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22. *Fault-forming Process of the Komyo Fault in Central Japan.*

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Abstract

In the fracture zone surrounding the Komyo fault, a large left-lateral strike-slip fault, there are many minor faults with distinct striations on their fault surfaces. The minor faults can be divided into two groups by their attitudes and by their senses of slip; one group consists of left-lateral faults trending about N15°W, and the other of right-lateral faults trending about N75°W. The mode of occurrence of the minor faults is not dependent on lithology except for ductile, weak rocks such as mudstone, but changes systematically with distance from the main (Komyo) fault. The minor faults occur mostly within a zone 2000 m wide adjacent to the main fault, and their frequency decreases with distance from the main fault. The frequency of left-lateral minor faults becomes considerably larger toward the main fault as compared with the frequency of right-lateral minor faults. The strikes of the left-lateral minor faults are, however, not necessarily exactly parallel to the main fault, but rotate counterclockwise up to 20° as they approach it.

The process of development of the Komyo fault comprises the following four stages; (I) flexuring stage, (II) minor fault-forming stage, (III) stage of minor fault proliferation and of appearance of the main fault, and (IV) stage of increasing displacements along the main fault and concurrent flexuring in the adjacent region. Thus it is inferred that minor faults were formed mostly at the earlier stages of the whole process of the Komyo fault development and then were rotated by the drag of strata due to the succeeding displacements along the main fault.

Three types of earthquakes observed with high accuracy are considered as examples of faulting at the present time. Earthquake faults which have been produced in association with the three earthquake types are compared with the four stages of the Komyo fault development. As the result, the Matsushiro earthquake, the Gifuken-chubu earthquake, and the Parkfield-Cholame earthquake are considered to represent, respectively, stage II to III, stage III, and stage IV of fault development.

1. Introduction

Rocks in the vicinity of a large fault have been fractured in various ways and in various degrees to form a "fracture zone" or "shear zone". Since the character of such a fracture zone is intimately related to

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mechanisms of faulting, the study of a fracture zone is important to help understand the characteristics of a fault and the mechanisms of the faulting.

Displacements on the Komyo fault, a large strike-slip fault, which we discuss in this paper, probably caused a number of large earthquakes in the past, because present-day shallow earthquakes are produced by faulting in the crust. Present-day large earthquakes are usually followed by aftershock series, which occur in well defined spaces called aftershock regions. A large fault related to the main shock is generally located within the aftershock region. Therefore the fracture zone around a large fault is considered to be equivalent to the aftershock region. Thus the structural analysis of rock deformation around a large fault hopefully will lead to elucidation of the events which occurred in a source region of earthquakes.

The mode of fracturing around a fault is affected by the size of the fault, the type of displacements, the faulting process, the depth of the fracturing, the lithology of fractured rocks, etc. In fact different faults have different modes of fracturing.

However, in some kinds of fracture zones there develop many slickensided surfaces with parallel striations. The surfaces are inferred to have been formed by shear fracturing. The direction of striations indicates that of shear movement of rocks. Such slickensided surfaces, therefore, give an important clue to the study of the formation of fracture zones. The surfaces themselves come genetically under the category of faults. Hence in this paper we call these surfaces *minor faults* in order to distinguish them from the main fault.

We have surveyed many conspicuous minor faults with parallel striations that developed in the rocks around the Komyo fault in the Misakubo region, Shizuoka Prefecture. We first describe the mode of occurrence of the minor faults, and clarify the genetic relation between the main fault and the minor faults, referring to the mechanism of formation of the Komyo fault. Then a model for a fault-forming process is presented. Finally, the Komyo fault is compared with three active faults that have produced earthquakes in recent years and have been surveyed with accurate seismological and geological observations.

2. Outline of geology

The Komyo fault trends north along the western margin of the Akaishi range in Central Japan. The Komyo fault, together with the Akaishi fault (or tectonic line) which parallels it about 5 km to the west, participated in the formation of the major geologic structure of Central Japan. The faults are intimately related to the sharp bend of the Median Tectonic Line, which trends west to the west of the bend, and trends north to the northeast of the bend. The Komyo and Akaishi faults join the Median Tectonic Line in the northeast part of the bend (Makiyama, 1950; Kimura, 1959 and 1961). Both faults have left-laterally displaced the zonal structure of Southwest Japan, as shown in Fig. 1. The strike separation of the Komyo fault is about 25 km, estimated from the displacement of the Butsuzo line, which is the boundary fault between the Chichibu and the Shimanto terrain (Fig. 1).

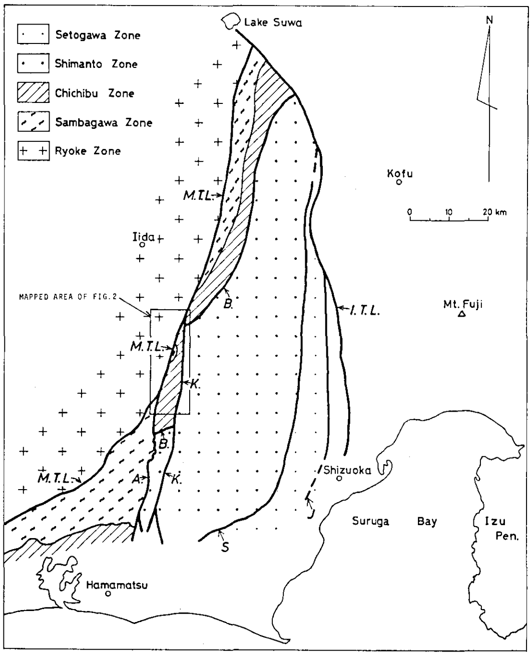


Fig. 1. Index map and major geologic elements around the Komyo fault. A: Akaishi fault. B: Butsuzo tectonic line. I.T.L.: Itoigawa-Shizuoka tectonic line. J: Jumaiyama tectonic line. K: Komyo fault. M.T.L.: Median tectonic line. S: Sasayama tectonic line.

The minor faults were studied near the northern segment of the Komyo fault in the Misakubo region, where the Komyo fault is the boundary between the Chichibu terrain on the west and the Shimanto terrain on the east (Figs. 1 and 2). According to the geologic map by Kimura (1959), Late Paleozoic, Upper Cretaceous and Paleogene strata occur on the western side of the Komyo fault (Fig. 2). These strata generally strike northeast and dip steeply. They are intensely folded and faulted. The Late Paleozoic strata consist mainly of sandstone, shale, and alternating sandstone and mudstone, with subsidiary chert,

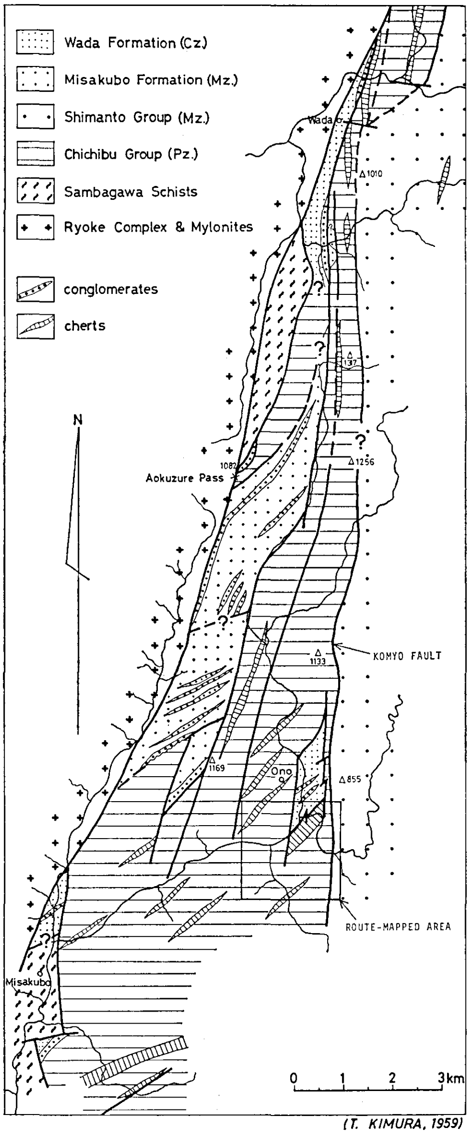


Fig. 2. Geological outline in and around the study-area. After Kimura (1959).

limestone, and basaltic lava and tuff. The age of the strata is Lower to Middle Permian, as shown by fusulinid fossils in the limestone.

The Upper Cretaceous strata are called the Misakubo formation, which consists of conglomerate, sandstone, mudstone, and alternating sandstone and mudstone. Gyliakian (Upper Cenomanian to Turonian) fossil shells from these rocks have been recently reported by Tamura (1975). The stratigraphic relation between the Paleozoic strata and the Misakubo formation is an angular unconformity in part and a fault in the other. Our present studies have not extended to the Misakubo formation.

