

Identification of an active fault in the Japanese Alps from DEM-based hill shading

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Abstract

Shaded-relief images created from digital elevation models (DEMs) are helpful in identifying faults in rugged mountains, because, unlike conventional airphoto interpretation, the method can enhance lineaments at different orientations by simulating topographic illumination under varied light directions. Interpretation of shaded-relief images of the Japanese Alps led to the discovery of a lineament unrelated to bedrock structure. Field surveys and detailed analysis of large-scale maps and airphotos revealed the lineament to be an active fault with high rates of vertical and lateral slip. The new fault can be regarded as the southernmost segment or branch of a known adjacent fault, and the rate and direction of its slip provide fresh insight into late Quaternary activities of the fault system. Because previous research mistook the fault scarp for a terrace scarp, discovery of the fault also led to revision of river-terrace correlation in the Northern Japanese Alps. This correction affects Pleistocene glacial chronology in the upstream area.

Key words: DEM, hill shading, active fault, surface displacement, Japan

Introduction

Faults are a major geomorphic focus in tectonically active areas. Based on extensive air-photo interpretation and literature surveys, the 55 researchers of the Research Group for Active Faults of Japan (1991) compiled an inventory of Japanese faults that moved at least once in the Quaternary. The inventory contains information on ca. 1,800 active faults, such as degree of certainty, activity,

and age of movement. Distribution of the faults is shown in 123 map sheets. The inventory probably is one of the most comprehensive lists of active faults in a given country or region of the world.

The RGAFJ (1991), however, has not fully investigated faults within rugged mountains, although steep mountains occupy much of the Japanese Islands. Attention was paid mostly to faults in piedmont areas, which often separate mountains from lowlands, and urbanized lowlands which are directly related to earthquake hazards in cities. In general, faults in mountain areas often remain undiscovered because of infrequent investigation and the lack of broad flat surfaces that clearly record surface displacement. The nature of the airphotos also restricts fault identification in mountains, since it is relatively difficult to identify faults with a north-south orientation in Japan. Because most airphotos were taken around noon to reduce shaded areas, the east- or west-facing scarps located along north-south-striking faults are not clearly illuminated or shadowed.

Simulated topography can be illuminated from an arbitrary direction and mapped using grid DEMs. This technique, analytical hill-shading, results in shaded-relief images (e.g., Yoeli, 1965; Thelin and Pike, 1991). These images are useful not only for the representation of terrain features but also for the identification of lineaments, because shaded relief shows bare-ground surfaces unobscured by other surface cover such as vegetation and land use. In addition, shaded-relief images under a light direction different from the conventional sun location may aid in identifying lineaments or faults that are hard to see by the usual methods of airphoto interpretation.

This paper describes how DEM-generated shaded-relief images contributed to discovering an active fault in the Northern Japanese Alps. The existence of the fault, confirmed by field surveys and detailed airphoto interpretation, has geomorphological and paleoenvironmental implications.

Shaded-relief images and fault identification

The Japanese Alps, located in central Honshu Island, are the highest non-volcanic mountains in Japan. The range consists of Northern, Central, and Southern components (Fig. 1). Summit altitudes are around 3,000 m, and the mountains are underlain mainly by Cretaceous granitic rocks, Paleozoic to Mesozoic sedimentary rocks, and Paleozoic to Mesozoic metamorphic rocks. The ranges are characterized by steep slopes with a dominant modal angle of ca. 35 degrees (Katsube and Oguchi, 1999).

Shaded-relief images for the Japanese Alps were created from 2.25"×1.5" DEMs provided by the Geographical Survey Institute of Japan. The grid interval of the DEMs at the center of the Japan Alps is nominally 50 m (ca. 56.5 m in the E-W direction and 46.2 m in the N-S direction). The DEM data were imported into SURFER (Golden Software) to make shaded-relief images using Lambertian reflection (Thelin and Pike, 1991; Keckler, 1995). Various light directions were used to create images; Fig. 1 is an example of northwest illumination.

