age of the Taga group in the Joban coal-field of Fukushima and Ibaraki Prefectures, *Res. Rep. Kochi Univ.* **22**, (Nat. Sci.), 103-124.

MOGI, K., 1968, Source locations of elastic shocks in fracturing process in rocks (1), *Bull. Earthq. Res. Inst.*, **46**, 1103-1125.

MORI, K., 1963, Geology and paleontology of the Jurassic Somanakamura group, Fukushima Prefecture, Japan, *Sci. Rep. Tohoku Univ., 2nd ser.*, **35**, 33-65.

NAKAMURA, K. and Y. TSUNEISHI, 1966, Ground cracks at Matsushiro probably of underlying strike-slip fault origin, I—Preliminary report, *Bull. Earthq. Res. Inst.*, **44**, 1371-1384.

NAKAMURA, K. and Y. TSUNEISHI, 1967, Ground cracks at Matsushiro probably of underlying strike-slip fault origin, II—The Matsushiro earthquake fault, *Bull. Earthq. Res. Inst.*, **45**, 417-471.

REID, H. F., W. M. DAVIS, A. C. LAWSON and F. L. RANSOME, 1913, Report of the committee on the nomenclature of faults, *Geol. Soc. Amer., Bull.*, **24**, 163-186.

SANFORD, A. R., 1959, Analytical and experimental study of simple geologic structures, *Geol. Soc. Amer. Bull.*, **70**, 19-52.

SCHOLZ, C. H., M. WYSS and S. W. SMITH, 1969, Seismic and aseismic slip on the San Andreas fault, *J. Geophys. Res.*, **74**, 2049-2069.

SUGAI, K., H. MATSUI, S. SATO, Y. KITAGAWA, M. SASAKI, M. MIYASHITA and H. KAWACHI, 1957, Geological map and explanatory text of the Joban coal field, *Geological maps of the coal fields of Japan*, **1**, 143 p. (*in Japanese with English abstract*).

SUGIMURA, A., 1967, Uniform rates and duration period of Quaternary earth movements in Japan, *Jour. Geosci. Osaka City Univ.*, **10**, 25-35.

TSUNEISHI, Y., 1964 MS, Tectonic analysis of the eastern margin of the Abukuma plateau, 66 p. *Master thesis of Geol. Inst. Univ. Tokyo*.

TSUNEISHI, Y., 1966, Geologic structure of the Hirono area in the Abukuma mountains, *Bull. Earthq. Res. Inst.*, **44**, 749-764. (*in Japanese with English abstract*).

TSUNEISHI, Y., 1970, Geologic structure of the Matsuzaka area and its vicinity, Southwest Japan, *Bull. Earthq. Res. Inst.*, **48**, 645-667. (*in Japanese with English abstract*).

TSUNEISHI, Y., 1976, Fault related to the Gifuken-chubu earthquake of September, 9, 1969, in Central Japan, *Mem. Geol. Soc. Japan*, **12**, 129-137. (*in Japanese with English abstract*).

TSUNEISHI, Y., 1979, Geologic structure of the Soma area in the Abukuma mountains (*in preparation*).

TSUNEISHI, Y. and K. NAKAMURA, 1970, Faulting associated with the Matsushiro swarm earthquakes, *Bull. Earthq. Res. Inst.*, **48**, 29-51.

TSUNEISHI, Y., S. YOSHIDA and T. KIMURA, 1975, Fault-forming process of the Komyo fault in Central Japan, *Bull. Earthq. Res. Inst.*, **50**, 415-442.

WATANABE, H. and A. KUROISO, 1970, Aftershocks of the Earthquake of the central part of Gifu Prefecture, September 9, 1969, *Bull. Earthq. Res. Inst.*, **48**, 1195-1208. (*in Japanese with English abstract*).

YOSHIDA, S., 1972, Configuration of Yamaguchi zone—Analytical study on a fold zone—, *Jour. Fac. Sci., Univ. Tokyo, sec. II*, 371-429.

5. 地塊運動の機構に関する地質学的実験的研究

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本論文では，日本の数ヶ所の地域における地塊運動の実際例が調査され，地塊の形成機構が地質学的かつ実験的研究によって議論された．各地塊を限っている断層は，正断層のみならず，高角逆断層および横すべり断層を含んでいる．

阿武隈山地では，中期白亜紀，前期中新世，後期中新世，後期鮮新世-更新世の少なくとも4回の時期に地塊運動が起こった．第1回目の地塊運動は，横すべり断層運動によって生じた．この運動により，双葉構造線，畑川構造線，井戸沢断層のような南北方向の断裂と，二ッ箭断層，赤井断層，湯ノ岳断層のような西北西方向の断裂とが，それぞれ左ずれおよび右ずれの横すべり断層として生まれた．第2回目以降の地塊運動は第1回目に形成された断層を利用しながら，今度は縦すべり断層運動としておこなわれた．阿武隈山地の構造解析は，相馬，広野，四倉の三地域で行われた．

相馬地域では，双葉構造線にそって，基盤岩類より構成される割山地塁が突出している．新第三系の被覆層は，地塁の両側に分布している．割山地塁は，それぞれ断層によって接する5個の岩体を含んだ複合体である．