The Paleogene strata are called the Wada formation, which is of Oligocene age based on bivalve fossils (Shikama, 1951). The Wada formation consists of conglomerate, breccia, sandstone and mudstone. The formation crops out mainly near Wada, and in a small area near Ono in the surveyed area.

On the other hand, the Shimanto group occurs on the eastern side of the Komyo fault. The group in the area is probably of Upper Cretaceous age, and consists of mudstone and alternating sandstone and mudstone. The strata strike N30°E in general and dip steeply.

3. Mode of occurrence of minor faults

A fault breccia zone with a width of a few tens of meters can be observed along the Komyo fault, although the plane of the fault itself does not crop out in the study-area. The rocks within the fault breccia zone are crushed into small rock fragments which are cemented with clay.

In the area outside the breccia zone the modes of fracturing are remarkably different on the western and eastern sides of the fault. In the western area the minor fault surfaces are one to ten meters in diameter, while in the eastern area much smaller slickensided surfaces are one to ten centimeters in diameter in general. In the present study we investigated and analyzed quantitatively only the minor faults in the western area.

The minor faults in the western area of the Komyo fault appear as ordinary joints in outcrops (Figs. 3 and 4). They are spaced at intervals of tens of centimeters to tens of meters. The amounts of displacement along the minor faults are generally unknown, but they measure 0.5 and 7 m in two cases where offset key layers have been discovered. The surfaces of the minor faults are often slightly undulated and not planar. The many parallel striations on the surfaces show that they are not joints but minor faults. The spacing between striations measures a few millimeters. The striations are occasionally cut and dislocated by very small but sharp scarplets perpendicular to the striations (Fig. 5). These features can be used to determine the sense of slip, as is mentioned in Section 5. The minor faults look like having no crush zone with the naked eyes, but they have micro-crushed zones subparallel to the fault surfaces under the microscope. Sand grains in the micro-crushed zone are fractured into pieces (Fig. 6).

The Paleozoic, Cretaceous and Paleogene strata on the western side of the Komyo fault have rather large minor faults or fractures, generally several meters or more in diameter on the road-cut cliffs. On the other hand, strata of the Cretaceous Shimanto group on the eastern side of the fault are generally fractured into small fragments 10 cm or less in diameter. There are two possible explanations for the difference of the modes of fracturing in these western and eastern areas. First, since the Komyo fault has a strike separation of 25 km, strata which are at present juxtaposed across the fault in the Misakubo region may not have been juxtaposed at the time of fracturing: they have been situated apart from each other up to a maximum of 25 km: hence the difference in the modes of fracturing between them may be attributed to the difference of the stress fields in the locations at the time of fracturing. The reasoning could be proved or disproved only by surveying over all the Komyo fault and by clarifying the distribution of the modes of fracturing along the fault and timing of fracturing.

Secondly, the difference in the modes of fracturing between the

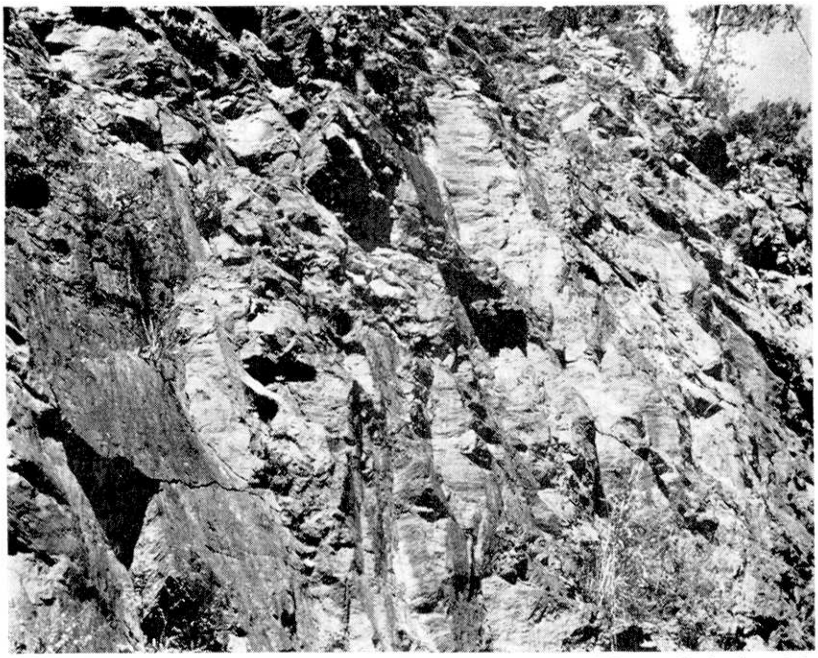


Fig. 3. Occurrence of minor faults of conjugate sets with nearly horizontal striations. Paleogene sandstone.

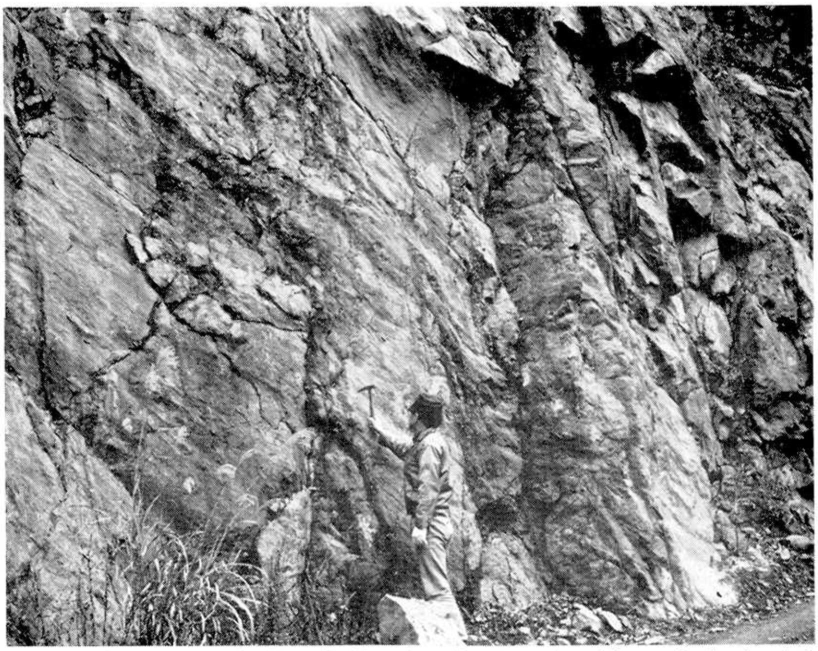


Fig. 4. Occurrence of minor faults of conjugate sets with nearly horizontal striations. Permian sandstone.

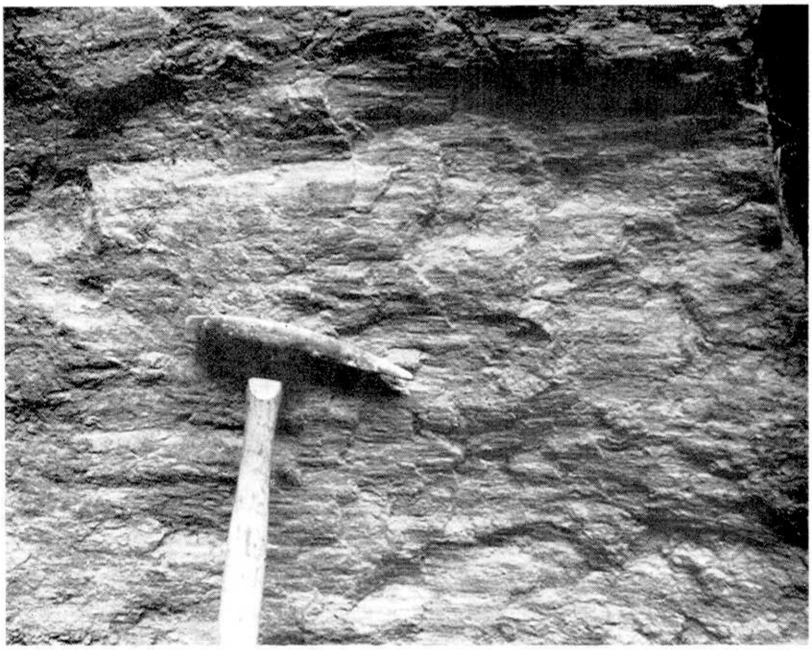


Fig. 5. Small step-like shape of striations designating the sense of slip. The photo shows a left-lateral displacement.