Visual interpretation of the shaded-relief images revealed lineaments not identified by the RGAFJ (1991). Comparisons between the distribution of the lineaments and geological maps suggest that most lineaments are related to bedrock structure rather than recent fault displacement. Some lineaments, however, appear unrelated to bedrock structure, implying that they are active faults. We

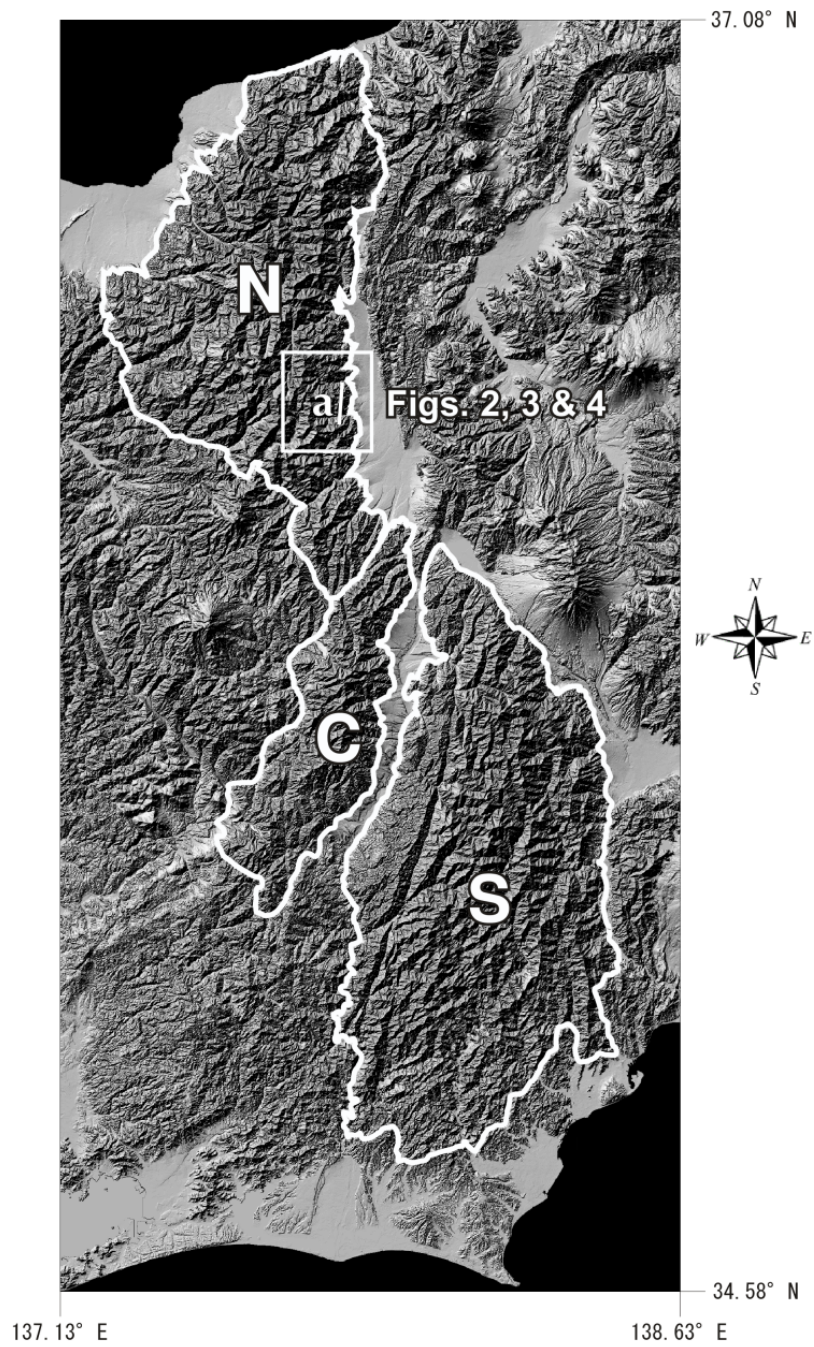


Fig. 1 Shaded-relief image of the Japanese Alps, showing N: Northern, C: Central, and S: Southern divisions and detailed area (a) imaged in Figs. 2 to 4. Source: 2.25''x1.5'' (50 m) DEM provided by the Geographical Survey Institute of Japan (GSIJ).

