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# Geological causes and geomorphological precursors of the Tsaoling landslide triggered by the 1999 Chi-Chi earthquake, Taiwan

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**Abstract**

The Tsaoling landslide, one of the largest landslide areas in Taiwan, has been affected by catastrophic events triggered by rain or earthquakes six times since 1862. These landslides, including that caused by the 1999 earthquake, have essentially not been reactivated old slides, but were sequential new ones that developed upslope, retrogressively. The landslide area is underlain by Pliocene sandstone and shale to form a dip slope with a bedding plane, dipping uniformly at 14°. The slip surface of the 1999 landslide was smooth and planar, parallel to the bedding plane with a slightly stepped profile; it formed within thinly alternated beds of fine sandstone and shale with ripple lamination or in a shale bed. The shale is weathered by slaking and probably by sulfuric acid, which is inferred to be one of the major causes of the intermittent retrogressive development of the landslides. The weathering was likely accelerated by the removal of overlying beds during earlier landslides in 1941 and 1942. The top margin of the 1999 landslide, in plan view, coincided with a V-shaped scarplet, which can be clearly recognized on aerial photographs taken before the landslide. This geomorphological feature indicates that this landslide had already moved slightly before its 1999 occurrence, providing precursory evidences.


*Keywords:* Chi-Chi earthquake; Landslide; Rockslide-avalanche; Weathering; Mass rock creep

## 1. Introduction

Landslides on dip slopes have been reported from many countries. In particular, earthquake-triggered rockslides on dip slopes often result in devastating rock avalanches (Heim, 1932; Eisbacher and Clague, 1984; Hermanns and Strecker, 1999; Chigira, 2000) that may move as far as 10 km at a velocity exceeding 200 km/h (Plafker and Ericksen, 1978; Okuda et al., 1985). This type of landslide is referred

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to as sturzstrom (Heim, 1932), rockslide-avalanche (Mudge, 1965), rockslide-debris flow (Cruden and Varnes, 1996), or just rock avalanche (Hungr et al., 2001). Typical historic rockslide-avalanches that have occurred on dip slopes have been found at Frank, a small town in Alberta, Canada, in 1903 (Cruden and Krahn, 1973), in the Gros Ventre Valley of Wyoming, USA in 1925 (Alden, 1928; Voight, 1978), and at Mt. Ontake in Japan in 1984 (Voight et al., 1983; Okuda et al., 1985; Kobayashi, 1987). The dip slopes on which these landslides occur dip more steeply than the bedding planes; in other words, the bedding planes have been laterally undercut. Prehistoric huge landslides, such as at Saidmarreh in Iran (Harrison, 1938; Watson and Wright, 1967) and on the Sawtooth Ridge, MT, USA, (Mudge, 1965) also occurred on dip slopes.

Although dip-slope rockslide-avalanches are well known, the formative mechanism of slip surfaces is usually poorly understood. Also, whether the avalanches were preceded by precursory phenomena or not has not been sufficiently documented, although such information is essential for predicting the occurrence of these avalanches. Knowledge about the geological and geomorphological characteristics of mountains, including the formation of slip surfaces and the deformation of slopes, must be used initially as a way of identifying potential rockslide-avalanche sites. It is not practical to use geophysical methods and drilling for precise monitoring and intensive investigation until we have first extracted potential sites from a wide area. This is particularly important in areas of high seismicity, because a great catastrophe could be generated by an earthquake without any

