Estimation of Continuity of a Fault Based on Composite Planar Fabric

Yasuhiko Wakizaka, Atsushi Kajiyama, Hiroyuki Watatani, and Mutsuo Kozuma

Abstract

In Japan, there are many faults at dam sites, and a low-dip fault in particular can cause serious geological problems for the design and construction of a gravity type dam. It is difficult to estimate accurately the distribution and continuity of a fault due to the presence of composite planar fabric in a fault. Usually, Y shear, R1 shear and P foliation are observed in faults, and a fault extends to Y shear. However, the contact planes between a fault and its wall rock are not necessarily Y shear. When the contact planes between a fault and its wall rock are R1 shear or P foliation, the fault will not extend to the contact plane. Actually, all contact planes of a fault and its wall rock were estimated to be the Y shear based on drilled cores and data from borehole camera at dam sites in Japan, and the estimated distribution of faults did not match the actual distribution obtained by observing the excavated plane. Accordingly, identification of Y shear based on observation of high-quality drilled cores in Chichibu accretionary complex, which is a typical accretionary complex was performed. Y shear was identified one third of faults based on the combination of P foliation and R1 shear. Accurate estimation of the fault continuity is possible using the dip and strike of Y shear obtained by images from a borehole camera.

Keywords

Dam • Low-dip fault • Composite planar fabric

1 Introduction

The Japanese Archipelago is located at the boundary of various plates, and as a result many faults are distributed in the area. Even if it is not active, a low-dip fault can cause serious geological problems for the design and construction of a gravity-type dam. This is because a low-dip fault may form a slip surface when the dam reservoir is filled, and the dam will then collapse due to a slip. The distribution of faults is usually estimated from surveys of outcrops, and observations of drilled cores and walls of adits. However, the information obtained by all of these surveys and observations is one dimensional or zero dimensional; it is difficult to obtain three dimensional information of faults for the following reasons:

1. The distances between boreholes are too long (the density of boreholes is too low) compared to the fault length.
2. The boundary between a fault and wall rock is disturbed in the case of ordinary drilled cores.
3. If cores are drilled by high-quality methods, the dip and strike of a fault are not determined using only the cores. To determine the dip and strike of a fault, data from a borehole camera is required.
4. The boundary between a fault and wall rock does not necessarily express elongation of the fault.

The first cause is a problem of borehole density, the second cause is attributed to drilling quality and the third cause is due to the fault dip and strike measurement method. Only the fourth cause is a geological problem, so this paper discusses the fourth cause.

2 Accuracy of Estimating the Location and Continuity of a Fault

The accuracy of estimating the location and continuity of a fault can be confirmed at a dam site, because the basement rock at the site is excavated. Figures 1 and 2 show the

---

Y. Wakizaka (✉)
Japan Dam Engineering Center, Ikenohata, Taito-ku, Japan
e-mail: dora1026@peach.ocn.ne.jp; wakizaka@jdec.or.jp

A. Kajiyama
CTI Engineering Co., Ltd., Dosho-machi, Chuo-ku, Osaka, Japan

H. Watatani · M. Kozuma
CTI Engineering Co., Ltd., Daimyo, Chuo-ku, Fukuoka, Japan

A. Shakoor and K. Cato (eds.), *IAEG/AEG Annual Meeting Proceedings, San Francisco, California, 2018—Volume 4*, https://doi.org/10.1007/978-3-319-93133-3_4

distribution of faults before and after excavation of basement rock at two dam sites. The distribution of faults before excavation was estimated by geological investigations such as observations of outcrops, drilled cores and walls of adits.

Figure 1 shows an example of high dip faults. Basement rock of the A-dam site is Cretaceous gneiss. Faults Fa′, Fi, F9 and Fe estimated before excavation were observed in the same locations after excavation, whereas the locations of the other faults estimated before excavation differed from the locations observed after excavation. Fault Ef did not appear when the basement rock was excavated. Figure 2 shows an example of low-dip faults at the B-dam site. The geology of the B-dam site is Miocene lapilli tuff. Eighteen low-dip faults were observed before excavation, and the continuity of all faults was estimated to be poor. However, eight faults indicated good continuity after excavation, as shown in Fig. 2. Estimation accuracy is not so good for high-dip and low-dip faults.