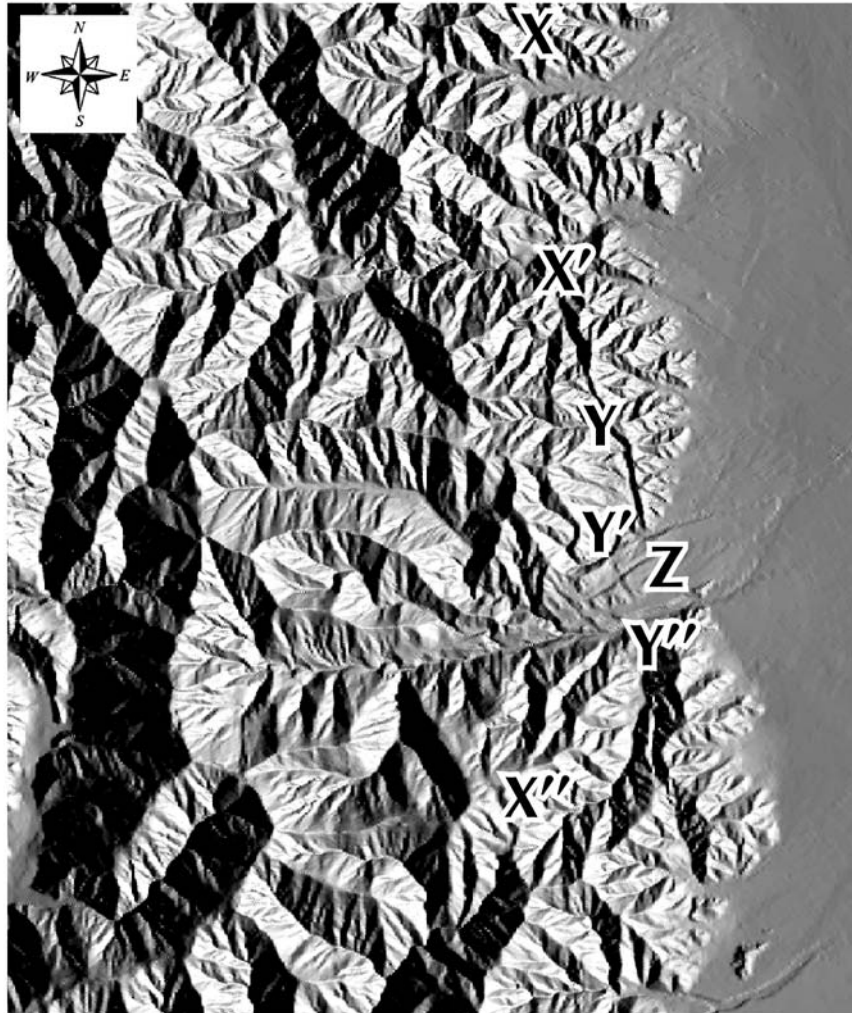


Fig. 2 Shaded-relief image of the Karasu River Basin and its surrounding, Northern Japanese Alps, under E illumination and 25° sun angle. Source: 0.45"×0.3" (10 m) DEM interpolated from GSIJ 50 m DEM.

X-X'-Y-Y'-Y'': Jonendake Fault, X'-X''': newly discovered active fault, X'-Y-Z: older fault.

Image is ca. 16 km × 20 km.