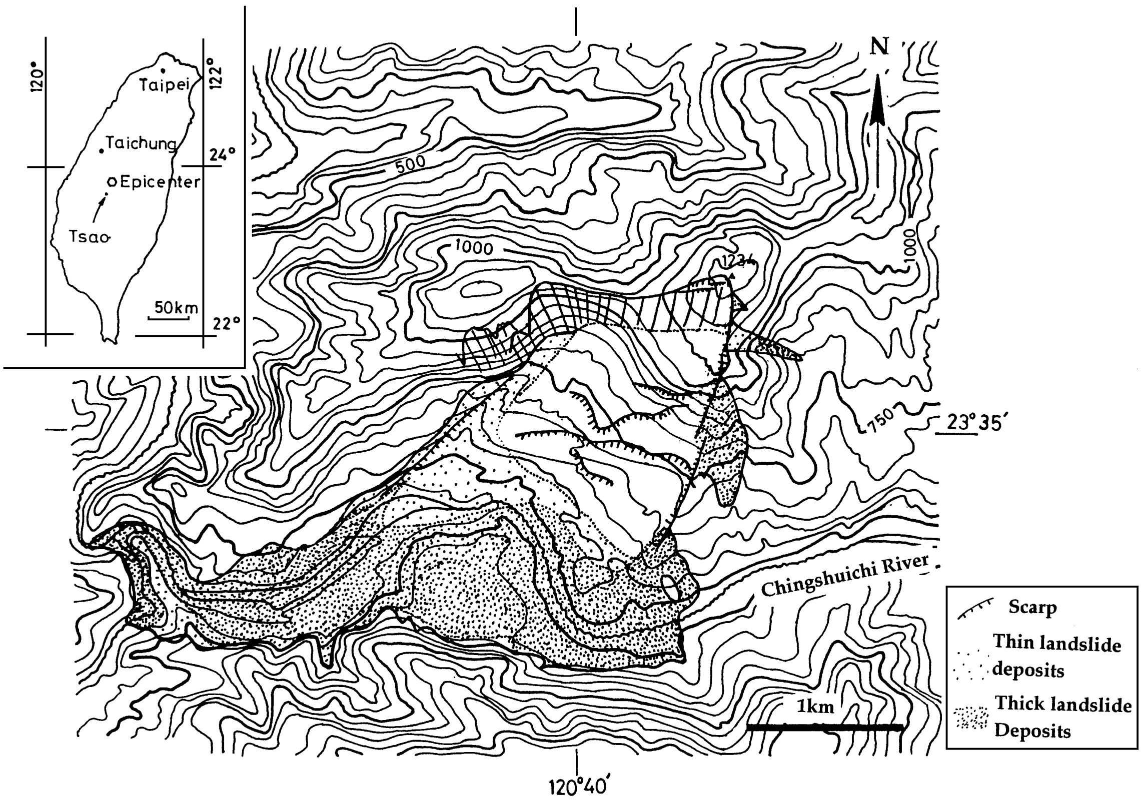


Fig. 1. Location and outline of the 1999 Tsaoling landslide. The base map is "Tsaoling" on a scale of 1:25,000 made by the Combined Service Force, ROC (Taiwan) in 1985.

warning, with the resulting rockslide-avalanche moving very fast and very far.

Gravitational deformation of mountain slopes, known as Sackung (Zishinsky, 1966, 1969), sagging (Varnes et al., 1989; Hutchinson, 1988), or mass rock creep, has been noted as one of the most important precursory phenomena of catastrophic rockslide-avalanches (Voight and Pariseau, 1978; Oyagi et al., 1994; Chigira and Kiho, 1994; Bovis and Evans, 1996; Chigira, 2000). However, there are many types of movement in the gravitational deformation of mountains, as suggested by Hutchinson (1988), and some may be the precursors of catastrophic landslides, while others are not. We must add to our knowledge of the geological and geomorphological features of catastrophic rockslide-avalanches by studying historical cases, particularly those cases where we can clarify, both before and after the events, what conditions were present.

An earthquake, which became known as the “921-earthquake”, occurred in central Taiwan on the night (01:47 local time) of 21 September 1999. This earthquake has also been called the “Chi-Chi earthquake” because its epicenter was located at 23.85°N, 120.81°E, near Chi-Chi, a small town in central Taiwan. The magnitude was $M_L = 7.3$, as measured by the Central Weather Bureau (CWB, Taiwan), or $M_S = 7.7$, as measured by the U.S. Geological Survey. The focal depth was about 10 km. About 26,000 earthquake-induced slope failures have been identified over an area of 375,000 ha by aerial-photo interpretation (Wang et al., 2000). Two huge rockslide-avalanches were triggered by this earthquake: the Chiu-fen-erh-shan landslide and the Tsaoling landslide (Kamai et al., 2000; Lee, 2000; Furuya, 2001; Fig. 1). The former killed 39 people, and the latter killed 29 people. We focus on the Tsaoling landslide.

The Tsaoling landslide is located in a mountainous area about 30 km southwest of the epicenter (Fig. 1). It has slid five times since 1862; landslides have developed retrogressively upslope from the first occurrence on 6 June 1862 (Kawada, 1942; Huang et al., 1983; Chang, 1984). The history of the Tsaoling landslide is summarized in Table 1. The trigger of the 1862 landslide is not known. Earthquakes triggered the 1941 and 1999 landslides, and rain induced the 1942 and 1979 landslides. Landslide dams were made by these landslides.