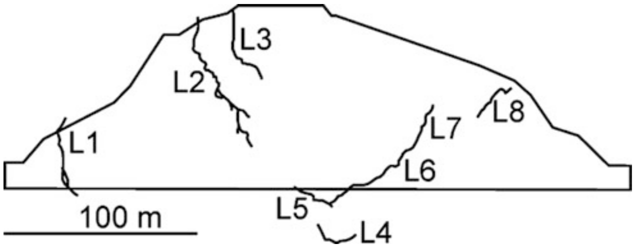


Fig. 2 Distribution of low-dip faults after excavation of basement rock indicated by the top view in B-dam, after Wakizaka (2015)

3 Geological Factors Affecting the Accuracy of Estimating the Continuity of a Fault

3.1 Formation Process of Faults

The process of formation of faults was studied by Riedel (1929) by performing experiments on the formation of an artificial fault. He made a cut box which consisted of two parts, and filled the box with a mixture of sand and clay. In this box, the cut plane was the displacement direction of a fault, and displacement could occur along the cut plane. At the stage of small displacement, staggered shear planes which crossed the displacement direction appeared, called Riedel shear planes. This experiment is called the Riedel shear test.

Tchalenko (1970) performed the Riedel shear test, and obtained the following results: staggered Riedel shear planes which crossed the displacement direction appeared when the displacement was small, other shear planes were formed in accordance with the progress of displacement, and finally each shear plane connected together and formed planes parallel to the displacement direction. Figure 3 shows the process of formation of a right lateral fault based on the test results of Tchalenko. The magnitude of displacement increased from (a) to (e). During the stage of development of the fault, the boundary between the fault and wall rock is not necessarily parallel to the direction of fault elongation as shown in Fig. 3(a) to (d).

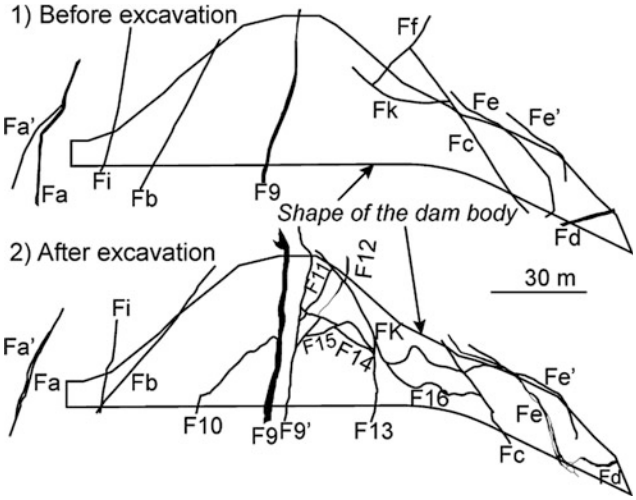


Fig. 1 Distribution of high-dip faults before and after excavation of basement rock indicated by the top view in A-dam, after Wakizaka (2015)

