

Micro-sheeting of granite and its relationship with landsliding specifically after the heavy rainstorm in June 1999, Hiroshima Prefecture, Japan

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Abstract

Certain types of granite in mountainous areas are microscopically sheeted to a depth of 50 m due to unloading under the stress field that reflects slope morphology. Micro-sheets generally strike parallel to major slope surfaces and gently dip downslope, forming cataclinal over-dip slopes. The cataclinal over-dip slope accelerates creep movement of micro-sheeted granite, which in turn loosens and disintegrates granite via the widening or neoformation of cracks, probably in combination with stress release, temperature change, and changes in water content near the ground surface. The surface portion of micro-sheeted granite is thus loosened with a well-defined basal front, which finally slides in response to heavy rain. Innumerable landslides of this type occurred in Hiroshima Prefecture, western Japan, following the heavy rainstorm of 29 June 1999. Following such landslides, the weathering of micro-sheeted granite exposed on the landslide scar recommences, setting the stage for future landslide. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Granite; Weathering; Sheeting joint; Micro-sheeting; Landslide; Rainstorm

1. Introduction

Granitic rocks commonly weather to as deep as 10–30 m, and innumerable slides in weathered granites have been documented in tropical and humid regions, resulting in great numbers of casualties. For example, Japan has sustained many recurring disasters in granitic areas following heavy rains, resulting in a total of more than 1000 casualties over the last 62 years, including 20 in Hiroshima City, in Hiroshima Prefecture in 1999 (Fig. 1). In the granite and gneiss areas of Rio de Janeiro in 1966 and 1967, severe rainstorms resulted in tens of thousands of landslides and

about 1000 casualties (Durgin, 1977). Southern Italy also has suffered from landslides in weathered granite (Calcaterra et al., 1996). Granitic rocks are known to be very sensitive to weathering and are vulnerable to landsliding; an exception are the granites of North America and Europe, which are not generally associated with landslides, because most of the weathered granites on these continents have been eroded by glaciation.

Weathering of granitic rocks has been studied by many researchers from a variety of disciplines, such as engineering geology, mineralogy, geochemistry, and geomorphology (Moye, 1955; Ruxton and Berry, 1957; Dearman, 1974; Kimiya, 1975, 1981; Gilkes and Suddhiprakarn, 1979; Pye et al., 1984; Ollier, 1984; Murphy et al., 1998; White et al., 1998). However, following the studies of Ruxton

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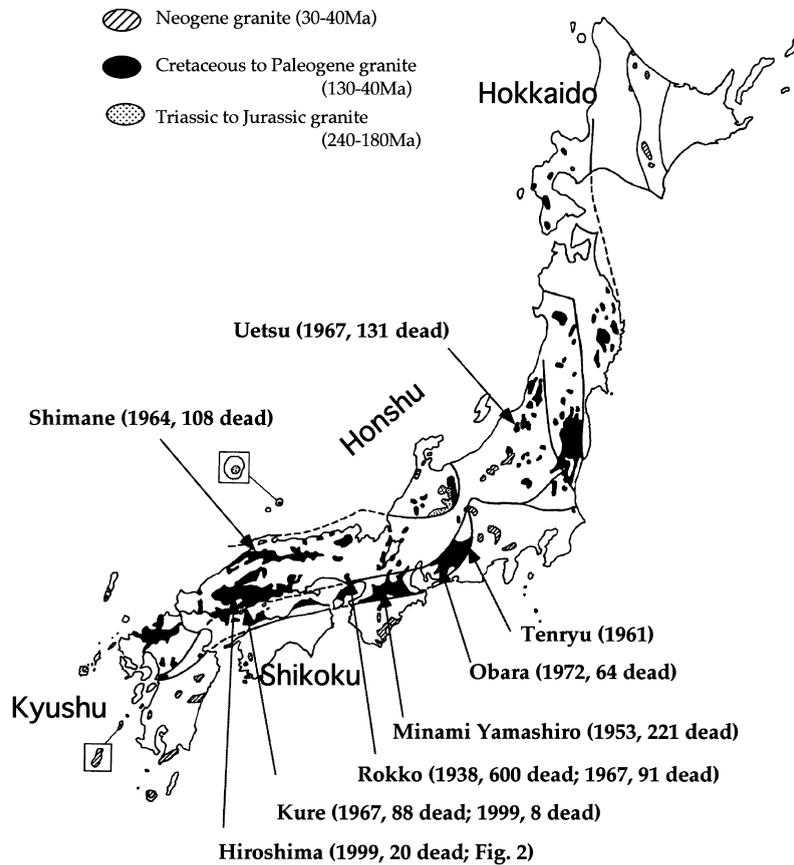


Fig. 1. Landslide disasters caused by heavy rain in granitic areas in Japan.

and Berry (1957) and Kimiya (1981), there has been insufficient investigation into weathering profiles, which are essential in terms of slope stability because they determine both the water infiltration behavior and the distribution of the strength of materials underground. The typical weathering profile of granite in subtropical climate consists of decomposed granite with core-stones in the lower part and saprolite in the upper part (Ruxton and Berry, 1957). The core-stones are formed by spheroidal weathering (Ollier, 1967). If decomposed granite is removed from core-stones, tors are left (Linton, 1955). Another type of weathering profile, which is not as commonly seen as that above, consists of saprolite in the upper part and a zone of micro-sheeting in the lower part (Hashikawa and Miyahara, 1977; Hashikawa, 1978; Folk and Patton, 1982). Micro-sheets, previously called laminations (Twidale, 1971), are thought to be made by

buttressed expansion due to unloading or a number of other factors (Folk and Patton, 1982).