Table 1
Landslide history of the Tsaoling landslide area

| Time | Trigger | Note |
|---|---|---|
| 6 June 1862 | Unknown | |
| 17 December 1941 | Earthquake | Slide volume: 100–150 million $m^3$. Landslide dam (70–200 m high). Several scarps formed, of which the highest was at an elevation of 950 m. |
| 10 August 1942 | Rain | Slide volume: 150–200 million $m^3$. Landslide dam (170 m high) formed, which failed on 18 May 1951, killing 147 people. |
| 15 August 1979 | Rain | Slide volume: 5 million $m^3$. Landslide dam formed, which was overtopped on 24 August. Scarp of Chinshui shale was made, and the rock mass downslope of this scarp slid. |
| 21 September 1999 | Chi-Chi earthquake | Slide volume: 125 million $m^3$. Landslide dam was made. |

Data of the 1999 Chi-Chi earthquake is from Lee (2000), and the data of other landslides are from Huang et al. (1983).

The 1999 event clearly divided the landslide into a source area and a deposition area (Figs. 1 and 2). The source area, a triangular to trapezoidal slope convex upslope to the northeast, had a crown at the top of a small mountain with an elevation of 1234 m and a base at elevations of 500–550 m, roughly along the bank of the Chingshuichi River. The size of the source area was 1.6 $km^2$. The maximum thickness of the zone of sliding bed was 180 m, as will be shown in the geologic cross-section later in Fig. 5. The depositional area occupied a valley bottom and the opposite slope, and forming extended upstream and downstream; the deposit buried the river for about 4 km, making a landslide dam (Fig. 2B). The area of deposition was 3.4 $km^2$. The debris volume was estimated to be 125 million $m^3$ (Lee, 2000). The landslide deposits included rock blocks as large as more than 10 m in diameter (Fig. 3A,B) and showed fraction banding, as indicated by the color streaks observed from the air (Fig. 2B). Such banding is very common for large rockslide-avalanches, such as the Mt. Ontake landslide in 1984 in Japan (Inokuchi, 1985). There had been houses