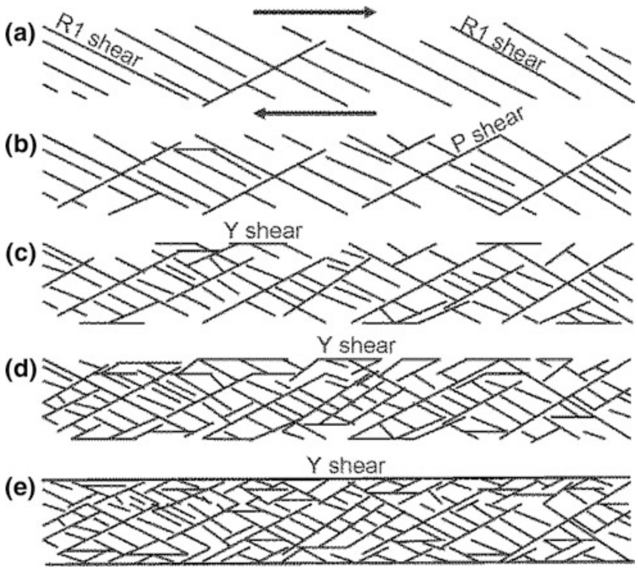


Fig. 3 Process of formation of a fault

3.2 Composite Planar Fabric and Continuity of a Fault

Various planes such as Riedel shear planes which appear during fault development are called composite planar fabric. Logan et al. (1979) gave the terms for each plane as shown in Fig. 4. Stearns et al. (1981) proposed a term of R instead of R1, and R′ instead of R2. R1 or R and R2 or R′ are Riedel shear planes, and Y, X and P are also shear planes. T is a tension crack. Among them, the direction of Y shear is that of elongation of the fault. P is not only a shear plane but also a foliated plane which consists of an arrangement of long axes of fragments or arrangement of mica. A shear plane of P is P shear, whereas a foliated plane of P is P foliation (Rutter et al. 1986). According to triaxial compression testing (e.g. Paterson 1978), the formation of a composite planar fabric is related to high confining pressure.

The boundary plane between a fault and wall rock in a developed fault may be composed of various planes such as Y, R1 and P shears, and the upper and lower surfaces of a fault in a drilled core show various planes. If the boundary plane between a fault and wall rock is P foliation or R1 shear, then the P foliation or R1 shear is mistaken for Y shear, and estimation of continuity of this fault is incorrect as shown in Fig. 5.

The boundary between a fault and wall rock does not necessarily express the elongation of the fault, as mentioned above. However, when the continuity of a fault is estimated by drilled cores, the direction of the boundary between a fault and wall rock obtained by the drilled cores is usually considered to be the direction of elongation, especially in the case of ordinary drilled cores without borehole camera data. The main geological factor affecting the accuracy of estimating the location and continuity of a fault is the presence of composite planar fabric in the fault.

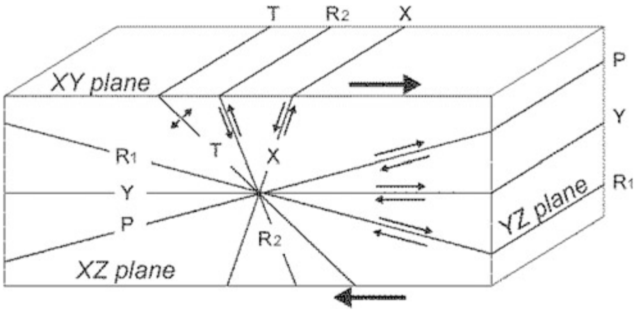


Fig. 4 Composite planar fabric of a lateral fault and its terms after Logan et al. (1979)

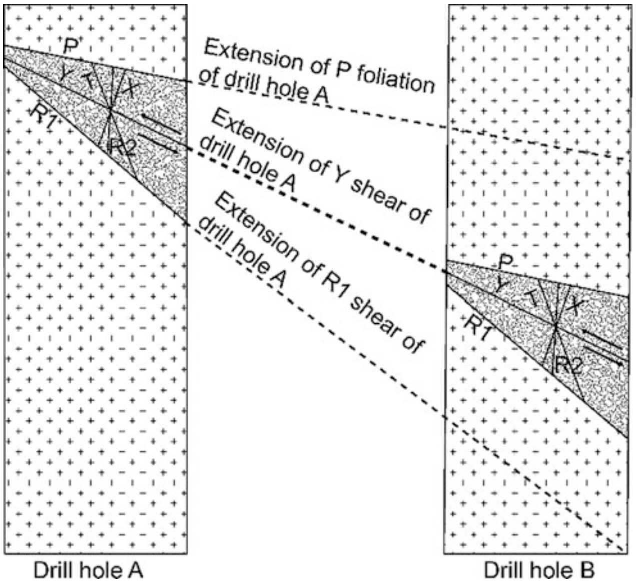


Fig. 5 Relationships between composite planar fabric and continuity of faults

4 An Example Estimating the Continuity of a Fault Based on Composite Planar Fabric

4.1 Geological Settings

Chichibu accretional complex is distributed in the example area. In the example area, the origin of this complex is an olistostrom, and is mainly composed of sandstone, mixed rock (chaotic rock) of sandstone and slate, slate and chert. Many low-dip faults are distributed in sandstone, slate, and mixed rock of sandstone and slate. It is planned to construct a gravity type dam in this area.