Several studies on rainstorm-related disasters have indicated that shallow landslides in granitic areas are closely related to weakly weathered decomposed granite, rather than to heavily weathered saprolite. Thus Oyagi (1968) reported that numerous shallow landslides occurred in areas of weakly weathered granite after a rainstorm in Shimane Prefecture, western Japan, in 1964. Durgin (1977) also discussed the relationship between the weathering stages of granite and the occurrence of landslides, and pointed out that shallow landslides or debris avalanches occur preferentially in decomposed, weakly weathered granitic areas. Iida and Okunishi (1979) and later Onda (1992) studied weathering profiles of granite underlying Obara Village, Aichi Prefecture, central Japan, where innumerable disastrous landslides

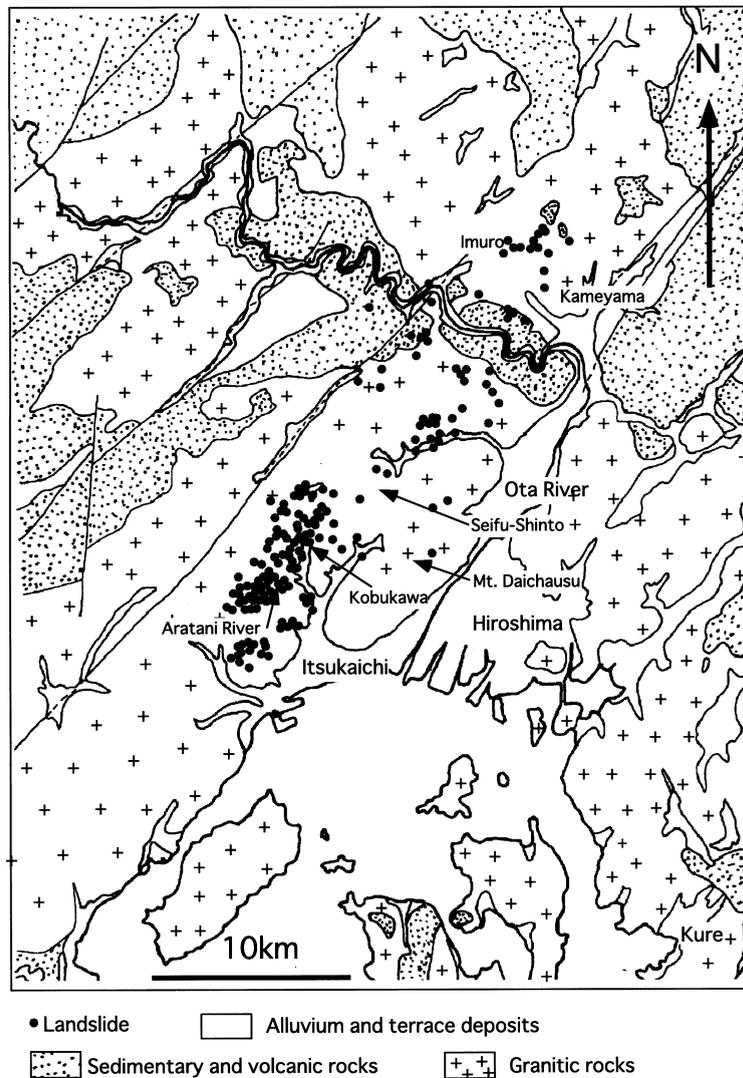


Fig. 2. Geologic map and the distribution of landslides in and around Hiroshima City (Yamada et al., 1986; Kaibori et al., 1999).

occurred following a heavy rainstorm in 1972. They found that the weathering front of the granite was abrupt and that water could collect among the loose surface rock, and they attributed the disastrous generation of landslides to these structural and hydrological features. Chigira and Ito (1999) studied reweathering of weathered granite on artificial cut slopes and found that, after artificial cutting, some weakly weathered granite could be reweathered quickly (i.e. over approximately 12 years) to a depth of as much as 1 m with a clearly-defined front due to

primarily physical disintegration. Although the above studies on the weathering profiles of granite did not find distinct micro-sheeting, the landslides occurring in Hiroshima Prefecture in June 1999 were closely related to micro-sheeting.

2. Landslides and rainfall in June 1999

Rainfall during the time of the June 1999 landslide disaster has been summarized by Ushiyama et al.

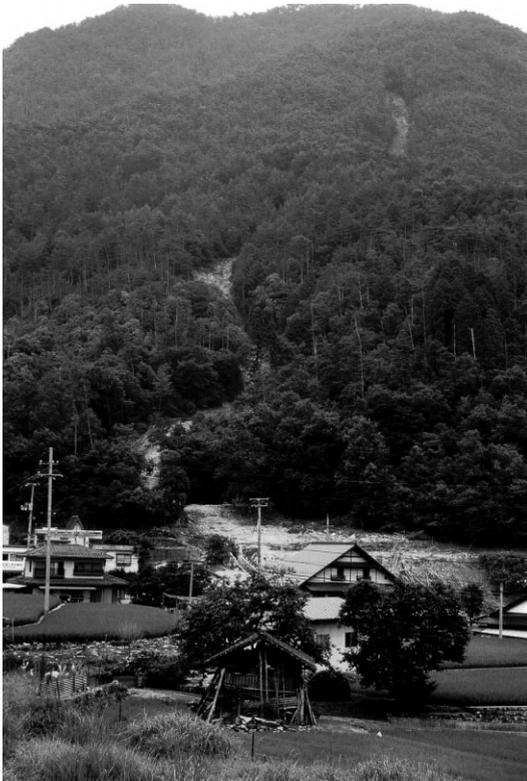


Fig. 3. Typical landslide on 29 June 1999.

(1999). Precipitation in Hiroshima City from 1–28 June was 310 mm, a value approximately equal to or slightly less than that in normal years. The rains began on the dawn of 29 June, then became heavier, with a maximum intensity of more than 50 mm/h between 2:00 and 5:00 p.m. of the same day. Cumulative precipitation on 29 June reached about 250 mm.

The Government of Hiroshima Prefecture (1999) announced that 139 debris flows and 181 landslides had occurred, but these numbers did not include landslides that occurred away from residential and indus-

trial areas or farms. Most debris flows consisted of fluidized materials that had transformed from slides on slopes, rather than the transportation of sediments from valley bottoms. Landslides took place in dense patterns within an elongate zone with a long axis trending NE–SW, which coincided with the zone of heavy rain of 50–70 mm/h from 3:00 to 5:00 p.m. (Fig. 2; Kaibori et al., 1999). Most of the landslides also occurred over this time interval, as determined from the government's data on telephoned requests for help. The individual landslides were relatively small, with lengths and widths of about 10–50 m and depths of only a few meters. The area in which landslides occurred most densely was Itsukaichi Town in western Hiroshima City, where about 24 landslides took place in an area of 1 km². Debris generated by a shallow landslide rushed down streams for a distance of as much as 1 km and struck residential houses in many locations (Fig. 3).