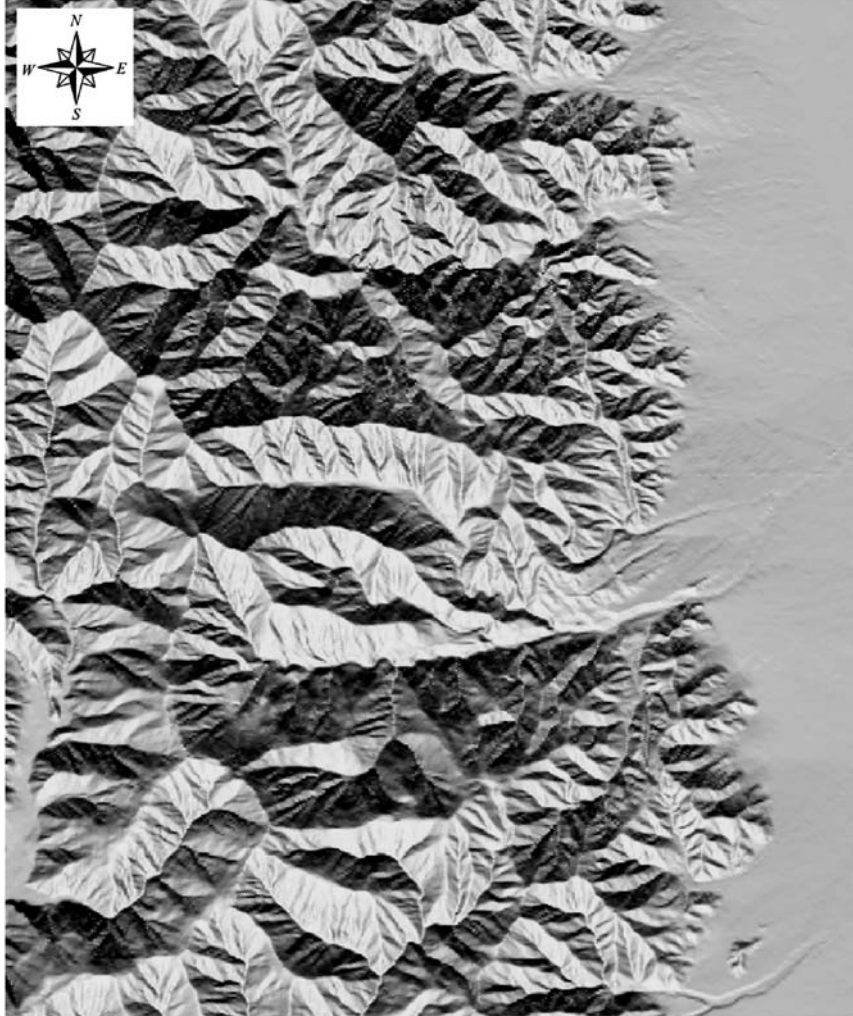


Fig. 3 Shaded-relief image of the same area as Fig. 2, but under S illumination and 54° sun angle.

observed one especially clear lineament unidentified by the RGAFJ (1991) in the eastern part of the Northern Japanese Alps (a in Fig. 1). The lineament is ca. 9 km long, strikes nearly north-south, and most of it is located in the catchment of the River Karasu, where fluvial and hillslope geomorphology was earlier investigated by Oguchi (1988, 1996).

To examine the lineament in detail, we prepared shaded-relief images for a smaller area around containing 286×427 grid points of the 50 m DEM. As noted by Yoeli (1965), shaded-relief images with pixels larger than 0.25 mm are inappropriate for representing terrain characteristics. If pixel size is set to 0.2 mm, the resulting image for the area has a dimension of ca. 65 mm ×85 mm, too small for the visual interpretation of terrain features. To solve this problem, the DEM data were interpolated to a finer resolution. Various methods of interpolating raster geographical data have been proposed (e.g., Schut, 1976; Desmet, 1997), kriging being one often applied to DEM data (e.g., Keckler, 1995). We generated a 0.45"×0.3" DEM with 1,430 ×2,135 grid points from the 50 m DEMs by kriging with a linear variogram model without drift and nugget effects. Shaded-relief images created under various light directions from the new DEM revealed that low-angle illumination from the east at a 25° sun angle best depicts the lineament of the inferred fault (X'-X" in Fig. 2). By contrast, the more conventional illumination shown in Fig. 3 (S at 54° sun angle) for the area fails to reveal the inferred fault on the image, even after the application of the sharpening filter, explaining why the fault remained undiscovered by conventional airphoto interpretation.

Validation and slip rates of the fault

To confirm the existence of a fault, detailed topographic features along the inferred feature were investigated by 1:5,000 topographic maps, 1:8,000 airphotos, and field surveys that included profile measurements. The results indicate that more than 10 locations are associated with topographic displacement by the fault (Fig. 4). One of them is a set of fluvial terraces along the west-to-east flowing River Karasu. Three different levels of terraces are displaced by the fault with left-lateral slip and the relative lowering of the eastern block (Figs. 5 and 6). The highest deformed terrace can be correlated to the Q2 surface defined by Oguchi (1996), and the lower two terraces can be correlated to the Q3 surfaces. Field surveys and the longitudinal profiles of terraces show that the vertical displacement of the Q2 surface is about 17 m and that of the Q3 surfaces is about 10 m (Figs. 6 and 7). Fig. 5 shows that the terrace scarp between Q2 and Q3 terraces is horizontally displaced by ca. 25 m. Some ridges along the fault also are subjected to left-lateral displacement and/or the lowering of the eastern block (Figs. 4 and 8). We also found the fault to outcrop at a(x) in Fig. 4, revealing a nearly vertical fault plane (Fig. 9). Therefore, the fault is confirmed to be active.

Tephrochronological surveys in and around the Northern Japanese Alps (Oguchi, 1988) and relative height of the terraces indicate that the Q2 terrace was formed at 40 to 60 ka BP, and Q3 terrace surfaces cut by the fault were formed at 25 to 35 ka BP. These ages and the amount of terrace displacement yield a horizontal slip rate of 0.7 to 1.0 mm/yr and a vertical slip rate of 0.3 to 0.4 mm/yr. Therefore, the net slip rate amounts to 0.8 to 1.1 mm/yr. The RGAFJ (1991) classified fault activities in Japan into three levels: A class (1 to 10 m / 1000 yr), B class (0.1 to 1 m / 1000 yr) and