広野地域では，双葉構造線は厚い被覆層の中に表現された撓曲構造とその中に生じた逆断層となっている．撓曲構造および逆断層は基盤が鉛直断層にそって，鉛直方向の差動運動をしたために形成されたと推定される．

四倉地域は中期白亜紀のあと，新期中新世に地塊運動をうけ，西北西と東北東走向の2組の縦すべり断層系が生じた．これらの断層は断層のずれの向きと両側の地塊の傾動方向との間に規則性がみとめられ，antithetic fault である．断層の傾斜角は基盤の中では鉛直であるが，被覆層の中にはいると正断層となっている．

鈴鹿山地の南部では，後期新生代に幾度もの縦すべり断層運動がくりかえし生じた．その結果，この地域は多数の断層地塊に分けられている．これらの断層を活動時期，走向，種類に基いて類別すると，単純な断層系の重なりであることが分かる．あるものは antithetic fault である．断層の傾斜は，正断層か逆断層かによらず，古い活動時期のものは急角度となっている．したがって，これらの断層は，元来，深部では高角（究極的には鉛直）で，浅所では緩くなるような断層面をもった曲面断層として形成されたと考えられる．

岐阜県の中部では，第四紀に，横すべり断層が活発に運動した．これらの断層は，第四紀になってはじめて形成されたものと，形成期はもっと前であるが，第四紀になって再活動したものとに分類される．これらの断層は，少なくとも第四紀を通じて，共役な断層系として定常的に活動してきたことがわかるので，これらの断層によって限られる15−25 km の大きさをもつ地塊は，この地域における地塊の最小単位を表わしていると考えられる．また，最近この地域に起こった地震と断層との関係が検討された．

松代地域では，1965-66年の松代群発地震に伴なって新らしく生まれた断層の形成過程が研究された．この断層運動は中央隆起帯というひとつの断層地塊を分割せんとする過程を示している．地表では断層は雁行する地割れ群として現われ，雁行配列の規則性などから左横すべり運動が推定された．地割れ変位の器機観測の結果えられた，断層を変位させた地震の分布状態から，この断層は深部でも，単一の剪断面をもたず，雁行する複数の断層の集合体となっていると推定される．

水窪地域では，過去に活動した大きな左横すべり断層である光明断層の深部構造が研究された．光明断層の近傍では，断層面上に条線が刻みこまれた特徴的な小断層が多数発達するが，これらの小断層が系統的に測定された．小断層は主断層から2000 m までの範囲内に発達し，その出現ひん度は主断層へ向かつて増加する．左ずれ小断層は，主断層から 1000 m 以上はなれると主断層方向に平行な方向に集中するが，逆に主断層に近いところでは20° 程度主断層方向よりも反時計まわりに回転した方向に集中する．この事実は主断層の左横すべり運動による引きずりと解釈され，小断層と主断層の形成順序をきめる手がかりを与える．

基盤の縦すべり断層運動が，その上の被覆層に与える変形を調べるために，一連の模型実験が行われた．装置は，基盤の断層の角度を 60° の逆断層から鉛直断層を経て 60° の正断層まで任意に変えることができる．被覆層の材料として，砂または粘土を混合した砂が用いられた．実験結果によると，被覆層の変形は基盤の断層傾斜に敏感に反応する．すなわち，基盤が 80° の高角逆断層にそって変

位すると，被覆層の中に強い撓曲と逆断層が現われる．基盤が鉛直断層にそって変位すると強い撓曲のほかに正断層と逆断層の組が現われる．基盤が 80° の高角正断層にそって変位すると，正断層がはっきりと現われ，逆断層と撓曲は弱くなる．基盤が 70° の正断層にそって変位すると，正断層だけが被覆層中に現われ，逆断層は出現しない．

上記の野外調査および実験にもとづいて，地塊運動の機構に関するいくつかの特徴が議論された．第1に，断層運動による岩石の破壊様式に関して，ミロナイト化，条線を付けた剪断面の形成，岩石の破砕作用が，この順に，封圧の減少，換言すれば，形成深度の減少につれて出現すると考えられた．第2に，断層の形成過程が主として松代地域と水窪地域の研究に基いて議論された．形成過程は次の4段階に分けられる．撓曲だけが現われる第1段階，小断層が出現しはじめる第2段階，主断層が現われ，小断層と共に成長する第3段階，小断層の発生は止まり，主断層の変位と撓曲運動だけが進行する第4段階，である．第4に，基盤の断層運動による被覆層の変形の仕方が考察された．基盤が事実上鉛直な断層運動をしたとしても，被覆層の中には異なった種類の断層が生じる場合がある．たとえば，阿武隈山地の広野地域では，逆断層が現われるのに対して，四倉地域では正断層が出現している．この差は被覆層に働く附加的な水平応力のセンスによって解釈された．最後に，地塊の境界断層の傾斜角について議論され，地塊運動に関係する断層は本質的には鉛直であろうという仮説が提出された．そのモデルでは，地殻のぜい性層が延性層の上に横わっていて，ぜい性層の破壊現象として，地塊運動を認識するという立場がとられている．破壊に要するエネルギーを考えることにより，境界断層の鉛直性が導かれた．さらに，最小単位としての地塊のサイズが存在することがモデルより導びかれ，この地塊の最小の寸法はぜい性層の厚さに相当すると考えられた．