Hiroshima Prefecture had sustained several rain-storm disasters prior to 1999, including storms on September 1945, July 1967, and July 1988 (Table 1). In all of these cases, the major disasters resulting from these rainstorms were due to landslides that occurred on weathered granite slopes.

3. Geological setting

Central Hiroshima City is on the delta of the Ota River surrounded by mountains, ranging in elevation from 300 to 700 m. The low-relief mountain tops to the west of Hiroshima City, 500–700 m high, are thought to correspond to the Kibi–Kogen Surface formed in the late Miocene to Pleistocene (Takahashi, 1991).

Most of the land area of the cities of Hiroshima and Kure is underlain by Cretaceous granitic rocks

Table 1
Previous disasters by heavy rain in Hiroshima Prefecture (Government of Hiroshima Prefecture, 1999)

Time	Total precipitation (mm)	Duration (hrs)	Hourly maximum intensity (mm/hr)	Casualty
September 1945	218.7	32	57.1	1154
July 1967	317	72	74.7	88
July 1988	264	16	57	14
July 1999	255	18	63	31

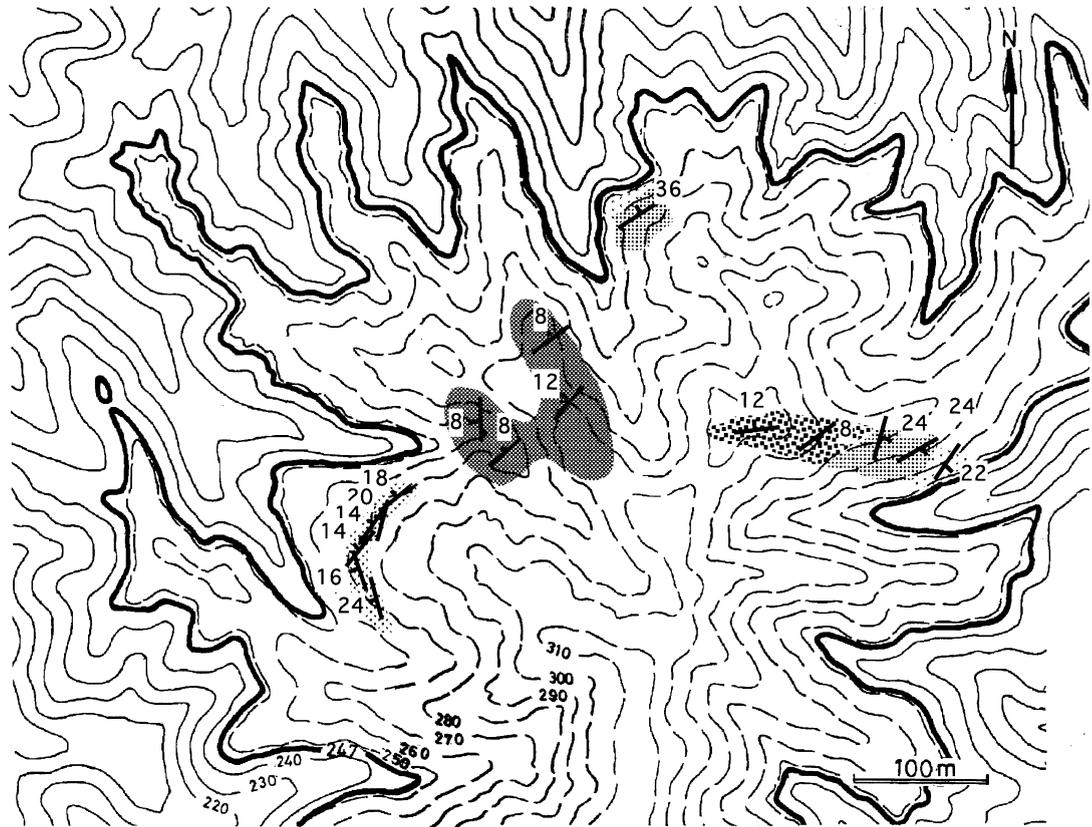


Fig. 4. Distribution of the attitudes of joints and micro-joints on a flat level 247 m (Seifu–Shinto). Roman numerals in the legend correspond to weathering grades proposed by Moye (1955) and Anonymous (1995). Grade II: slightly weathered; III: moderately weathered; IV: highly weathered; V: completely weathered. Arabic numbers are dips of sheeting or micro-sheeting joints.

consisting of medium- to coarse-grained and fine-grained granites, collectively referred to as the Hiroshima Granites (Fig. 2; Yamada et al., 1986). The fine-grained granite is resistant to weathering and forms the upper regions of the mountains. The medium- to coarse-grained granite consists mainly of quartz, orthoclase, plagioclase, and biotite, sometimes with hornblende. It is massive and equigranular to porphyritic: large quartz grains up to 1 cm in diameter are contained as “phenocrysts” and are not connected to each other to form a framework. Orthoclase and plagioclase are contained as grains of a few to 10 mm in diameter, and biotite as grains of less than a few millimeters. Apatite is included as an accessory mineral. Fine-grained granite is massive and equigranular, and rarely porphyritic. Its main constituents are quartz, orthoclase, plagioclase, and biotite, and each

grain is less than a few millimeters in size. The Hiroshima Granites consist of mostly sensu-stricto granite in modal compositions. Permian to Jurassic sedimentary rocks are distributed locally in northern Hiroshima City and are exposed to contact metamorphism by the Hiroshima Granites.