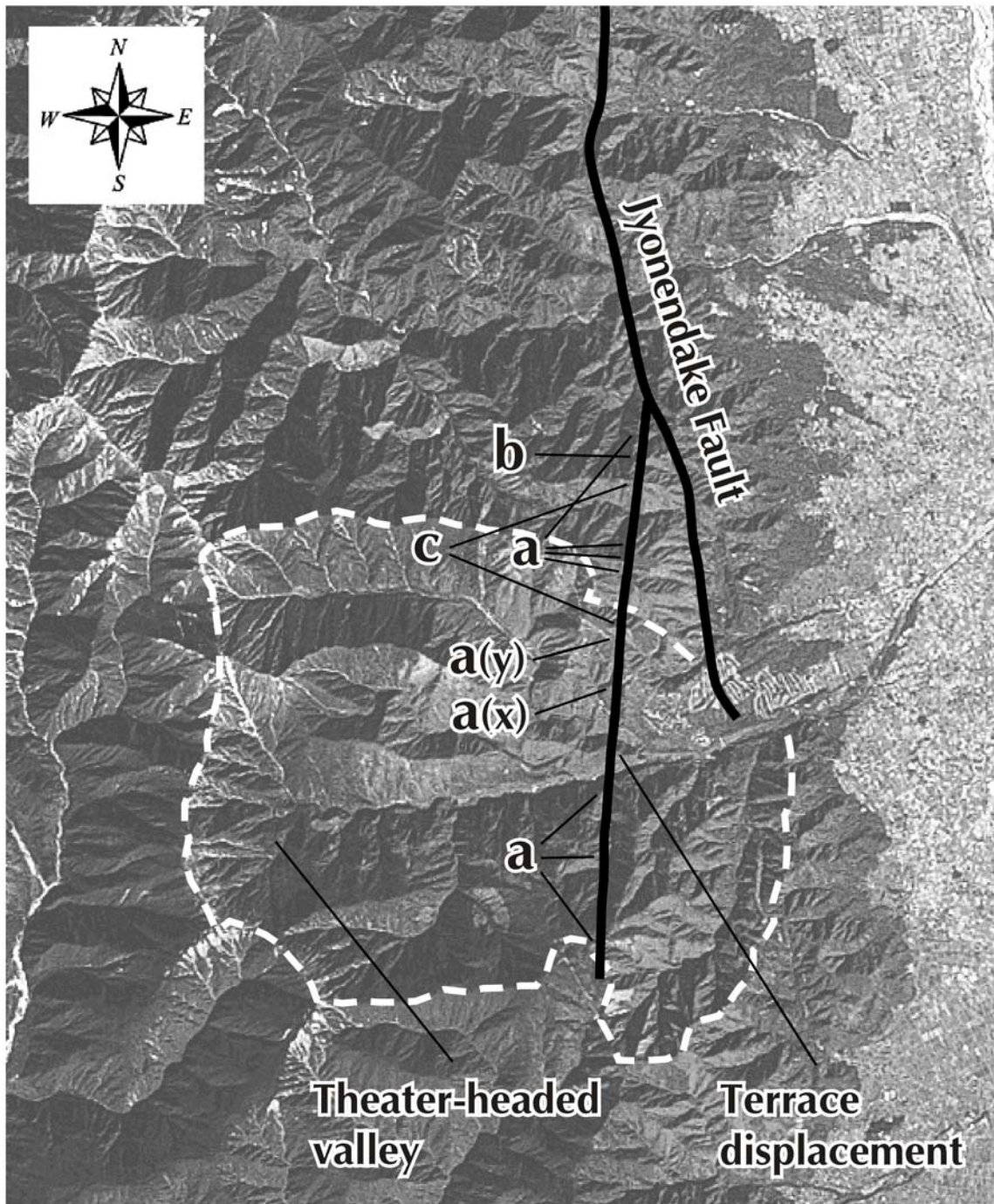


Fig. 4 Map showing locations of topographic features displaced by the newly discovered fault. a: ridge displacement by left-lateral strike slip and relative lowering of the eastern block; b: ridge displacement by left-lateral strike slip; c: ridge displacement with relative lowering of the eastern block; x: fault outcrop shown in Fig. 9; y: ridge displacement shown in Fig. 8.

Image is ca. 16 km × 20 km.