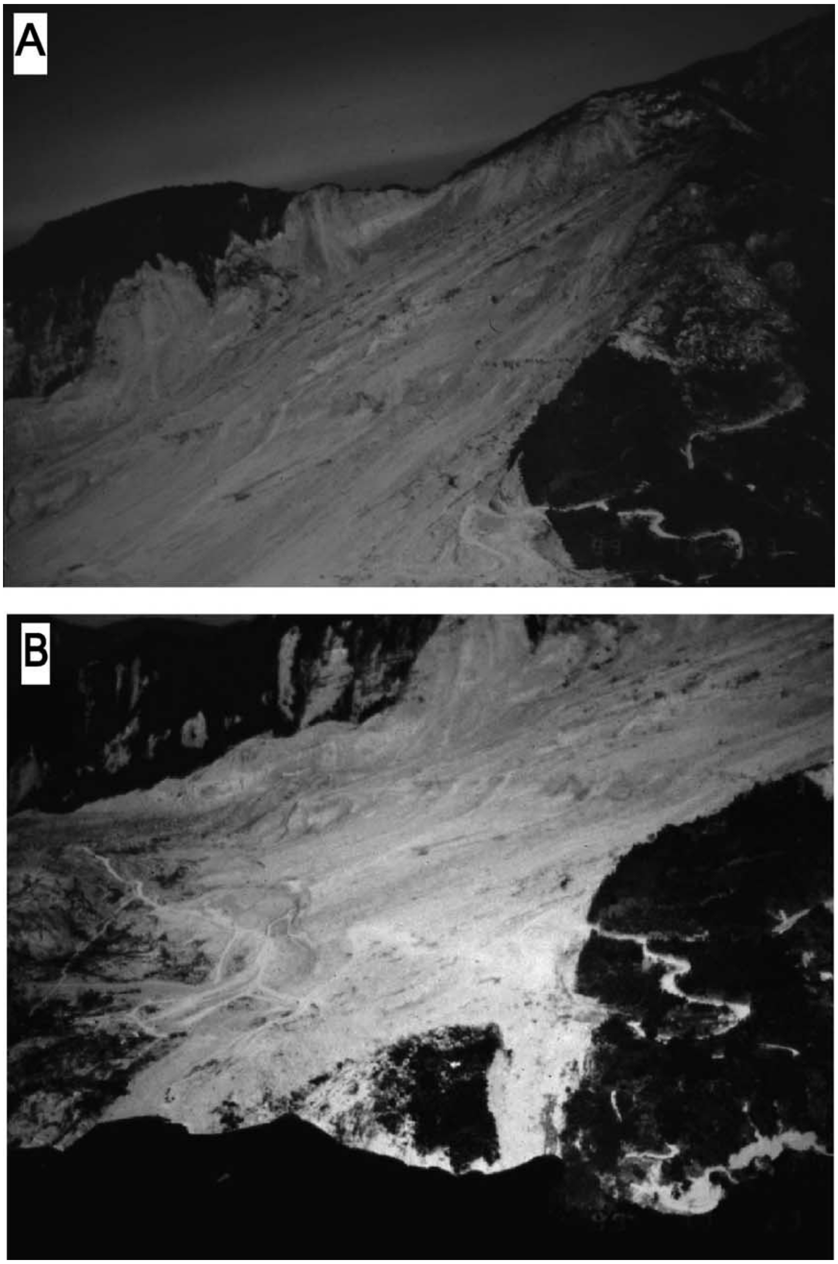


Fig. 2. Overview of the Tsaoling landslide (Photo by Dr. H. Suwa). (A) Source area. (B) Deposition area.

near the 1234-m peak, which moved on the landslide material and were transported to the deposition area. After the landslide, some of the destroyed houses were still on the surface of the deposit without being buried in it.

Just after the landslide of 1999, the landslide scar was mostly buried by debris, but the debris was subsequently washed away and the slip surfaces were widely apparent by March 2000. The slip surfaces are parallel to the bedding plane and are separated into