4. Micro-sheeting

4.1. Occurrence of micro-sheeting

The most common type of landslide triggered by the 1999 rainstorm consisted of loosened, medium to coarse-grained granite with dense, low-angle micro-joints, which have similar textural features and are identified as micro-sheeting joints as stated below. This

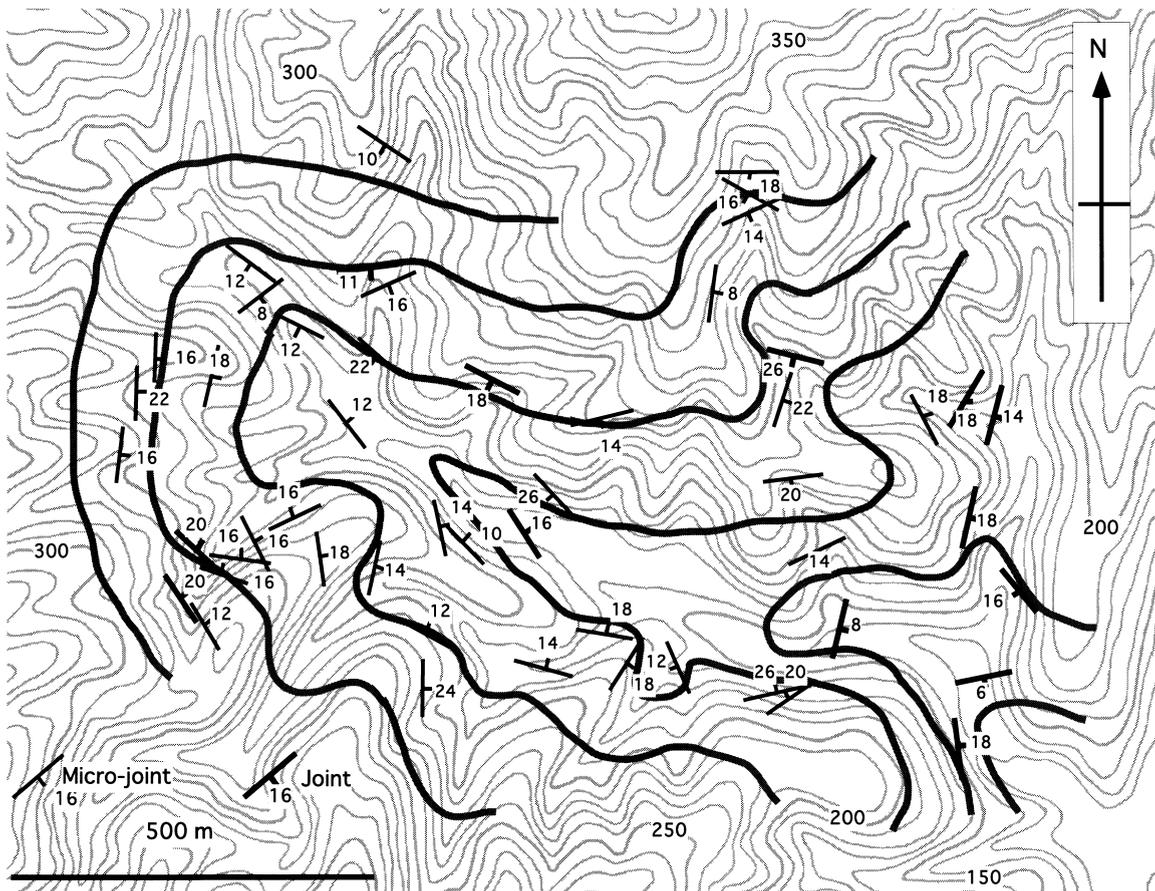


Fig. 5. Attitudes of low-angle joints and micro-joints in the watershed of the Aratani River.

section describes the occurrence of low-angle micro-joints in three areas in Hiroshima City: Seifu–Shinto, the Aratani River, and Mt. Daichausu (Fig. 2).

4.1.1. Seifu–Shinto

An excavation was made to develop residential area west of Hiroshima City by removing the upper portion of a mountain from its peak elevation of 300 m down to a level of about 256 m. Consequently, a flat cut surface with an area of 400,000 m² was made, with low-angle major and micro-joints readily observable. Fig. 4 shows the distribution of rock exposure and the attitudes of the low-angle joints within granite at the excavation surface. Around the center of the mountain, where about 35 m of overburden was removed, low-angle joints trending NE could be observed, roughly parallel to the strike of the previous slope

surface, and dipping about 10 degrees downslope. The joints were developed in granite showing grade II (slightly weathered) to III (moderately weathered) weathering according to the scale of Moye (1955) and Anonymous (1995), at intervals of 5 to as many as 100 cm. On the other hand, granitic rock masses close to the previous slope surfaces were of weathering grade IV (highly weathered) to V (completely weathered) and had low-angle, densely developed micro-joints. The micro-joints struck parallel to the nearby slope surfaces and dipped gently from 15 to 35 degrees downslope. This parallelism was observable at three locations within the excavated surface, where each slope dipped toward W, NW, and SE, respectively. Particularly, in the southwest of the surface, the strike trace of low-angle micro-joints curved so as to follow the contour lines of the slope surface

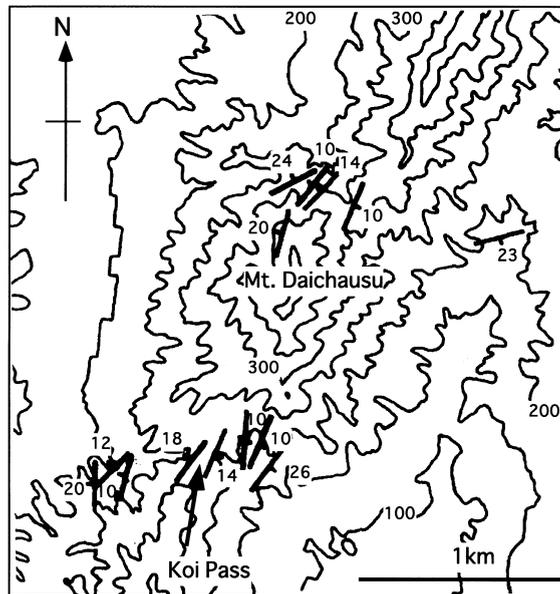


Fig. 6. Attitudes of micro-sheeting near Mt. Daichausu.