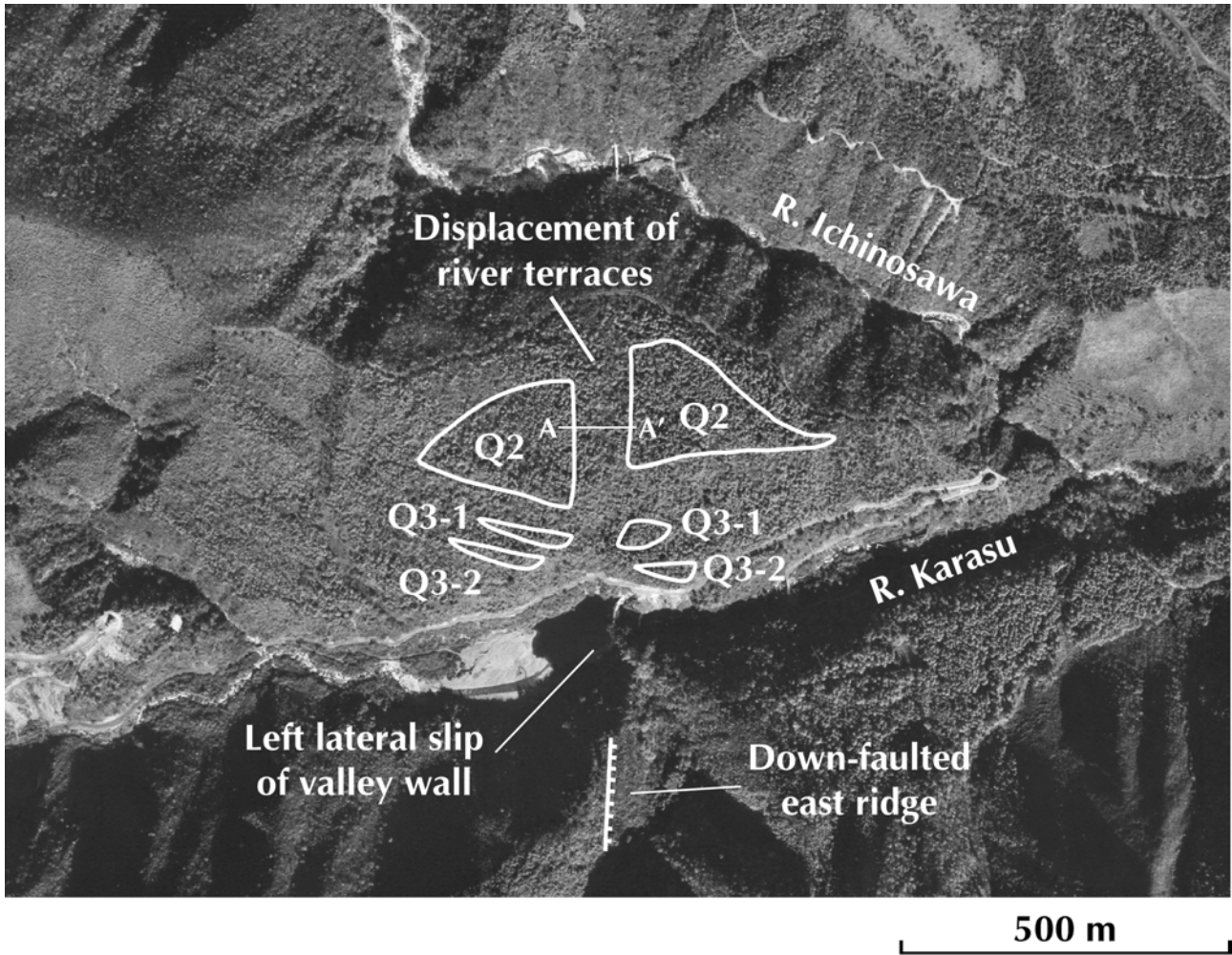


Fig. 5 Airphoto showing displaced terraces in the middle reach of the Karasu River.

A-A': Location of topographic profile in Fig. 7.

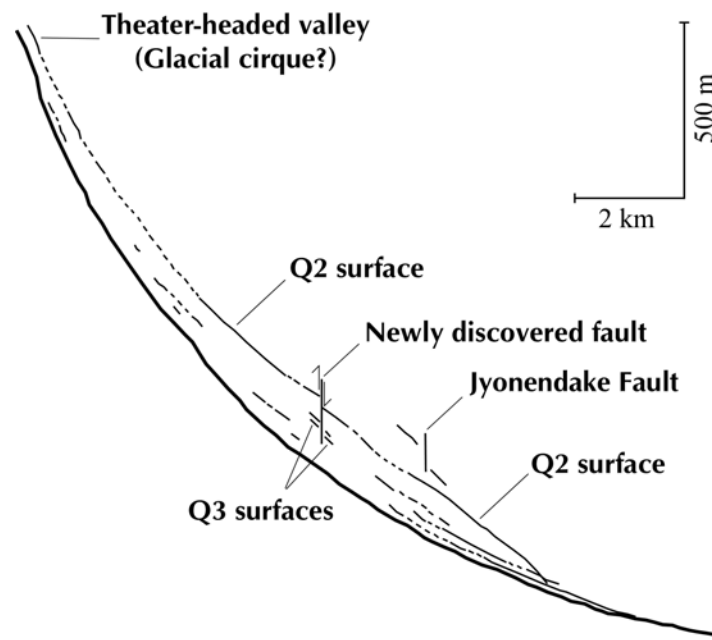


Fig. 6 Longitudinal profiles of river terraces along the Karasu River.