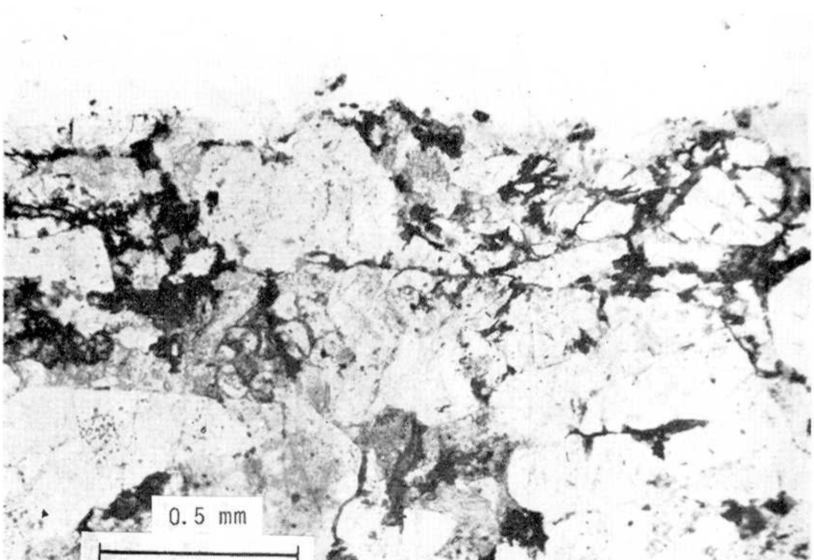


Fig. 6. Photomicrograph of fracturing in sandstone near a minor fault surface. The thin section is bounded on the upper limit by the fault surface. Cut perpendicular to the striations. Paleozoic sandstone.

western and eastern blocks on the two sides of the fault might alternatively be interpreted as having been caused by the difference in the lithology of fractured rocks, even if the stress conditions were essentially uniform along the Komyo fault. The western block consists mainly of massive medium to coarse sandstone and folded chert of Permian age, as well as massive medium to coarse sandstone of Paleogene age. On the other hand, the eastern block consists mainly of mudstone and thinly alternating sandstone and mudstone beds of the Cretaceous Shimanto group. It might, therefore, be inferred that rocks in the western block were fractured by relatively widely spaced fault sets because of the high strength of rocks, whereas rocks in the eastern block were fractured by closely spaced numerous faults of smaller size because of the low strength of rocks. This inference is strongly supported by the fact that mudstone beds intercalated in the western Permian formations are also fractured in the same way as those of the eastern block. We think now the second explanation is more plausible than the first one, although we need surveying throughout the whole area along the Komyo fault to reach a final conclusion.

4. Procedures of investigation

The minor faults to the west of the Komyo fault were surveyed according to following procedures. Routes for investigation were laid along local highways in the Misakubo region so as to make conditions for sampling as uniform as possible, and the minor faults were measured on the outcrops of the roadside cliffs. However, since the nature of the outcrops varies from place to place along the routes, it is necessary to choose for the measurements the portions of routes where outcrops are good. Fig. 7 shows the routes for investigation and the segments of good exposure along the routes. Because a pacing method was employed for mapping, the error due to this method is at most several percents (Sato, 1970). However, this is not serious for discussions of the present paper. The total length of the routes is 7,166 m, and the sum of the segments of good exposure is 4,215 m, which is 58.8% of the total.

We recorded all minor faults with parallel striations that crop out in the range from foot level to 2 m high. In such a way, 629 minor faults were measured on the outcrop surfaces whose areas total 8,230 m^2.

In the survey, the locations of minor faults and the kinds of faulted rocks were described, in addition to the measurement of minor faults. The strikes and dips of minor faults as well as the plunges of striations were measured to the nearest 2 degrees with an ordinary clino-compass. In cases where a fault plane was somewhat curved,

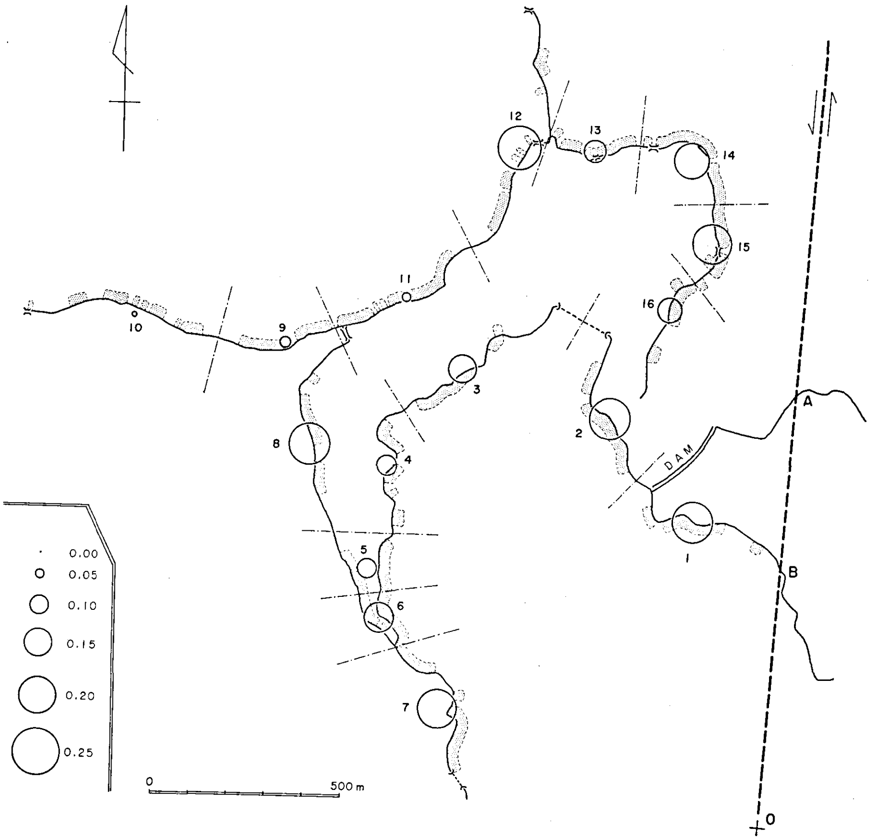


Fig. 7. Studied routes and frequencies of minor faults in sections 1-16. Shaded segments denote good exposures. The broken line is the Komyo fault. The figures in the inset show the frequencies of minor faults per one meter along the route.

we estimated the general trend. The bearings of striations were not measured directly, but they were instead evaluated from the data of strikes and dips of the fault planes and of plunges of the striations by means of the numerical table devised by Tsuneishi and Yoshida (1975). The procedure was successful in obtaining plausible data. In addition, we observed carefully the shapes of striation surfaces and the offsets of key layers in order to infer the sense of slip of minor faults. However, only a small proportion of minor faults displayed evidence for inferring the sense of slip.

5. Results and analysis

Directional distribution of minor fault planes and striations

629 sets of minor fault planes and striations are projected on the equal-area nets (Fig. 8). It is clear from Fig. 8 that most of the

fault planes dip steeply, and that the striations plunge gently, nearly horizontally. This indicates that most of the minor faults are strike-slip faults. The histograms in Fig. 8 show the frequencies of fault planes and striations that were counted 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 striation bearings also have two peaks in the same directions.

The trace of the main fault in the study-area trends N4° E, which is determined by connecting two points, A and B in Fig. 7. The regional trend of the main fault is nearly north, when it is read from Fig. 2. Comparing the predominant strike of the minor faults, N15° W, with that of the main fault, it is noticed that the former has a strike rotated counterclockwise by about 15 degrees from the