(Fig. 4). This consistent relationship between low-angle joints or micro-joints and slopes strongly suggests that these joints were made under the influence of slope morphology.

4.1.2. The Aratani River

The landslides of June 1999 stripped vegetation cover from the mountain slopes, exposing underlying micro-joints in granite. In the watershed of the Aratani River west of Hiroshima City, 32 landslides were surveyed and 25 landslides were recognized to have low-angle micro-joints in the granite of their landslide scars, as shown in Fig. 9. The scars of the other seven landslides were made within debris. The micro-joints struck nearly parallel to major slope surfaces, disregarding small dells less than 100 m wide (Fig. 5). The dips of the micro-joints were 10 to 25 degrees down-slope. In addition, the strikes of the micro-joints could be smoothly connected to form strike traces. This geometrical situation of low-angle micro-joints was observed over an area of 1.5 km². The micro-joints appeared at higher elevations in the slopes, while low-angle joints with larger intervals of 10–100 cm appeared along the river bottom. These widely spaced joints dipped downstream at the central part of the

river, and those joints at the sides of the river dipped toward the river.

4.1.3. Mt. Daichausu

Densely-developed low-angle micro-joints were well observed along two roads crossing the NNE-trending ridge of Mt. Daichausu in western Hiroshima City (Fig. 6). The micro-joints struck roughly parallel to the ridge trend and dipped to the east on the east-side slopes of the ridge and to the west on the west-side slopes. Their dips ranged from 10 to 25 degrees. These geometrical features indicated that these micro-joints were micro-sheeting.

4.2. Origin of the low-angle micro-joints

Parallelism between the strikes of low-angle joints, widely-spaced or densely-developed, and major slopes has been recognized in three areas in Hiroshima City as stated above, irrespective of the slope directions. In addition, this relationship was observed in three dimensions and was not a function of the shape of granitic rock bodies or foliations. These facts strongly suggest that these joints were not made tectonically, but rather that they were made by unloading under the stress field that reflected



Fig. 7. Typical occurrence of micro-sheeting in a cut slope at Seifu-Shinto. The micro-joints strike parallel to the cut slope and dip downslope.

slope morphology. In other words, the micro-joints were micro-sheeting and the major joints sheeting. Hashikawa and Miyahara (1977) and Hashikawa (1978) recognized these micro-joints in the Chugoku region, including Hiroshima Prefecture, and suggested that they were formed by unloading and would destabilize slopes. However, their data were mainly based on observations in exploratory adits for the investigation of dam foundations; the directions of micro-joints were shown and discussed on two-dimensional vertical cross sections. Due to insufficient data on the microscopic characteristics and three-dimensional distribution of the micro-joints, the question of whether or not they are of tectonic origin has previously been a subject of controversy. Folk and Patton (1982) described nearly horizontal micro-joints in Texas and proposed that they were formed by unloading and buttressed expansion; however, the origin of the Texas micro-joints also remains to be clarified.

Micro-joints, which are identified as micro-sheeting from their geometrical relationship with nearby slopes, have common structural characteristics. To the naked eye, they appear as parallel planar cracks 5–30 cm long at intervals of 2 mm–1 cm (Fig. 7). However, under the microscope it can be seen that they are not planar cracks in the strictest sense. That is, they are not sharp, planar cracks, but rather are undulate, jagged, and anastomose in a complex manner (Fig. 8). They frequently occur along grain boundaries, cleavages of biotite and plagioclase, lamellae of perthite, and microcracks within quartz. Their apertures vary in size from place to place but principally are free from filling materials. Fig. 8 shows micro-joints with a maximum aperture of 1 mm spaced at about 5 mm intervals. Granite containing such micro-joints is severely deteriorated and cannot be sampled without using an impregnating fluid resin. However, the constituent minerals of these granites have not been altered except for slight discoloration of biotite. Based on these features, the conclusion is that micro-sheeted granite, and particularly loosened micro-sheeted granite, is highly permeable. Along high-angle existing joints, if they exist, micro-sheeting sometimes curves and becomes parallel to the joints locally. The opening of microcracks obviously has occurred near the ground surface under a small overburden.

5. Landslide and micro-sheeting

As explained above, thorough geological surveys of each landslide in the watershed of the Aratani River have shown that the 1999 landslides occurred essentially or exclusively on slopes characterized by micro-sheeting. Fig. 9 shows the distribution of landslides and strike traces of micro-sheeting, indicating that, without exception, the dip direction of a slope embracing a landslide had a component in the dip direction of micro-sheeting. The micro-joints exposed on the landslide scars were almost without conspicuous openings, and the rock masses there are generally tight, even though they can be easily broken by the strike of a hammer (weathering grade of IV). On the other hand, the slide materials were mainly coarse-grained sand and almost free from rock fragments of gravel size, suggesting that the materials that slid had