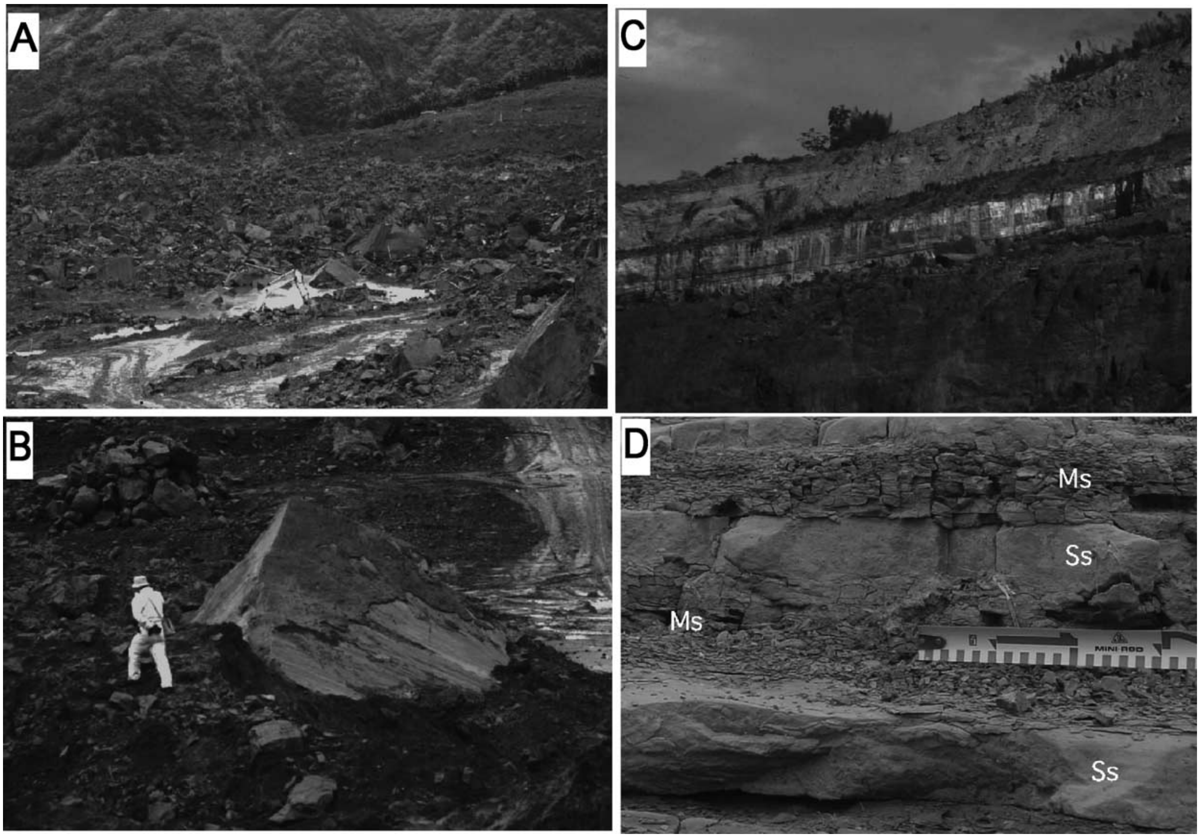


Fig. 3. Deposition and source areas. (A) Debris in the middle of the deposition area. (B) Large rock blocks in the deposits. (C) White sandstone scarp in the middle of the source area. (D) Slaking of the shale intercalated with sandstone of the middle member of the Cholan Formation. The shale is fragmented but sandstone is not.

three parts by two small scarps, as will be described later.

## 2. Geology of the landslide area

### 2.1. Stratigraphy and geological structure

The geologic map before the 1999 event and the cross-section before and after the event are shown in Figs. 4 and 5, in which the formation names, the location of fold axes, and some of the bedding-attitude data are from Huang et al. (1983). The geologic traces within the landslide area were reconstructed on the basis of geological survey after the event. The study area is underlain by the Pliocene Chinshui Shale and Cholan Formation. The Chinshui Shale, thicker than 100 m, consists mainly of massive mudstone and shale, frequently intercalated with fine to very fine-grained sandstone lamina. The upper part of the Chinshui Shale consists of alternating beds of shale and fine to very fine-grained sandstone with ripples. The Cholan Formation, which conformably rests on the Chinshui Shale, is divided into lower (Chl), middle (Chm), and upper (Chu) members. Chl is 25–30 m thick and consists of sandstone with subordinate shale thin beds in its middle part. This sandstone is gray, medium-grained arenite, which is referred to as white sandstone because white precipitates are predominant on its cliff surface within the landslide scar during relatively dry periods (Fig. 3C). Chm, about 130 m thick, consists of alternating beds of sandstone