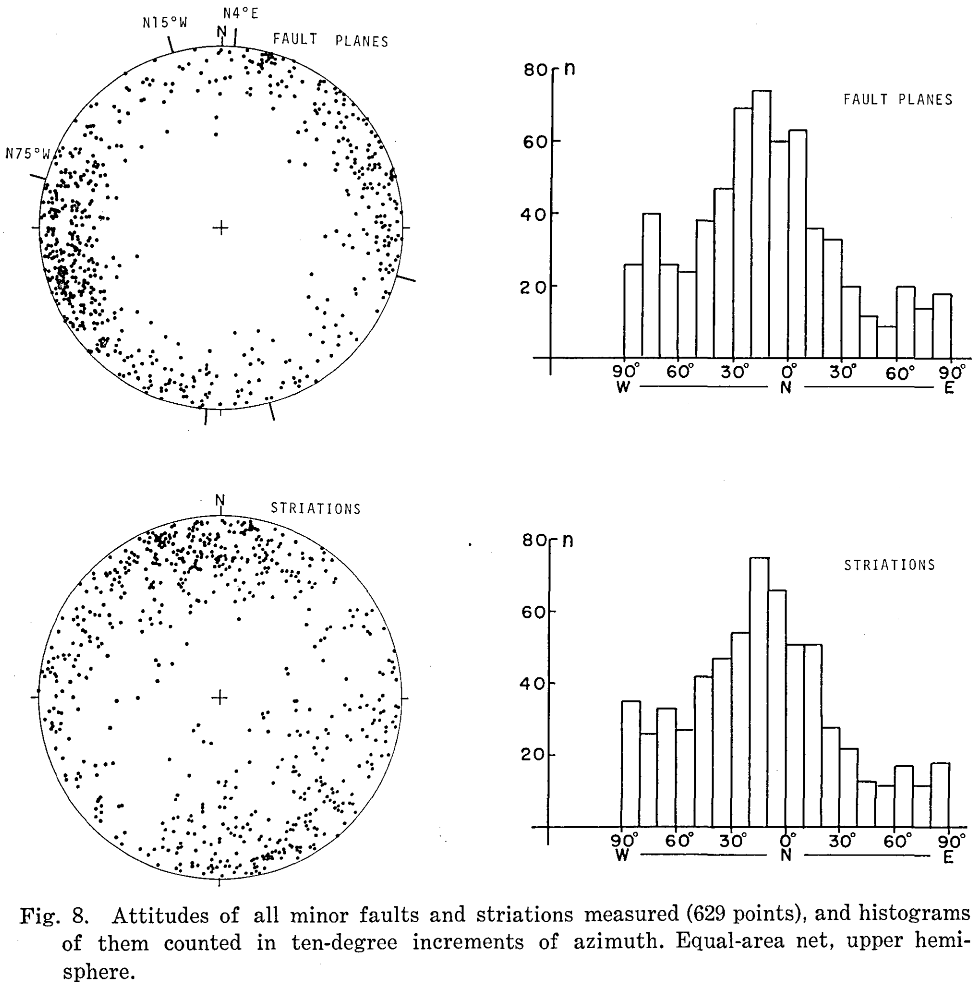


Fig. 8. Attitudes of all minor faults and striations measured (629 points), and histograms of them counted in ten-degree increments of azimuth. Equal-area net, upper hemisphere.

latter. The difference between the two strikes will be interpreted and discussed in detail later. Briefly, it is concluded that the minor faults, which formed initially parallel to the main fault, have been rotated by later movements along the main fault.

Fig. 9 is an equal-area projection of those minor faults whose sense of slip is discernible by the displacement of key layers or by the shape of striations on fault surfaces. In the latter case, the sense of slip was determined by a kind of step-like shape of striations, and some of them are somewhat similar in appearance to flutecasts, as shown in Fig. 5. The direction of relative movement which appears to have displaced the two opposite slickensides smoothly is the sense of slip. The senses of slip estimated by these striations are consistent with the senses determined by offset marker beds. Among 629 fault planes, there are only 32 minor faults whose slip sense is discernible. They have a general tendency such that minor faults trending about N15° W are left-lateral, and those trending about N75° W right-lateral. Thus, the two groups of minor faults in Fig. 8 trending about N15° W and N75° W, respectively, probably make a conjugate set of strike-slip faults with a shear angle of about 60°.

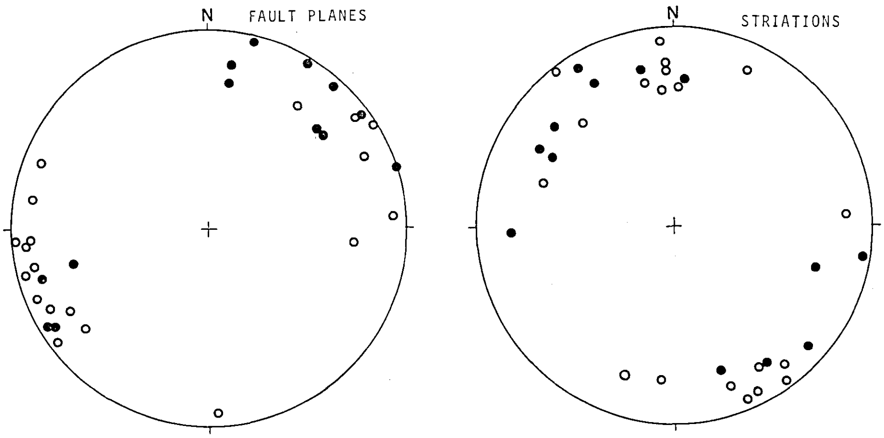


Fig. 9. Attitudes of left-lateral (open circles) and right-lateral (solid circles) minor faults and striations. Equal-area net, upper hemisphere.

Effect of lithology on faulting

It is also necessary to check whether or not the attitudes of minor faults and striations are affected by lithology. The rocks in the study-area consist mainly of sandstones and bedded cherts of Permian age and sandstones and conglomerates of Paleogene age (Fig. 10). The attitudes of minor faults and striations were grouped according to the above rock types and they were then plotted on

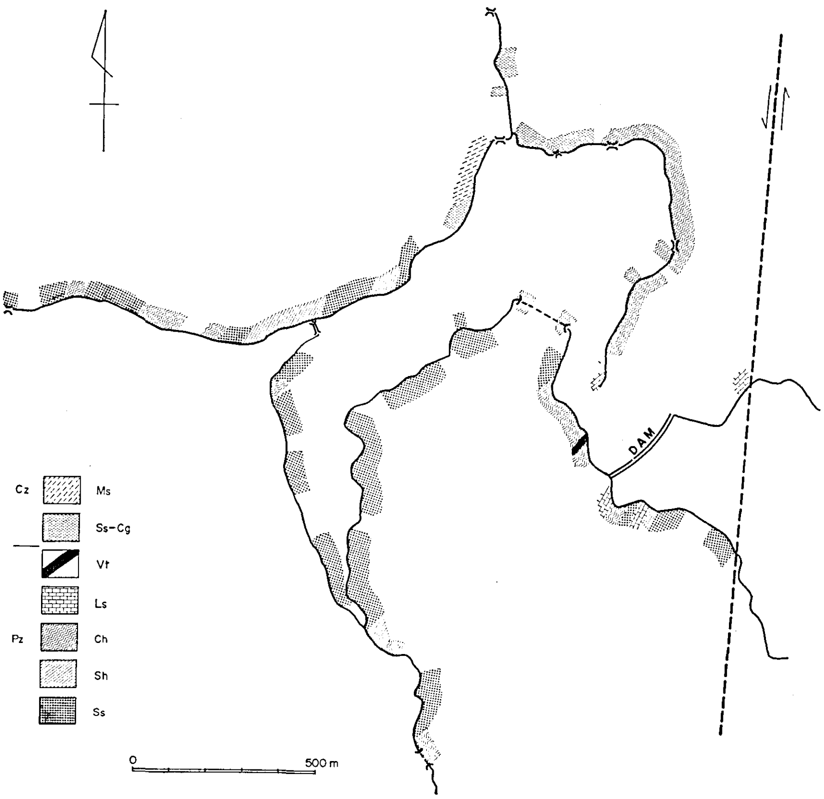


Fig. 10. Lithology along the routes.
Cz: Cenozoic. Pz: Paleozoic. Ss: Sandstone. Sh: Shale. Ch: Chert. Ls: Limestone. Vt: Basaltic lava and tuff. Ss-Cg: Coarse sandstone and conglomerate. Ms: Mudstone.

equal-area nets (Fig. 11). It is concluded from Fig. 11 that the attitudes are not affected by lithology. It is especially notable that the attitudes developed in the Permian strata and those in the Paleogene strata cannot be distinguished. This is also the same for the frequencies of minor faults in both of the strata, as is mentioned later.

Changes of attitudes of minor faults with increasing distance from the main fault

Attitudes of the minor fault planes and striations change systematically with distance from the main fault. This was quantitatively examined. Fig. 12 shows the equal-area projection of those attitudes measured in three zones which are 0-500 m, 500-1000 m, and 1000-1500 m apart from the main fault. Three features which vary with distance from the main fault can be read from Fig. 12 as follows:

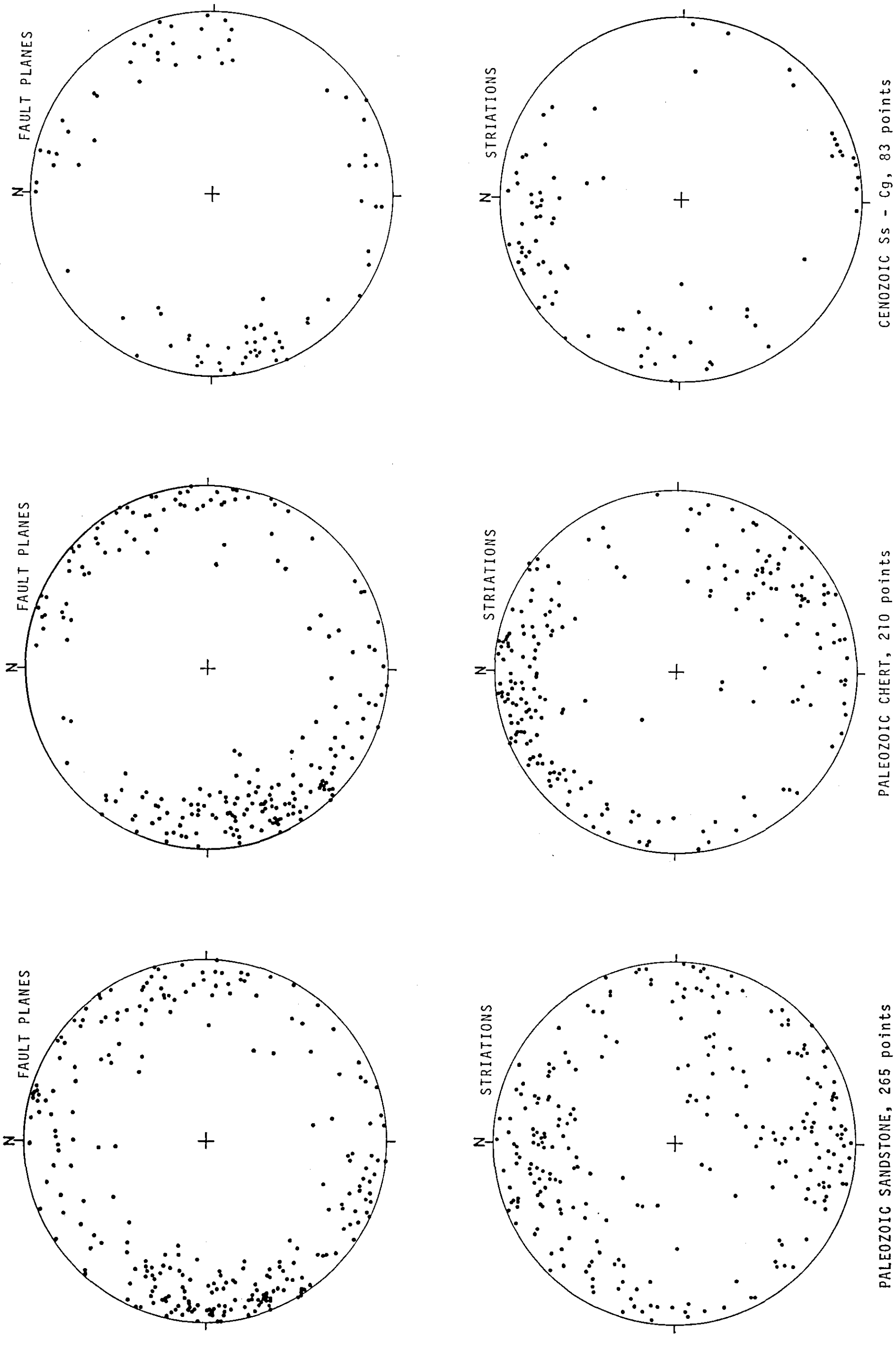


Fig. 11. Attitudes of minor faults and striations developed in three kinds of lithology. Equal-area net, upper hemisphere.

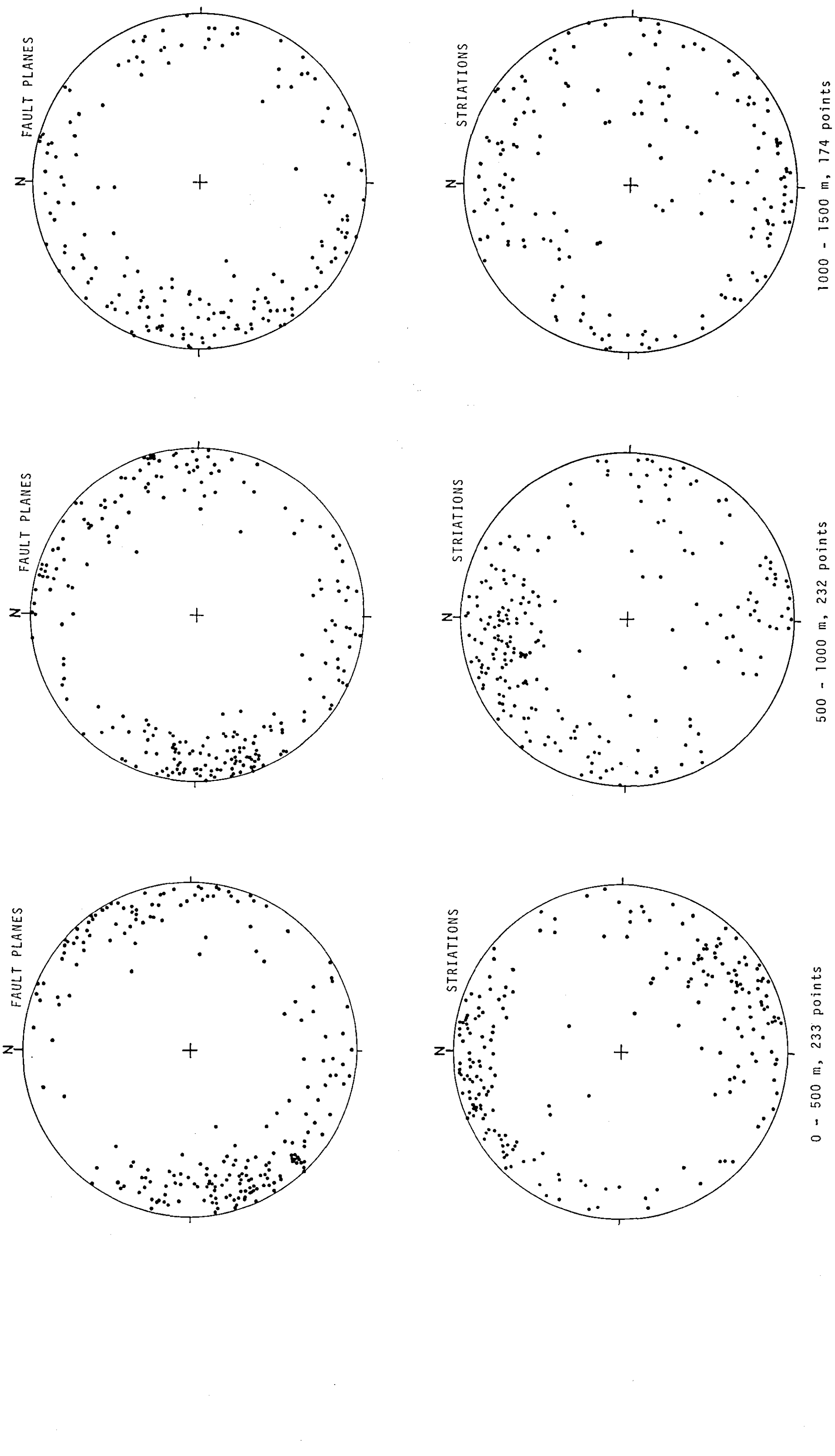


Fig. 12. Attitudes of minor faults and striations grouped with regard to distance from the main fault. Equal-area net, upper hemisphere.

(1) The concentration of the attitudes of fault surfaces and striations becomes less distinct as distance from the main fault increases.

(2) The strikes of the conjugate fault surfaces change their directions counterclockwise up to a maximum of about 20 degrees, as they approach 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 (N-S) in areas distant from it.

(3) The ratio of faults subparallel to the main fault to those which are conjugate to them becomes smaller as distance from the main fault increases.

Two interpretations are given for the change of the concentration of the attitudes (Characteristic-1 mentioned above). A high concentration of minor faults and striations in the neighborhood of the main fault may be attributed to a relatively uniform stress direction, whereas a low concentration may result from a fluctuation of the stress direction in the area away from the main fault. Another possible interpretation is given as follows. Since the average level of stress is considered to decrease with distance from the main fault, even when the stress direction is uniform, the attitudes of minor faults and striations may become more affected by the heterogeneity of bed rock structures in the area away from the main fault than in the neighborhood. For this reason, their directions may fluctuate, even if the stress direction is uniform throughout the area.

Counterclockwise change of the strikes of fault planes toward the main fault (Characteristic-2) is probably 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. Consequently, minor faults that were developed in the strata were subsequently rotated counterclockwise together with the strata. The rotation was larger in the neighborhood of the main fault. Therefore, the strikes of present-day minor faults change direction counterclockwise as they approach the main fault.

The change of the ratio of subparallel faults to the conjugate faults (Characteristic-3) comprises two problems. One problem is why the two groups of conjugate minor faults do not develop equally. The other problem is why the minor faults subparallel to the main fault become more dominant toward the main fault. According to the Coulomb-Navier criterion, conjugate shear fractures of two directions should be formed equivalently. However, one of the two develops dominantly over the other in the actual process of fracturing.