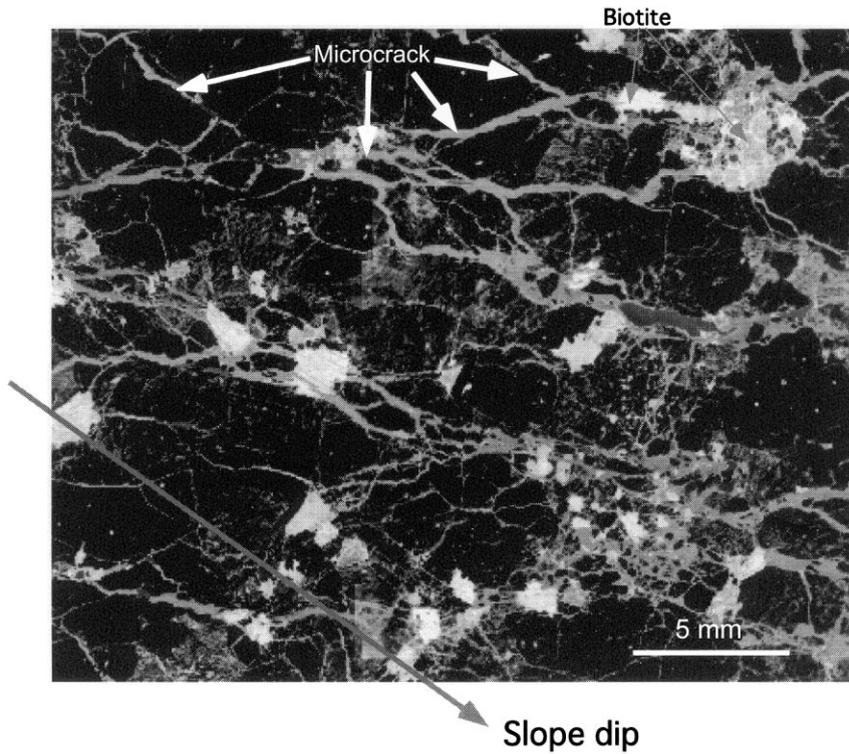


Fig. 8. Micro-sheeting in a vertical cross section under the microscope. An oriented thin section was made by impregnating a pink fluid resin into the rock in the field, and cutting and polishing in the laboratory. This photograph was made by reversing the brightness of a photomicrograph under plane-polarized light.

already been separated from the intact underlying rock mass before the landslide. Landslides took place on slopes of low elevations, up to 320 m, with no landslide occurring at a higher elevation. This difference was due in part to a difference in slope inclination: the inclination was 35–40 degrees at the lower elevations near stream beds and was 15–20 degrees at higher elevations. However, this inclination difference, in turn, seems to reflect differences in the properties of the rocks: granite is more intensively weathered at higher than at lower elevations; in the former case, intensively weathered granite forms saprolite with obscured micro-sheeting and can be observed in sporadic roadcut outcrops.

Micro-sheeting results in slopes of unstable structure, which, combined with mechanical disintegration of micro-sheets, leads to landsliding, as shown schematically in Fig. 10. Micro-sheeting generally dips

10–30 degrees downslope to form an overdip cataclinal slope, as described by Cruden (1989), which is a favorable structure for the rock mass to creep, as is frequently observed in densely foliated schists or laminite (Chigira, 1992). In addition, cracks in micro-sheeting and other related microcracks widen and increase in number due to stress release, temperature change, changes in water content near the ground surface, and creep movement. Alteration and expansion of biotite may also accelerate this disintegration process (Wahrhaftig, 1965; Isherwood and Street, 1976; Tassell and Grant, 1980; Hill, 1996). Although the precise factors affecting this disintegration process are not well understood, field observations indicate that this process extends to a depth of a few meters from the ground surface when a slope inclines some 40 degrees. The extent of disintegration seems to abruptly change at the base of a loosened zone,

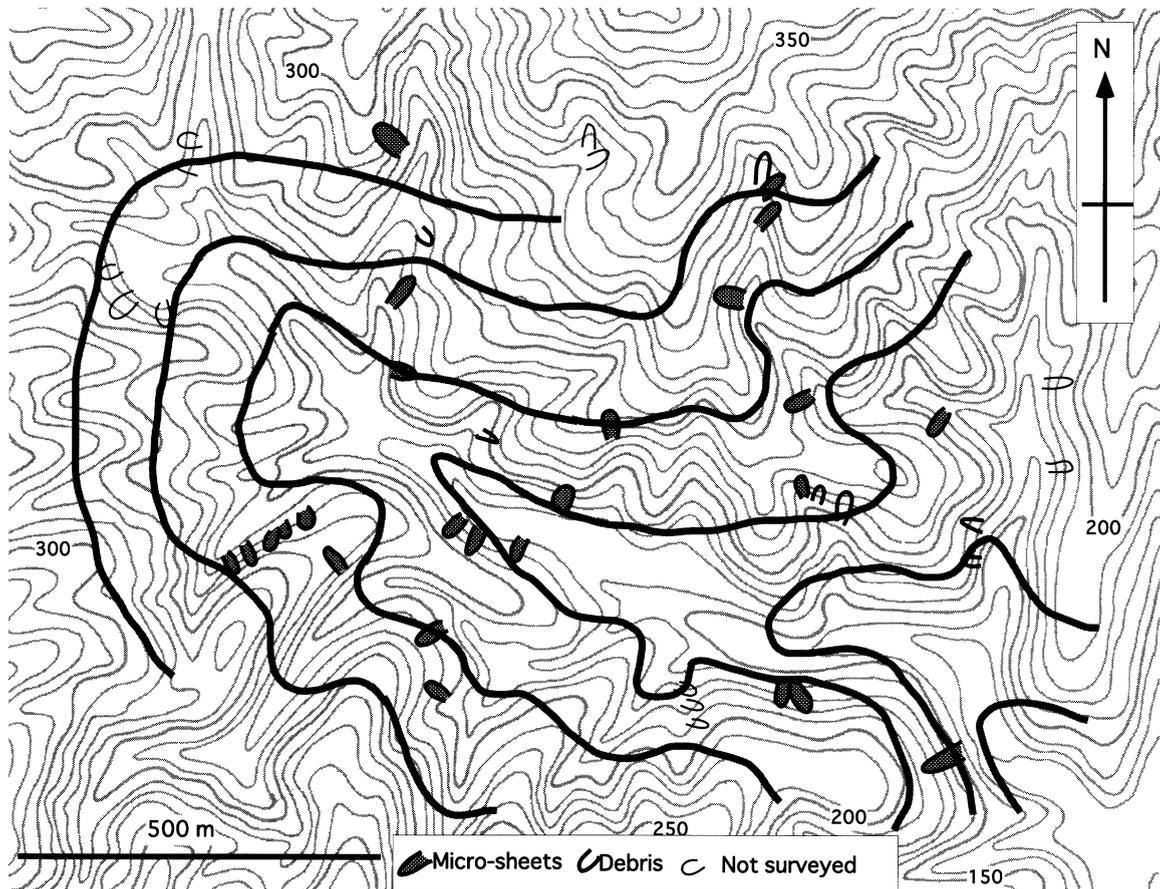


Fig. 9. Landslide distribution and the strike traces of micro-sheeting in the watershed of the Aratani River.

probably due to the fact that creep and widening, as well as neoformation of microcracks, occurs interconnectedly. In other words, microcrack increase accelerates creep movement and vice versa, both resulting in disintegration of micro-sheets. Thus, loosened granite increases in thickness and partly changes into debris, which finally slides as a result of heavy rainfall, exposing the micro-sheeted tight granite at the base of landslide scars.