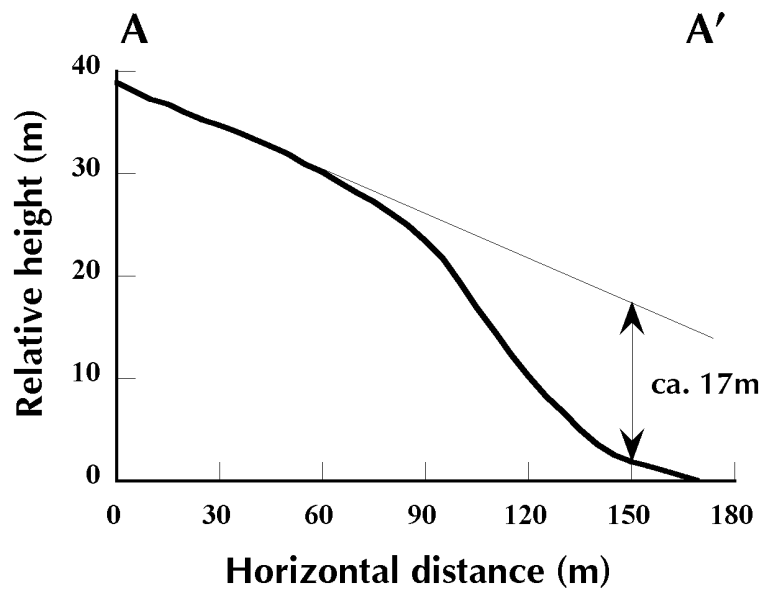


Fig. 7 Topographic profile surveyed in the field showing ca. 17 m vertical displacement of Q2 terrace by the newly discovered fault. Location of profile is shown in Fig. 5.



Fig. 8 Photo of faulted ridge at y in Fig. 4, looking north. Arrow shows position of fault. Left-lateral slip and downfaulting of eastern block are evident.

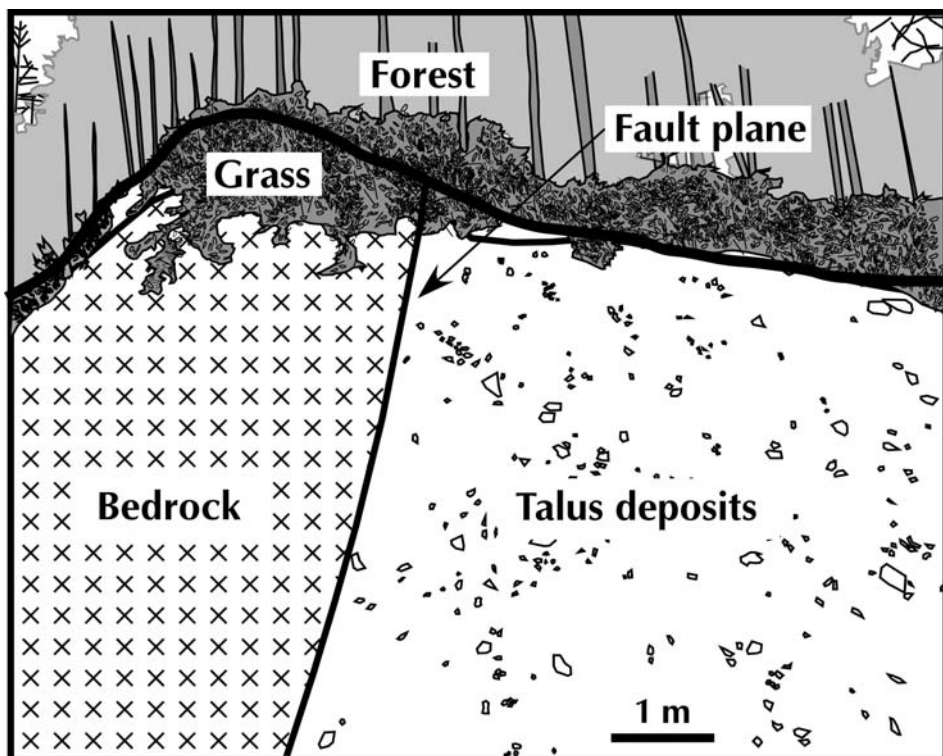


Fig. 9 Sketch of fault outcrop observed at x in Fig. 4, showing nearly vertical fault plane.