An explanation for the problems has been given by Tsuneishi (1971). According to him, one group of conjugate faults develops more dominantly than the other when the deformed rocks are rotated relative to the stress system and the angle of internal friction of rocks increases during the deformation. As shown in Fig. 13, let

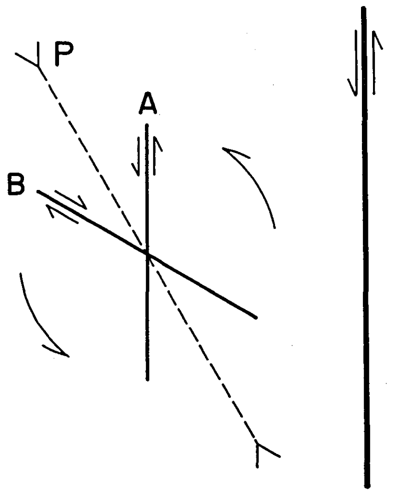


Fig. 13. Explanation figure for preferred development of either of conjugate minor faults. See text for details.

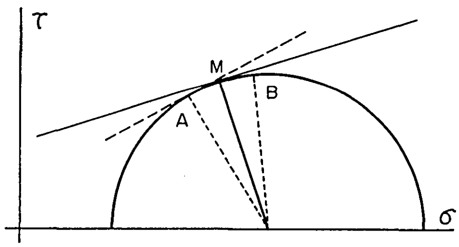


Fig. 14. Mohr diagram for minor faults before and after the rotation. See text for details. After Tsuneishi (1971).

a conjugate set of minor faults, A and B, originate near a main fault under the same stress P that forms the main fault, and let the fault A be parallel to the main fault. The faults A and B are rotated in the direction of the arrows by the succeeding deformation, while the stress system remains fixed. As shown by the Mohr circle in Fig. 14, the angle between fault A and the principal stress becomes smaller, and the angle between fault B and the principal axis becomes larger. Supposing that a failure occur again in this stage, it occurs more easily along either A or B, if the rotation is not large, rather than along a surface represented by the point M of Fig. 14. Now, the choice between A and B to produce further faulting is probably determined by the change in the angle of internal friction. If the angle of internal friction becomes larger with the progress of faulting, the slope of the Mohr envelope should be increased. Consequently, the failure occurs along fault A but not B. It has been reported that the angle of internal friction becomes larger with increased microfracturing when a rock is experimentally deformed (Koide and Hoshino, 1967; Hoshino, 1967; Rosengren and Jaeger, 1968).

The change in the ratio of subparallel faults to conjugate faults (Characteristic-3) in the Misakubo region can be interpreted as follows on the basis of the fault-forming hypothesis mentioned above. As the degree of drag of the strata becomes larger toward the main fault, the angle of rotation of the strata relative to the stress system becomes larger toward the main fault. At the same time, the angle of internal friction also becomes larger toward the main fault as a result of increased deformation. Consequently left-lateral minor faults are produced abundantly.

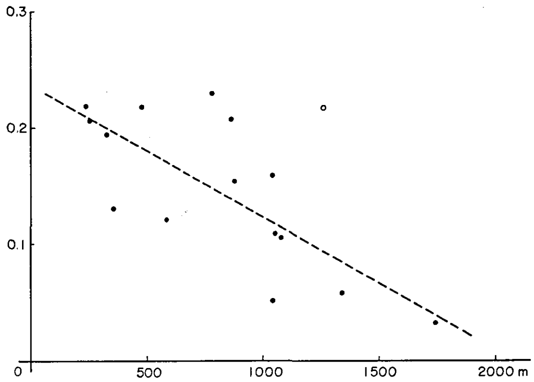
Both of the above mentioned characteristics, the counterclockwise change of the fault direction and the increase of the subparallel fault ratio, are related to the drag of strata associated with the displacements along the main fault. Namely, the ratio of subparallel faults to the conjugate faults increased in the early stage when minor faults were produced abundantly, and counterclockwise drag and rotation of the strata occurred to some extent at that time. Further counterclockwise rotation of the strike of minor faults was brought about by the drag that continued in the later stage after the formation of minor faults. Accordingly, the amount of rotation up to a maximum of 20° is thought to represent the sum of drag during the two stages. In fact the strata in the Misakubo region near the study-area have a trend of NE in the areas away from big faults and have a trend of NNE in the vicinity of the big faults, as shown in Fig. 2.

Frequency of minor faults

To examine the distribution of the frequency of minor faults in the study-area, the surveyed routes are divided into sixteen sections (Fig. 7). The frequency of minor faults per one meter of route is calculated by dividing the number of minor faults counted in a section by the total length of outcrops in the section. In Fig. 7 the frequencies thus calculated are shown by circles whose diameters designate the frequency values and whose centers are situated on the representative points in individual sections. The points were determined geometrically as the centers of gravity on the segments of good exposure in each section.

In order to determine the regularity of frequency distribution of minor faults, the value of the frequency of each section is projected on two axes intersecting at right angles one another: one axis is parallel to the main fault and the other axis perpendicular to it (Fig. 15). The zero-point of the axes is designated at the point O of Fig. 7. The open circle in Fig. 15 gives the value of section 8, which is much larger than those of the neighboring sections. The rocks along section 8 appear to be somewhat loose, probably due to weathering or to slight landsliding, and so the value is not discussed at present.

In Fig. 15 the upper diagram that contains the projection on the axis perpendicular to the main fault shows a systematic change; the



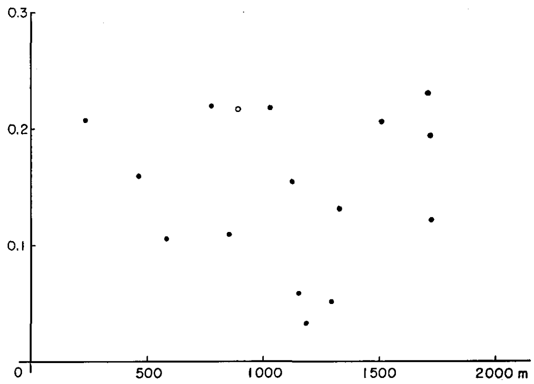


Fig. 15. Frequency distributions of minor faults with regard to an axis perpendicular to the main fault (upper), and with regard to an axis parallel to the main fault (lower).

frequency clearly increases toward the main fault. On the other hand, the lower diagram that contains the projection on the axis parallel to the main fault shows no systematic changes. A straight line was fitted to the upper diagram in Fig. 15 by the least squares method. The correlation coefficient of the regression line is 0.75. Judging from the fact that the regression line intersects the X-axis at the point 2000 m away from the main fault, minor faults are expected to develop to this distance. In other words, the western fracture zone of the Komyo fault has a width of 2000 m, if the fracture zone of the fault is defined by the zone in which minor faults develop. Incidentally, if there were a continuous outcrop 2 m high extending westward from the Komyo fault, we would expect to observe 247 minor faults along the 2000 m route.

6. Discussion

Tectonic significance of the Komyo fault

Strike-slip movements on the Komyo fault are considered to have been taking place at least during the late Oligocene and early Miocene, as judged from the following lines of evidence. The Paleozoic, Cretaceous and Oligocene strata have a similar structural trend of NE to NNE in the area surrounding the Komyo fault, as shown in Fig. 2, although their internal rock-deformation patterns are different. Fig. 16, which was reproduced from the paper of Kimura (1959), reveals that the Paleozoic and the Oligocene strata are disposed indistinguishably from each other with regard to their general trends in the Misakubo region. As described in Section 5, furthermore, few differences are recognized between the attitudes of minor faults in the two formations (Fig. 11). Furthermore, the frequency of minor faults in the Oligocene strata which are distributed in sections 12 and 13 of Fig. 7 are not different from those in the surrounding Paleozoic strata. From the above-mentioned facts, we can conclude that left-lateral strike-slip faulting on the Komyo fault occurred mostly after deposition of the Oligocene formation, although some faulting may have occurred before Oligocene time to form the Oligocene basin.

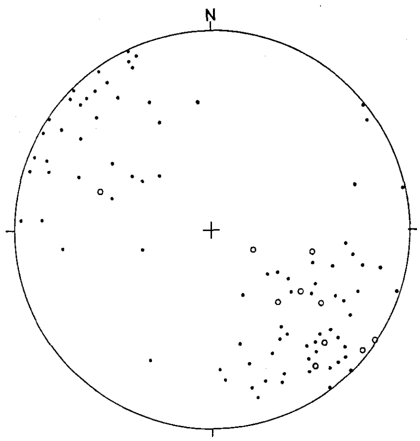


Fig. 16. Attitudes of bedding planes of the Cenozoic (open circles) and the Paleozoic strata (solid circles). Equal-area net, upper hemisphere.

On the other hand, the Futamata formation, which is correlative with the Lower Miocene Oigawa group, is distributed on the southern part of the Komyo fault. The formation has been also faulted by the Komyo and its related faults. However, the faulting is of normal character and not strike-slip, although the strata of the formation along the Akaishi fault parallel to the Komyo fault show sparse minor strike-slip faults (Kimura, 1961). Therefore, it is obvious that strike-slip faulting along the Komyo fault had been almost completed before deposition of the Lower Miocene Futamata formation.