The relationship between the slopes and the sheeting or micro-sheeting in the Aratani River watershed indicates that the slopes developed under the control of sheeting and micro-sheeting. As mentioned above, all slopes in this watershed have a dip component in the dip direction of micro-sheeting, and no slopes dip in the opposite direction. This relationship strongly

suggests that the outline of the landform in the watershed is determined by the geometrical arrangement of the major streams toward which the sheeting and micro-sheeting dip. The granite body is carved by stream dissection and also by landsliding of loosened micro-sheets at stream walls, which are over-dip cataclinal slopes. At higher elevations, heavily weathered granite, or saprolite, also slides intermittently: saprolite would be destabilized by iterative shallow landslides of micro-sheeted granite in lower elevations and finally slide. Rainfall patterns causing landsliding of loosened micro-sheeted granite are different from those causing landsliding of saprolite. The former landslides are triggered by relatively brief but intense rain. Loosened micro-sheeted granite is highly permeable but forms a thin zone a few meters

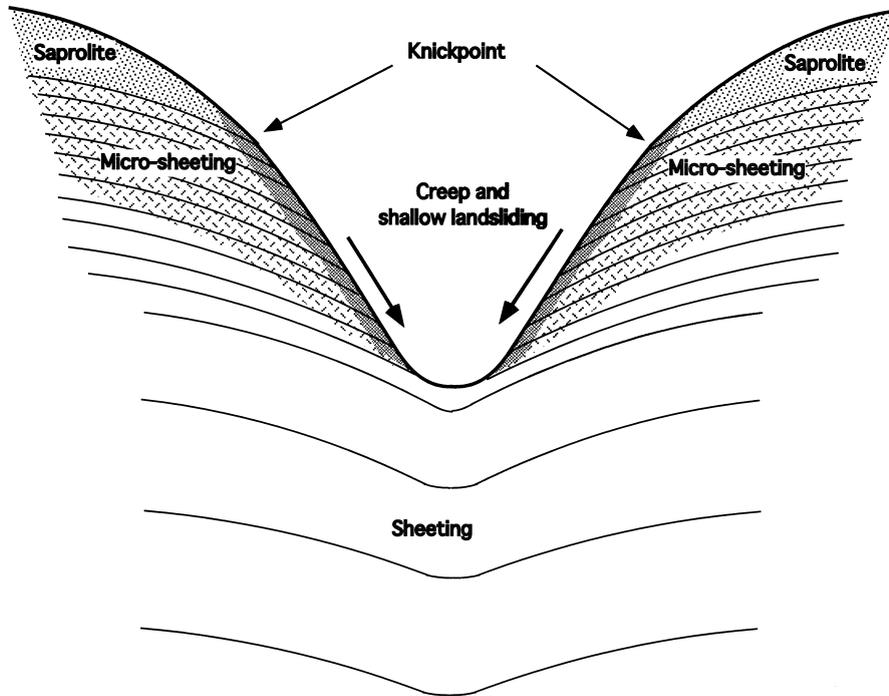


Fig. 10. Schematic sketch showing the development of micro-sheeting and a slope.

thick; thus, it is easily saturated by intense rainfall. Saprolite at higher elevations, on the other hand, is thick and is less permeable because of chemical alteration. Therefore, the volume of rainfall required to trigger a landslide of saprolite would therefore be greater than the volume required to trigger a landslide of loosened micro-sheeted granite, although the rainfall will not necessarily have to be as intense.

6. Conclusions

This study investigated the weathering mechanism of granite in Hiroshima Prefecture, western Japan, where numerous landslides occurred following heavy rain on 29 June 1999. The granite had a unique weathering profile that met the basic requirements for a shallow landslide as follows:

1. Low-angle joints, widely spaced, are formed near stream beds or in the interior of mountains in the study sites, and strike roughly parallel to slope

contours and dip gently downstream or downslope. This occurrence, recognized in wide areas in Hiroshima Prefecture, indicates that they are sheeting joints produced by unloading.

2. Low-angle, parallel micro-joints are densely formed within granite on slopes at the study sites; these micro-joints are parallel to the sheeting joints described above when both types are present. In addition, the strikes of the micro-joints roughly follow slope contours and their dips are toward major streams, indicating that they also have been produced by unloading. This micro-sheeting extends as deep as 50 m beneath the ground surface.
3. Micro-sheets, separated by micro-sheeting, are loosened and disintegrated by widening or neoformation of microcracks. This process is presumably proceeded by stress release, temperature change, changes in water content near the ground surface, and creep movement. The loosening is essentially limited to a few meters beneath the surface, so that permeability and strength change abruptly at the bottom of the loosened zone. The loosened zone

thickens with time and finally slides due to heavy rainfall when it is immediately saturated.

4. The most common type of landslide triggered by the rainstorm of June 1999 was a landslide of loosened, medium- to coarse-grained granite that had dense micro-sheeting.