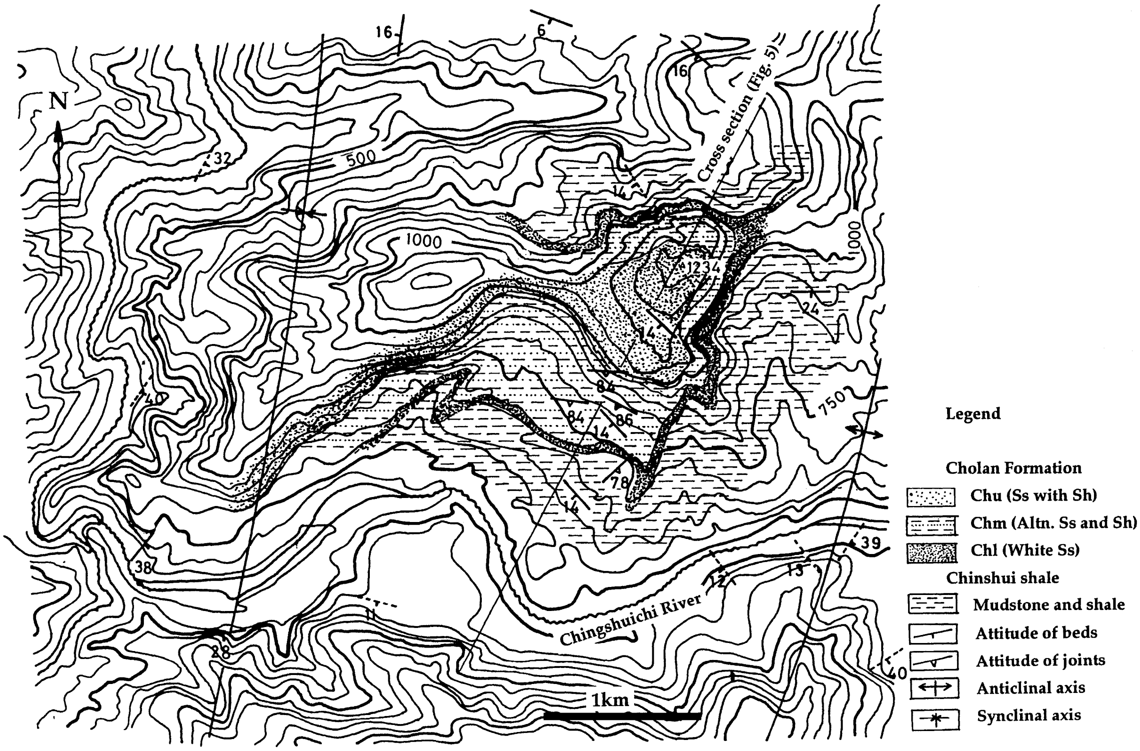


Fig. 4. Geologic map of the Tsaoling landslide area. Locations of the fold axes are from Huang et al. (1983).

and shale with well-developed ripples. Its sandstone is fine-grained, and the shale is a clay shale. The clay shale is prone to disintegration by slaking (Fig. 3D). Chu, thicker than 100 m, consists of bedded sandstone with shale.

The Tsaoling landslide area is located between a NNE-trending synclinal axis to its west and a parallel anticlinal axis to its east (Fig. 4). These axes plunge gently to the south. The attitude (strike/dip) of the strata is N30°–70°E/30°–40°SE on the west limb of the syncline, N40°W/14°SW in the landslide area, and N30°–60°E/40°SE on the east limb of the anticline. The strata in the landslide area are well bedded, and their attitudes are very consistent. The strata between the two axes are continuously observed along an E-trending road 1.5 km north of the landslide area, but no distinct flexural-slip faults were found in the limb, probably because the gentle and planar attitude of the beds. Flexural-slip faults formed slip surfaces in the Chiu-fen-erh-shan landslide (unpublished data), another gigantic landslide in Miocene strata generated by the 1999 earthquake. However, within the Tsaoling landslide area, no faults were observed and also no mappable displacement of beds was detected or inferred.

The strata in the landslide area are moderately jointed. Two joint sets were observed; one trends EW and dips steeply to the south, and the other trends NE and dips steeply to the SE (Fig. 4). The former joints are parallel to the trend of the scarps in the middle of the landslide scar (Fig. 1), while the latter are parallel to the southeastern margin of the landslide (Fig. 1), suggesting that the joints determined the margin of the landslide.

### 2.2. Weathering of the rocks

After the 1999 landslide, the scarp on the white sandstone (Chl) of the Cholan Formation appeared in the middle part of the source area (Figs. 2C and 5).