The large-scale geologic structure of Central Japan is characterized by a northward sharp bend of the east-trending zonal structures of Southwest Japan, as well as by the existence of two large left-lateral strike-slip faults, the Akaishi and the Komyo, associated with the northward bend (Fig. 1). To the east of the Komyo fault, the Cretaceous Shimanto zone, the Paleogene Setogawa zone and the Neogene Tanzawa zone are distributed, successively toward east (Kimura, 1973). They are dislocated by the Sasayama tectonic line, Jumaiyama tectonic line (Tokuyama, 1972a, b; Ono, 1973), and the Itoigawa-Shizuoka tectonic line. These large faults have north trends, parallel to the Komyo fault. Strata of the Shimanto and the Setogawa zone are subjected to left-handed drag along the above-mentioned faults (Kimura, 1967). The Southern Fossa Magna region in the Tanzawa zone subsided and accumulated thick volcanic and clastic sediments of Neogene age. The amount of the subsidence is strongly contrasted between the regions on the two sides of the Itoigawa-Shizuoka tectonic line (Matsuda and others, 1967). This suggests that the fault along the Itoigawa-Shizuoka tectonic line had been already formed before Miocene time. From these lines of evidence, we conclude that a series of the large faults parallel to the Komyo fault had formed as left-lateral strike-slip fault just before Miocene time under the same regional stress field as that near the Komyo fault.

Several strike-slip faults which have been active in Quaternary time are known to the northwest of the Akaishi range, where the Komyo and related faults are located (Research Group for Quaternary Tectonic Map, 1969). Among them, left-lateral strike-slip faults have northwest trends, whereas right-lateral ones have northeast trends.

On the other hand, north-trending strike-slip faults including the Komyo and related faults have been inactive in recent geologic time, although the middle part of the Itoigawa-Shizuoka tectonic line, trending northwest in the central Fossa Magna region, is known to be active. The difference of the direction of strike-slip faulting between the two groups might be due to the change of stress direction from pre-Miocene time to the present.

However, there are some lines of evidence which do not necessarily support this interpretation. In the Izu Peninsula, 100 km southeast of the Komyo fault, are the Tanna fault and the Irozaki fault. The former is a north-trending left-lateral strike-slip fault which broke during the Kita-Izu earthquake of 1930, whereas the latter is a northwest-trending right-lateral fault which broke during the Izu-Hanto-oki earthquake of 1974 (Murai and Kaneko, 1974). This means that the present stress direction in the area to the southeast of the

Akaishi range is different from that to the northwest of it: the Akaishi range is situated between the two different present stress fields.

An alternative explanation may be required for the question of why the faults in the Akaishi range are not active. Since the Akaishi range is known to be in a field of recent predominant land upheaval, on the basis of the topography and the results of precise levelling (Dambara, 1971), it is certain that the crustal force is large below the range. However, the seismic activity of the area is relatively low (Katsumata, 1970). Therefore, it is plausible that there is no adequate *differential stress* which is sufficient to cause the Komyo and related faults be currently active.

Genetic relation between a main fault and minor faults

The experimental results on micro-fracturing of rocks carried by Mogi (1968) are very revealing in suggesting a genetic relation between a main fault and associated minor faults. In his experiments, several beams of granite or other rocks were bent, and the source locations of elastic shocks generated by micro-fractures were determined. The micro-fracturing process is divided into three stages; the initial stage in which no appreciable elastic shocks occur, the second stage in which elastic shocks begin to occur and their source locations are randomly distributed in the specimen, and the last stage in which the sources of elastic shocks gradually concentrate in a limited region centering on the location of the future main rupture. This process is applicable to formation of actual faults. However, the main fracturing in experiments, occurs only once, whereas in nature dislocations along a main fault are repeated intermittently during a long geologic period.

From the results of structural analysis of minor faults in the Misakubo region, as well as from the experimental results of Mogi (1968), we suggest the following process for the formation of a fault (Fig. 17). In the first stage, rocks in a limited region begin to deform under increasing crustal forces and eventually form a flexure zone. However, no appreciable brittle fracturing occurs during this stage. In the second stage, minor faults begin to develop and, as deformation increases, they continue to increase in number and magni-

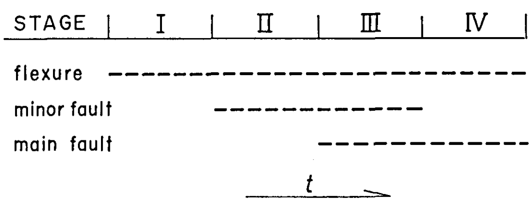


Fig. 17. Stages of Komyo fault development.

tude in the axial part of the flexure zone. Minor faults, which have a sense of slip compatible with the rotational sense of the flexuring of strata, predominate in the axial part of the flexure, as described in the previous Section. In the third stage, a main fault comes into existence within the most densely clustered zone of minor faults. The main fault continues to grow with minor faults. The combination of a main fault and its adjacent fracture zones develops during this stage. In the fourth stage, further formation of minor faults declines and brittle deformation is essentially restricted to the main fault plane. However, plastic deformation of the rock body around the main fault still proceeds as flexuring, so that the preexisting minor faults are rotated together with the rock body. In the Misakubo region, such counterclockwise rotation of minor faults reaches a maximum of about 20 degrees.

Relation between a fault and an earthquake

Shallow earthquakes are thought to occur as a result of brittle fracturing of rocks. Each earthquake corresponds to the formation of a new fault or to the reactivation of a preexisting one. Thus, the study of faults and their fracture zones may lead to the clarification of the mechanism of the earthquake generation, and vice versa.

The Komyo fault and associated minor faults which we can observe on the earth's surface have been brought to their present surficial position by uplifting and denudation, after they were formed at a certain depth in the crust. Probably the Komyo fault must have generated a large number of earthquakes during its active period, although it is inactive at present. We now examine three examples of recent earthquake phenomena which were observed with high accuracy. Then we examine them in the light of the results of structural analyses of the Komyo fault and suggest a correlation with the stages of development of a fault shown in Fig. 17.

(i) Matsushiro swarm earthquakes

A left-lateral strike-slip fault on the ground surface accompanied the activity of the Matsushiro swarm earthquakes (Nakamura and Tsuneishi, 1966, 1967; Tsuneishi and Nakamura, 1970). The earthquake swarm comprised more than 60,000 felt shocks with a maximum magnitude of 5.1 (JMA, 1968). The fault (Matsushiro fault) was formed along a zone corresponding to the area with the highest seismic activity (Hagiwara and Iwata, 1968). The surface trace of the fault is recognized as an assemblage of minute ground cracks arranged in double èchelon, and by a number of deformed man-made structures. These evidences of the fault movement are distributed in a zone with a length of 7 km and a width of 500 m. The width of fracture zone seems to be very large compared with its length. It is known from geological and physiographic evidence that the fault was newly formed, accompanying the swarm earthquakes, and that it was not a reactivated preexisting fault. This fact probably explains the large width of the fracture zone.

Fig. 18 is reproduced from the paper of Tsuneishi and Nakamura (1970). It shows the relation between the fault and the hypocentral distribution of major earthquakes. Those earthquakes which are shown as solid circles are considered to have been caused by displacements on the fault, as ascertained by instrumental measurements. 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 fault is made up of a group of shear planes instead of a single fault plane, at depth as well as on the surface.

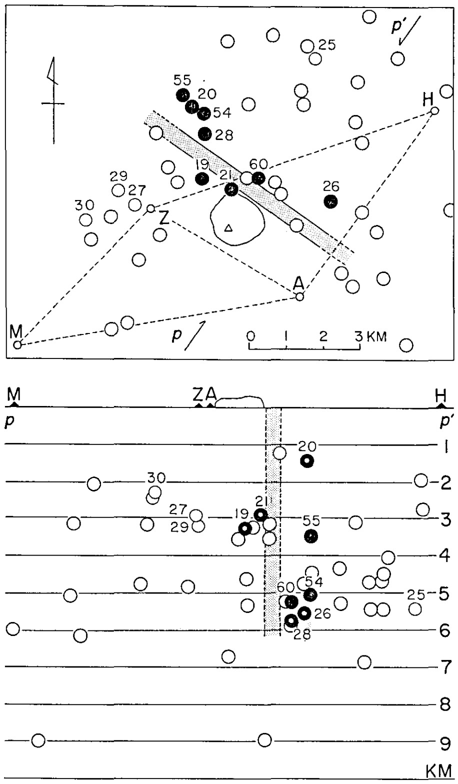


Fig. 18. Hypocentral distribution of major shocks of the Matsushiro swarm earthquakes. Solid circles denote the earthquakes related with surface faulting. After Tsuneishi and Nakamura (1970).