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References

- Anonymous, 1995. The description and classification of weathered rocks for engineering purposes. *Q. J. Engng. Geol.* 28, 207–242 Geological Society Engineering Group Working Party Report.
- Calcaterra, D., Parise, M., Dattola, L., 1996. Debris flows in deeply weathered granitoids (Serre Massif-Calabria, Southern Italy). In: Senneset, K. (Ed.). *Proceedings, Seventh International Symposium on Landslides*. Balkema, Trondheim, pp. 171–176.
- Chigira, M., 1992. Long-term gravitational deformation of rocks by mass rock creep. *Engng. Geol.* 32, 157–184.
- Chigira, M., Ito, E., 1999. Characteristic weathering profiles as basic causes of shallow landslides. In: Yagi, N., Yamagami, T., Jiang, J.-C. (Eds.). *Slope Stability Engineering*, vol. 2. Balkema, Rotterdam, pp. 1145–1150.
- Cruden, D.M., 1989. Limits to common toppling. *Can. Geotech. J.* 26, 737–742.
- Dearman, W.R., 1974. Weathering classification in the characterisation of rock for engineering purposes in British practice. *Bull. Int. Assoc. Engng. Geol.* 9, 33–42.
- Durgin, P.B., 1977. Landslides and the weathering of granitic rocks. *Geol. Soc. Am., Rev. Engng. Geol.* 3, 127–131.
- Folk, R.L., Patton, E.B., 1982. Buttressed expansion of granite and development of grus in Central Texas. *Z. Geomorph. N. F. Bd.* 26, 17–32.
- Gilkes, R.J., Suddhiprakarn, A., 1979. Biotite alteration in deeply weathered granite, I. Morphological, mineralogical, and chemical properties. *Clays Clay Miner.* 27, 349–360.
- Government of Hiroshima Prefecture, 1999. Quick report on the debris disaster on 29 June 1999. 7 pp. (in Japanese).
- Hashikawa, K., 1978. Weathering structure of the granitic rocks in the dissected pediment. *J. Jpn Soc. Engng. Geol.* 19, 45–59 (in Japanese with English abstract).
- Hashikawa, K., Miyahara, K., 1977. Structure of the weathered granitic rocks and its engineering significance. *J. Jpn Soc. Engng. Geol.* 15, 47–57 (in Japanese with English abstract).
- Hill, S.M., 1996. The differential weathering of granitic rocks in Victoria, Australia. *J. Aust. Geol. Geophys.* 16 (3), 271–276.
- Iida, T., Okunishi, K., 1979. On the slope development caused by the surface landslides. *Geogr. Rev. Jpn* 52, 426–438 (in Japanese with English abstract).
- Isherwood, D., Street, A., 1976. Biotite-induced grossification of the Boulder Creek Granodiorite, Boulder County, Colorado. *Geol. Soc. Am. Bull.* 87, 366–370.
- Kaibori, M., Ishikawa, Y., Ushiyama, M., Kubota, T., Hiramatsu, S., Fujita, M., Miyoshi, I., Yamashita, Y., 1999. Debris flow and slope failure disasters in Hiroshima Prefecture caused by heavy rainfall in June, 1999 (Prompt report). *J. Jpn Soc. Erosion Control Engng.* 52 (3), 34–43 (in Japanese with English abstract).
- Kimiya, K., 1975. Tensile strength as a physical scale of weathering in granitic rocks. *J. Geol. Soc. Jpn* 81, 349–364 (in Japanese with English abstract).
- Kimiya, K., 1981. Distribution of weathering crusts and their formative period in the Mikawa Highland, Central Japan. *J. Geol. Soc. Jpn* 87, 91–102 (in Japanese with English abstract).
- Linton, D.L., 1955. The problem of tors. *Geogr. J.* 121, 470–486.
- Moye, D.G., 1955. Engineering geology for the Snowy Mountain scheme. *J. Inst. Engng. Aust.* 27, 287–298.
- Murphy, S.F., Brantley, S.L., Blum, A.E., White, A., Dong, H., 1998. Chemical weathering in a tropical watershed, Luquillo Mountains, Puerto Rico, II. Rate and mechanism of biotite weathering. *Geochim. Cosmochim. Acta* 62, 227–243.
- Ollier, C., 1967. Spherical weathering, exfoliation and constant volume alteration. *Z. Geomorph.* 11, 103–108.
- Ollier, C., 1984. *Weathering*. 2nd ed. Longman, England.
- Onda, Y., 1992. Influence of water storage capacity in the regolith zone on hydrological characteristics, slope processes, and slope form. *Z. Geomorph. N. F.* 36, 165–178.
- Oyagi, N., 1968. Weathering-zone structure and landslides of the area of granitic rocks in Kamo-Daito, Shimane Prefecture. *Reports of Cooperative Research for Disaster Prevention, National Research Center for Disaster Prevention*, vol. 14, pp. 113–127. (in Japanese with English abstract).
- Pye, K., Goudie, A.S., Thomas, D.S.G., 1984. A Test of petrological control in the development of bornhardts and koppies on the Matopos Batholith, Zimbabwe. *Earth Surf. Process. Landforms* 9, 455–467.
- Ruxton, B.P., Berry, L., 1957. Weathering of granite and associated erosional features in Hong Kong. *Bull. Geol. Soc. Am.* 68, 1263–1292.
- Takahashi, Y., 1991. *Geology of the Hiroshima District*. Quadrangle Series, Scale 1:50,000, *Geol. Surv. Japan*, 41. (in Japanese with English abstract).
- Tassell, J.V., Grant, W.H., 1980. Granite disintegration, Panola Mountain, Georgia. *J. Geol.* 88, 360–364.
- Twidale, C.R., 1971. *Structural Landforms: Landforms Associated with Granitic rocks, Faults and Folded Strata*. MIT Press, Cambridge, Massachusetts.
- Ushiyama, M., Satohuka, Y., Kaibori, M., 1999. Characteristics of heavy rainfall disasters in Hiroshima Prefecture on June 29, 1999. *J. Jpn Soc. Natl. Disaster Sci.* 18, 165–175 (in Japanese with English abstract).

- Wahrhaftig, C., 1965. Stepped topography of the southern Sierra Nevada, California. *Geol. Soc. Am. Bull.* 76, 1165–1190.
- White, A.F., Blum, A.E., Schulz, M.S., Vivit, D.V., Stonestrom, D.A., Larsen, U.S., Murphy, S.F., Eberl, D., 1998. Chemical weathering in a tropical watershed, Luquillo Mountains, Puerto Rico: I. long-term versus short-term weathering fluxes. *Geochim. Cosmochim. Acta* 62, 209–226.
- Yamada, N., Higashimoto, S., Mizuno, K., 1986. 1:200,000 Geological Map of Hiroshima. *Geol. Surv. Japan.* (in Japanese with English abstract).