4.2 Method

Seven high-quality drilled cores of diameter 70 mm were observed. These drill holes (A to G drill holes) were arranged on the same measured line. The positions of low-dip faults and detailed structures such as composite planar fabric of faults were observed. A low-dip fault was defined as a fault having dip of less than 35°. When fabric was determined, P foliation was initially recognized based on Fig. 6, because the displacement of each shear plane is not usually determined by a drilled core, so each shear plane is not

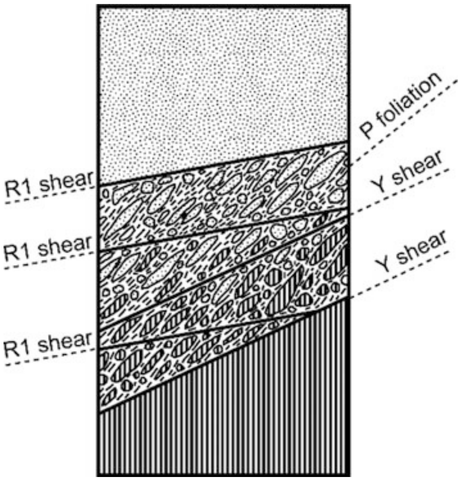


Fig. 6 Determination of P foliation, R1 and Y shears in a drilled core

determined by displacement. P foliation is expressed by the arrangement of the long axis of fragments and/or mica minerals. The dip and strike of the shear planes and foliation were determined from images taken by a borehole camera. The dip and strike of planar fabric were plotted on a Schmidt net diagram to confirm the accuracy of determination of the shear planes and foliation and to divide the strike and dip of Y shear. Y shear was accurately determined when Y and R1 shears, P foliation and unspecified planes showed nearly the same range of strike within 20°. Accurate Y shears were divided into some groups based on their dip and strike. The apparent dip of Y shear was plotted in the section by the same dip and strike group. Finally, the continuity of Y shear which is the continuity of the low-dip fault was determined based on the section.

4.3 Results

Determined planar fabric

The numbers of observed low-dip faults were as follows: drilled core A: 15, B: 11, C: 17, D: 13, E: 11, F: 7, G: 11. Figure 7 shows apparent dips of the upper and lower surfaces of the low-dip faults. The upper and lower surfaces were determined by the upper and lower boundaries, respectively, between a fault and wall rock. Low-dip faults are mainly distributed in slate, and mixed rock of sandstone and slate. It is impossible to estimate the continuity of faults because the direction of the upper and lower surfaces is very complicated.

Figure 8 shows example photographs of the determined planar fabric. The arrangement of the long axis of fragments was observed in Fig. 8a, b, and the arrangement of mica minerals was recognized in Fig. 8b. These arrangements were considered to be P foliation. The R1 and Y shears were determined by the P foliation and the relationships between planes as shown in Fig. 4. When P foliation was determined, the old P foliation which was formed in accretion was neglected. Rock that shows old P foliation. This rock is perfectly consolidated.

Y shear was confirmed by the relationships between its strike and the strike of other shear planes and foliation. The strike of the confirmed Y fabric had the same or nearly the same strike as the other shear planes and foliation. Figure 9 shows the dip and strike of the confirmed Y shear; the dip and strike was divided into two groups, group A and group B. The range of dip and strike of group A is 10°–30° and N10°W–N60°E respectively, and that of group B is 10°–32° and N10°W–N60°W respectively.

Distribution of Y shear

Figure 10 shows the apparent dips of Y shear and similar planes of Y shear of group A in geological section. Figure 11 also expresses the apparent dips of Y shear and similar planes of Y shear of group B. Y shear and similar planes of Y shear are called Y shear below. Comparing the apparent dips of Y shears in both groups with the apparent dips of the upper and lower surfaces of the faults as shown in Fig. 7, the apparent dips of Y shears naturally show the same direction.

5 Discussion

5.1 Continuity of Faults

The continuity of low-dip faults was estimated based on the distribution of the apparent dips of Y shears as shown in Figs. 10 and 11. In these figures, if Y shears are distributed at the elongation of the other Y shears, these Y shears are considered to be continuous with each other. However, measurement of the dip and strike of Y shears from the borehole camera images had some errors. Therefore, when estimating the continuity of Y shears, some width in the direction of elongation is required.