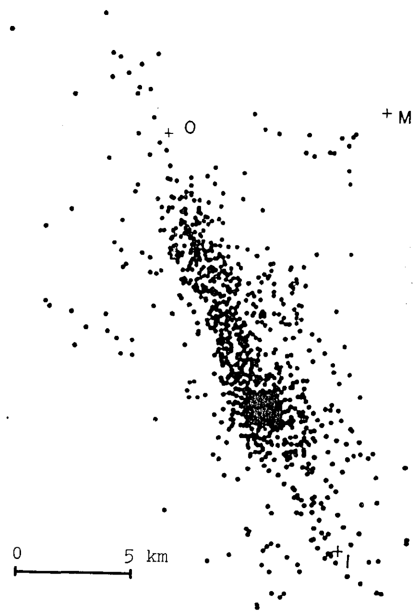


Fig. 19. Epicentral distribution of aftershocks of the Gifuken-chubu earthquake. After Watanabe and Kuroiso (1970).

The Matsushiro earthquakes are of swarm type, and their immediate cause may be attributed to an increased pore pressure rather than an increased regional crustal stress. It may not be appropriate, therefore, to compare the Matsushiro fault with the Komyo fault. However, we can safely discuss on the meachanical process of the formation of the fault.

The following generalization is possible in case of the Matsushiro swarm earthquakes. At first, numerous small fractures which are known from the occurrence of the swarm earthquakes were produced in a certain domain. Later, a main fault developed in a zone where small fractures were most densely concentrated. The fault of this stage is not composed of a single fault plane but of a group of smaller faults which are arranged en-échelon. These features are of the early stage of formation of a fault. The process observed in the example of the Matsushiro swarm earthquakes is correlated to stages II to III of Fig. 17.

(ii) Gifuken-chubu earthquake

The Gifuken-chubu earthquake with a magnitude of 6.6 occurred in 1969. Fig. 19 shows the epicentral distribution of the aftershocks determined by Watanabe and Kuroiso (1970). A fault related to the earthquake was recently discovered by Tsuneishi (1976). The fault has a length of 17 km, strikes north-northwest, and dips 80° to the southwest.

The lateral change of the epicentral distribution is asymmetrical, as shown in Fig. 19; there is a narrow aseismic zone along the west-southwestern boundary, whereas the number of aftershocks gradually decreases toward the east-northeast. Watanabe and Kuroiso (1970) suggested a slip plane related to the main shock along the narrow aseismic zone. This hypothesis is also supported by the results of the geological survey (Tsuneishi, 1976). The narrow aseismic zone of the aftershocks may correspond to the fault breccia zone along the Komyo fault.

The great majority of aftershocks occurred on the east-northeastern side of the main fault. The geology of the seismic area is composed of Cretaceous rhyolitic welded tuff on both sides of the fault. However, the deep-seated rocks are presumed to be granitic rocks on the east-northeast side of the fault and Paleozoic sediments and/or crystalline schist on the west-southwest side (Tsuneishi, 1976). Generally speaking, granitic rocks are more brittle than sedimentary rocks. When the two types of rocks, abutting each other on two sides of a fault, are subjected to a certain strain, granitic rocks are more likely to be broken down in a brittle manner, whereas sedimentary rocks are more likely to yield in a ductile manner. Therefore, it is presumed that aftershocks of the Gifuken-chubu earthquake were generated by brittle fracturing of granitic rocks. The situation is analogous to that of the Komyo fault. That is to say, in the Misakubo region minor faults with horizontal striations develop on the western side of the main fault, whereas they are not observed on the eastern side, as already described in Section 3.

The Gifuken-chubu earthquake showed a remarkable activity of aftershocks as well as a slippage along the main fault. Therefore, the fault related to the earthquake is considered to be in stage III of Fig. 17.

(iii) Parkfield-Cholame earthquake

In 1966 the Parkfield-Cholame earthquake (M=5.5) occurred along the San Andreas fault, and a right-lateral strike-slip fault developed. The surface trace of the fault was 38 km long, and ground cracks were arranged en-échelon within a zone only 3 m wide along most of the surface trace (Brown and Vedder, 1967). The surface features of the fault form a striking contrast with those of the Matsushiro swarm earthquake. Fig. 20 shows hypocenters of aftershocks of the earthquake as determined by Eaton and others (1970). The hypocenters are distributed within a very narrow zone, virtually on a single slip plane.

The San Andreas fault has a long history of activity and a large amount of displacement. It is naturally supposed that a large fault have a wide fracture zone. In fact the San Andreas fault is known to have a wide fracture zone encompassing the main fault plane. Nevertheless, most parts of the fracture zone are not active, and con-

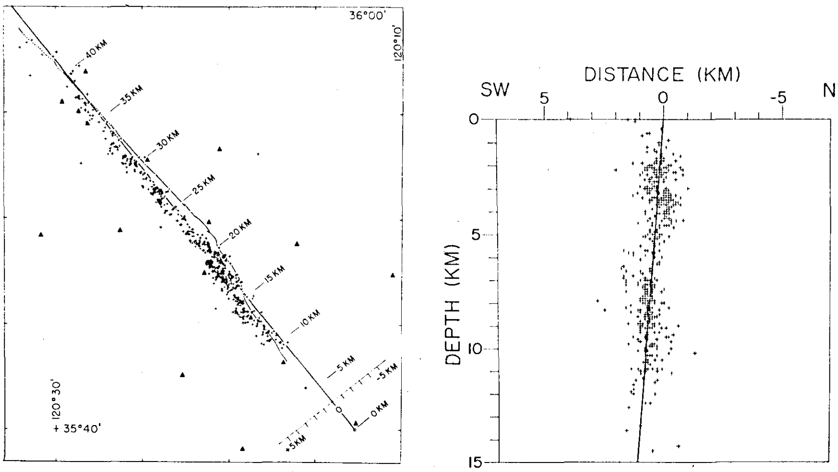


Fig. 20. Hypocentral distribution of aftershocks of the Parkfield-Cholame earthquake. After Eaton and others (1970).

temporary brittle fracturing is restricted on the main fault plane, although there is an exception of the Borrego Mountain earthquake of 1968 (Allen and Nordquist, 1972). It appears that the formation of the fracture zone has already been completed. These lines of evidence suggest that parts of the San Andreas fault are in stage IV of Fig. 17, the most matured stage of a fault development.

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22. 赤石山地西縁の光明断層の発達過程

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木村敏雄

(昭和 50 年 12 月 25 日受理)

光明断層は赤石山地の西縁にそう大きな左横すべり断層で，その主要な活動時期は漸新世後期―中新世前期と考えられる．光明断層の周辺部には多数の小断層が発達しており，それらの断層面上には断層運動の方向を示す条線が明瞭にきざまれている．この論文では，まず静岡県水窪地域に発達する小断層の解析結果が示される．つぎに，その結果を用いて光明断層の形成過程を考察したのち，地震断層への適用が試みられる．小断層は N15°W に集中する左ずれ変位の断層と N75°W に集中する右ずれ変位の断層とに分類される．小断層の発達状態は，頁岩のような延性の高く強度の小さい岩種の場合を除き，一般に岩質に依存しないが，主断層からの距離に従って系統的に変化する．すなわち，小断層は主断層からの距離が 2000 m までの範囲内に発達しているのであるが，その発達密度は主断層からはなれるにつれてほぼ直線的に減少する．また，主断層からはなれるにつれて，小断層面および条線の集中性が悪くなる．主断層と同じ向きのずれをもつ左ずれ変位の小断層は，主断層に近づくとき，右ずれ変位の小断層よりも著しくその数が増加する．左ずれ変位の小断層は主断層と全く平行ではなく，主断層に近いほど，最大 20° 反時計まわりに回転した方向をとっている．小断層の解析結果を茂木 (1968) による岩石破壊実験の結果と合わせて考察すると，光明断層の形成過程は次の四つの段階に区切られることがわかる．I: 鉛直な回転軸をもつ撓曲運動の段階，II: 小断層形成の段階，III: 小断層の成長と主断層発生の段階，IV: 主断層の変位の累進とそれにともなう撓曲運動の進行の段階．したがって，光明断層周辺の小断層は光明断層発達の全過程のうちの比較的初期に形成されたことがわかる．その後，これらの小断層は主断層の運動にともなう地層の引きずりによって回転運動をうけたと考えられる．最後に，現在進行中の断層運動とみなされる地震現象のうち，精度の高い観測結果が得られている三つの地震がとりあげられる．本震を発生させた主断層面と小断層の形成の場と考えられる余震域との関係に着目しながら，これらの地震に関連する地震断層と光明断層の発達段階との比較が行われた．その結果，松代地震は II から III にかけての段階，岐阜県中部地震は III の段階，Parkfield-Cholame 地震は IV の段階における断層運動を表わしているものと考えられる．