C class (0.01 to 0.1 m / 1000 yr). Class A faults are relatively few and regarded as very active. The slip rate of the newly discovered fault corresponds to the border between A and B classes, indicating that the fault has relatively high movement among Japanese active faults.

Although the displaced topographic features in Fig. 4 are located at various altitudes and their maximum height difference is about 850 m, the fault trace is linear, indicating a nearly vertical slip plane. This inference is consistent with the observed dip of the fault plane at the outcrop (Fig. 9).

Geomorphological and paleoenvironmental implications of the fault

Discovery of the fault provides some new insights into tectonic geomorphology of the Northern Japanese Alps. The northern end of the fault (X' in Fig. 2) seems to converge into the Jyonendake Fault (X-X'-Y-Y'-Y" in Fig. 2) which already has been described by the RGAFJ (1991). Ito (1983) and Oguchi (1990) noted that the highest river-terrace surface in the region (Q1 surface in Oguchi, 1996) was displaced by the Jyonendake Fault (Y'-Y" in Fig. 2), but lower surfaces including Q2 and Q3 were not clearly displaced. The gravel of Q1 terrace is almost directly overlain by the A-Pm tephra (Ito, 1983), indicating that the terrace formed around 300 to 350 ka BP. Because the Q2 terrace formed around 50 ka BP, the Y'-Y" segment of the fault must have been active at some time between 50 and 350 ka, although it has been inactive at least since ca. 50 ka.

The shaded relief image in Fig. 2 shows another clear lineament (Y-Z) near the southern end of the Jyonendake Fault. This lineament converges with the Jyonendake Fault at location Y, and its strike is similar to that of the Jyonendake Fault north of the convergence. The lineament is probably older than the segment of the Jyonendake Fault between locations Y and Y", because terrace surfaces to the south of location Z were not displaced. These observations indicate that the activity along the fault south of location X' shifted from east to west in the following order: X'-Y-Z, X'-Y-Y" and X'-X". Accordingly, the newly discovered fault can be regarded as a currently active segment or branch of the Jyonendake Fault.

The RGAFJ (1991) suggested that the slip rate of the Jyonendake Fault lies between Classes B and C. However, this study has revealed that the current southern branch of the fault has a higher rate, which may reach Class A. Furthermore, the fault branch has a high horizontal slip rate, although the RGAFJ (1991) notes that the Jyonendake Fault induced only vertical displacement. The area in and around the Japanese Alps is under the compressive stress of WNW-ESE direction (Tsukahara and Ikeda, 1991; Nakagawa et al., 2001). Because this stress can cause left-lateral slip of N-S oriented faults, the lateral slip of the southern part of the Jyonendake Fault can be attributed to regional tectonism. The vertical slip of the fault may reflect rapid granite intrusion beneath the western block (Harayama, 1992).

The discovery of the fault in the catchment of the Karasu River also forces revision of glacial chronology along the upper reach. Ito (1983) suggested that fluvial terraces of ca. 100 ka widely occur in the upper reach of the river, whereas, terraces of ca. 50 ka (Q2) and younger ones are dominant in the lower reach. He also suggested that glaciers developed in cirques near the top of the range around 100 ka, because the 100-ka terraces are topographically continuous to a theater-headed

valley in the uppermost reach (Figs. 4 and 6). Although Momose et al. (1984) and Oguchi (1988) cast doubt on the existence of wide 100-ka terraces, Ito's (1983) correlation and glacial chronology have been used in later studies (e.g., Sakaguchi, 1988; Ono, 1990; Hasegawa, 1996). Most of the 100-ka terraces identified by Ito (1983) occur only in areas upstream from the newly discovered fault, however, and the boundary of 100-ka and Q2 terraces suggested by Ito (1983) is located where the terraces are displaced by the fault. These observations indicate that Ito (1983) misinterpreted the fault scarp as a terrace scarp. Consequently, Ito's (1983) 100-ka terraces should be reclassified as Q2 terraces formed around 50 ka, and his glacial chronology needs to be revised. Moreover, it remains undetermined whether the theater-headed valley is a glacial cirque (Momose et al., 1984).

Conclusions

DEM-based hill shading has led to the discovery of an active fault in the Japanese Alps, which had not been found by conventional airphoto interpretation. Only unconventional illumination could reveal the existence of the fault-related lineament. The fault discovery has provided new insights into not only regional tectonics but also river-terrace correlation and Pleistocene glacial chronology. We conclude that creation and careful interpretation of shaded-relief images can contribute significantly to solving various problems in geomorphology and tectonics.

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