Figures 12 and 13 show the estimated elongation of the faults based on the apparent dip of Y shears of group A and group B, respectively. In group A, two faults are estimated to continue. One continues from the drill hole D to G in mixed rock of sandstone and slate, and the other is continues from drill hole D to F in slate. In group B, two faults are also estimated to continue. One is elongated from drill hole A to B in slate, and the other continues from drill hole C to D in mixed rock of sandstone and slate. The continuity of faults is accurately determined based on observation of Y shear.

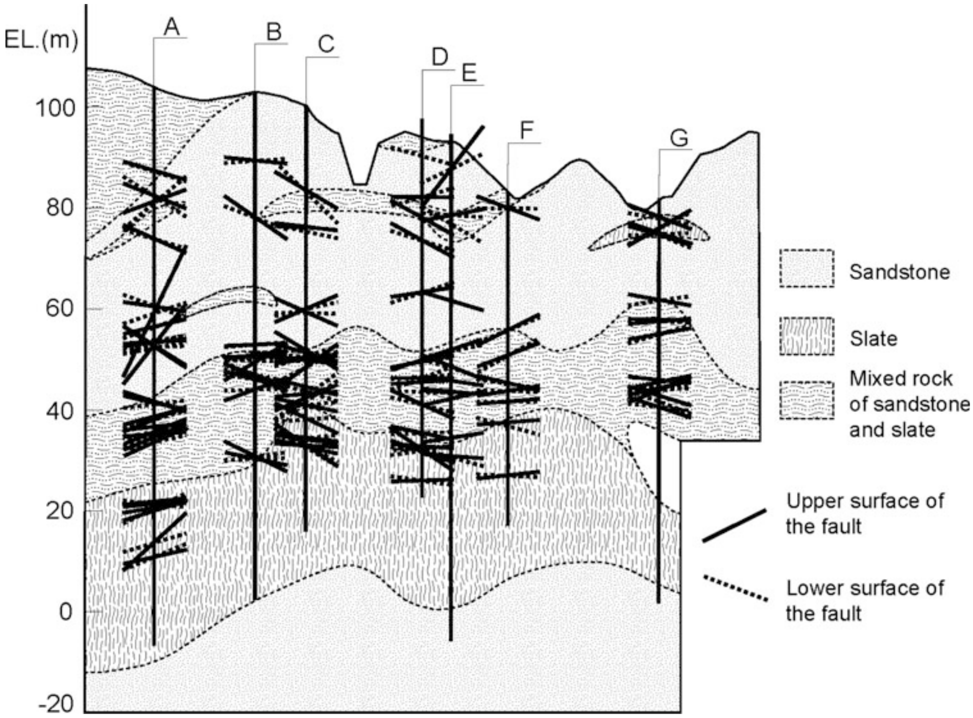


Fig. 7 Apparent dip of upper and lower surfaces of faults

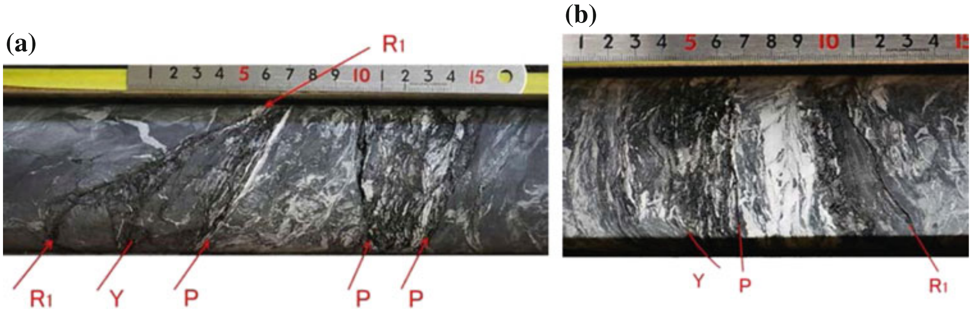


Fig. 8 Examples of determined composite planar fabric

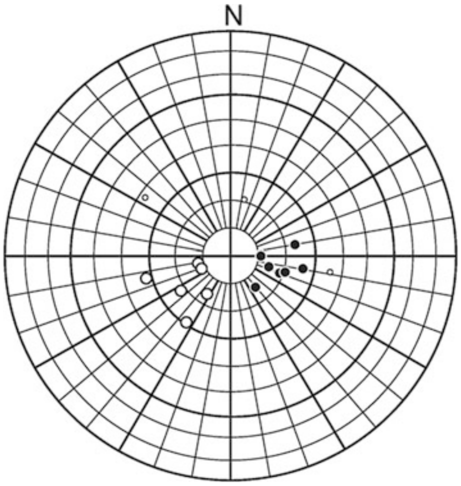


Fig. 9 >Schmidt's polar net plots of Y shear dip and strike (lower-hemisphere projection). Solid circles: Y fabric of group A. Large open circles: Y fabric of group B. Small open circles: Y fabric of another group

5.2 Problems in Determining Composite Planar Fabric

There are some problems in determining composite planar fabric as follows.

1. Shear planes and foliation are not observed in the fault part, because the core is disturbed by drilling even though the core is high quality.
2. Shear planes and foliation are not present in the fault part, because the length of the fault is shorter than the interval between shear planes or foliation.
3. Shear planes are not specified, because P foliation is not present.

To the problems 1 and 2, all faults distributed in two drill holes next to each other are considered to be connected each other. To solve problem 3, all shear planes are considered to be Y shear.

Fig. 10 Apparent dip of Y shears of group A

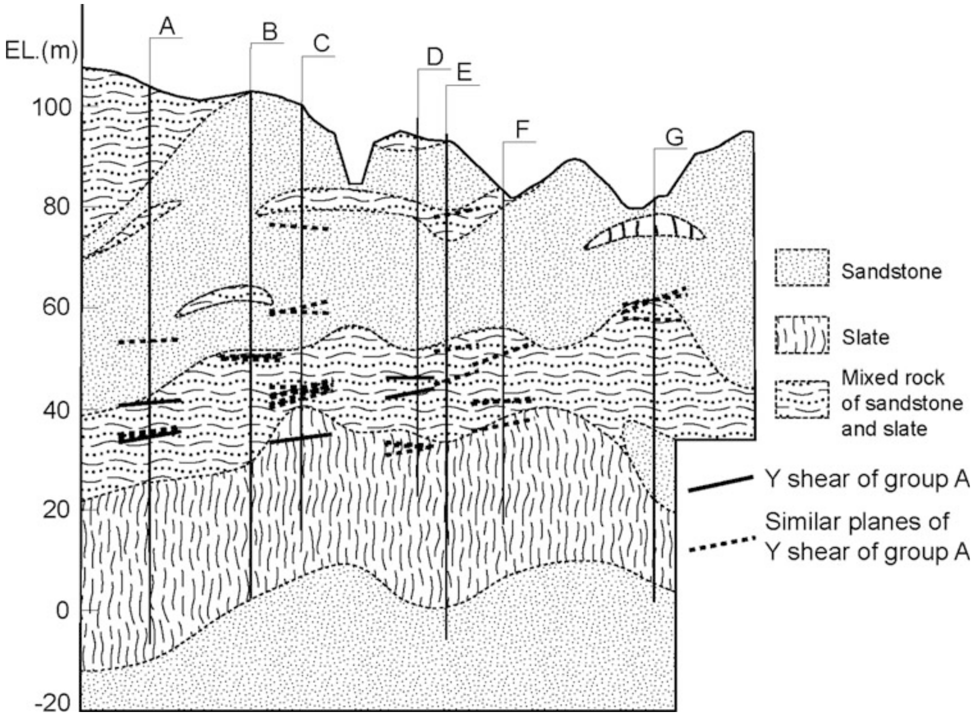


Fig. 11 Apparent dip of Y shears of group B

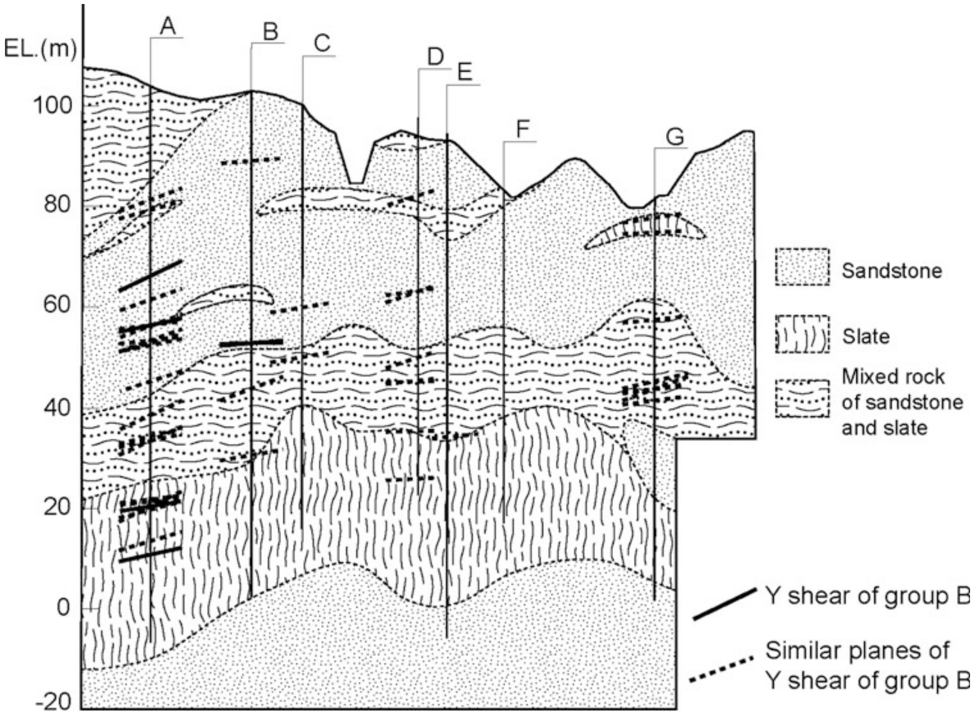


Fig. 12 Estimated elongation of Y shears of group A

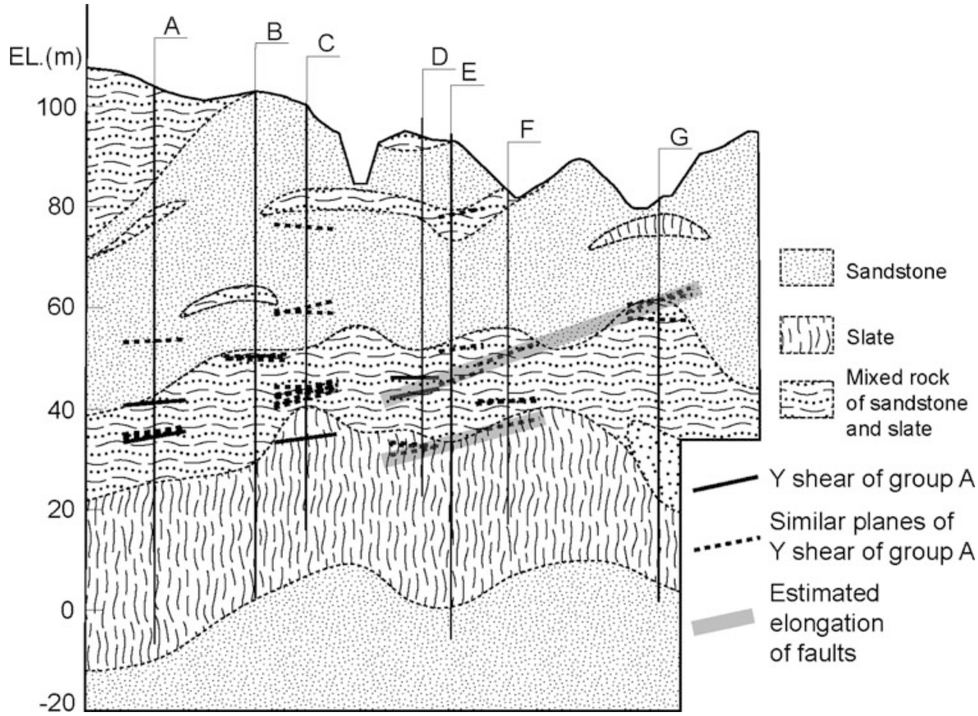
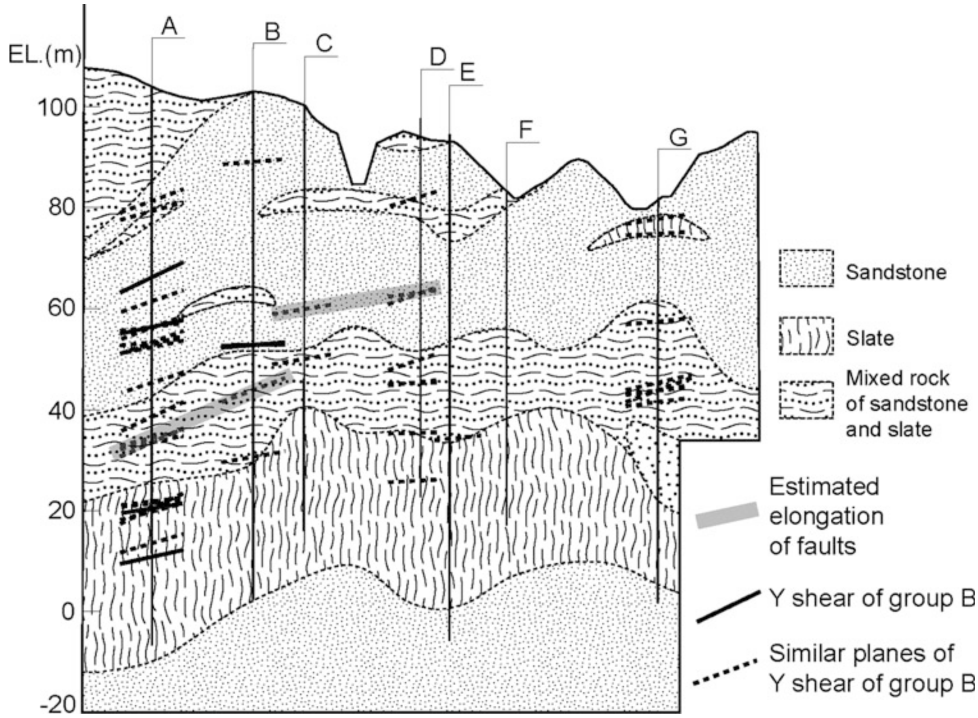


Fig. 13 Estimated elongation of Y shears of group B



6 Conclusion

It is difficult to estimate the distribution and continuity of faults by drilled cores, because faults have composite planar fabric. A fault elongates along only the direction of Y shear. The contact planes between a fault and its wall rock have various fabrics such as Y, R1 shears and P foliation, and so contact planes between a fault and its wall rock are not necessarily expressed by Y shear. Therefore, it is necessary to determine Y shear I order to accurately estimate the continuity of faults. Y shear and similar planes of Y shear were determined using high-quality drilled cores in an example area belong to the Chichibu accretionary complex. It is considered that continuity was accurately estimated by determining Y shear and similar planes of Y shear.

References

Logan, J.M., Friedman, M., Higgs, N., Dengo, C., Shimamoto, T.: Experimental studies of simulated gouge and their application to studies of natural fault zones. USGS Open File Report 79-1239, pp. 305–343 (1979)

Paterson, M.S.: Experimental Rock Deformation, The Brittle Field, 254p. Springer, Berlin (1978)

Riedel, W.: Zur Mechanik geologischer Brucherscheinungen: ein Beitrag zum Problem der “Fiederspälten”: Zentralblatt für Mineralogie, Geologie, und Palaeontologie, Abt B, pp. 354–368 (1929)

Rutter, E.H., Maddock, R.H., Hall, S.H., White, S.H.: Comparative microstructures of natural and experimentally produced clay-bearing fault gouges. Pure. appl. Geophys. **124**, 3–30 (1986)

Stearns, D.W., Couples, G.D., Jamison, W.R., Morse, J.D.: Understanding faulting in the shallow crust: contributions of selected experimental and theoretical studies, In Carter, N.L., et al. (eds.) Mechanical Behavior of Crustal Rocks, The Handin Volume, vol. 24, pp. 215–229. American Geophysical Union, Geophysical Monograph (1981)

Tchalenko, J.S.: Similarities between shear zones of different magnitudes. Geol. Soc. Am. Bull. **81**, 1625–1639 (1970)

Wakizaka, Y.: Modeling of ground and points to note for modeling for engineering geology. In: Proceedings of 2015 Symposium, Japan Society of Engineering Geology, pp. 9–20 (2015) (in Japanese)