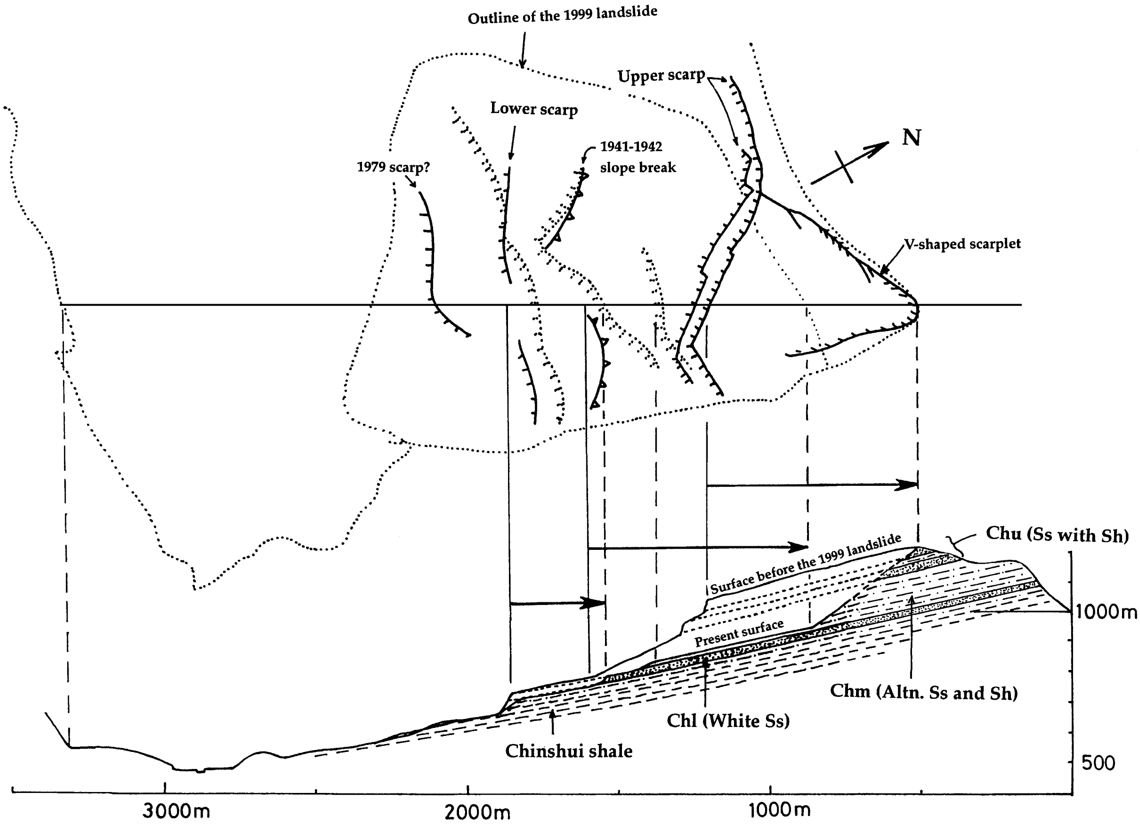


Fig. 5. Geologic cross-section and the locations of scarps and slope breaks within the Tsaoling landslide area. A cross-sectional line is shown in Fig. 4.

The sandstone was thick bedded and conspicuously appeared along a vertical cliff in the middle part of the landslide scar within the horizons of slip surfaces. The vertical cliff of this sandstone was covered with white precipitates of weathering product. The white precipitates were identified by X-ray diffraction as hexahydrite ($MgSO_4 \cdot 6H_2O$), mirabilite ($Na_2SO_4 \cdot 10H_2O$), melanterite ($FeSO_4 \cdot 7H_2O$), gypsum ($CaSO_4 \cdot 2H_2O$), kieserite ($MgSO_4 \cdot H_2O$), and jarosite ($KFe_3^{3+}(SO_4)_2(OH)_6$), which are all sulphate minerals. Among these, hexahydrite dominated the mass. The magnesium probably comes from dolomite, which was identified in the samples from the white sandstone as well as the Chinshui shale. Water issuing out from the white sandstone evaporated, and these minerals precipitated. Sulphate minerals are common as weathering products of pyrite-bearing sedimentary rocks as well as evaporite in deserts (Chigira, 1990; Goudie and Viles, 1997). Although pyrite was scarcely detected by X-ray analysis, it is probably contained in small amounts in these rocks.

Groundwater was discharging from the lower southeastern part of the landslide area after the avalanche. This was sampled on 16 November 2000 and analyzed for its major components by using inductive coupled plasma spectrometry and atomic adsorption analysis. The groundwater was probably from the bottom of the white sandstone of the Cholan Formation on the Chinshui shale, although the discharge point was covered by land-

Table 2
Chemical composition of the groundwater sampled at the Tsaoling landslide area (unit in mmol/l)

| Alkalinity | Ca | Mg | Na | K | Si | $SO_4$ | Al | Mn | Fe | Cl | $NO_3$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 6.3 | 1.61 | 1.04 | 25.23 | 0.42 | 0.23 | 13.22 | ND | ND | ND | 0.07 | 0.08 |

pH: 8.1, EC: 0.295 S/m.

slide debris and could not be specified. Huang et al. (1983) also found groundwater from the white sandstone. The chemical composition of the sampled water is shown in Table 2. This water is classified as having sodium-sulphate type chemistry (Back, 1961), which is commonly observed in the landslide area of sedimentary rocks in Japan (Suda et al., 2001). The sulphate-type groundwater is consistent with the precipitation of sulphate minerals on the white sandstone cliff, and the sulphate is likely due to pyrite oxidation. Iron-stained joints, which were observed to cross the white sandstone from the top of the scarp to its bottom at the cliff, also indicate the occurrence of oxidation.

In addition to chemical weathering, the shale, particularly clay shale alternating with thin sandstone beds, is highly sensitive to slaking (Fig. 3D), which is known because when it is air-dried and immersed in water, it is broken into mud or fragments smaller than 5–10 mm. The shale of the Chinshui shale and Cholan Formation consists of quartz, feldspar, illite, kaolinite, and a small amount of smectite with or without calcite and dolomite. Pyrite was not detected by X-ray diffraction analysis.

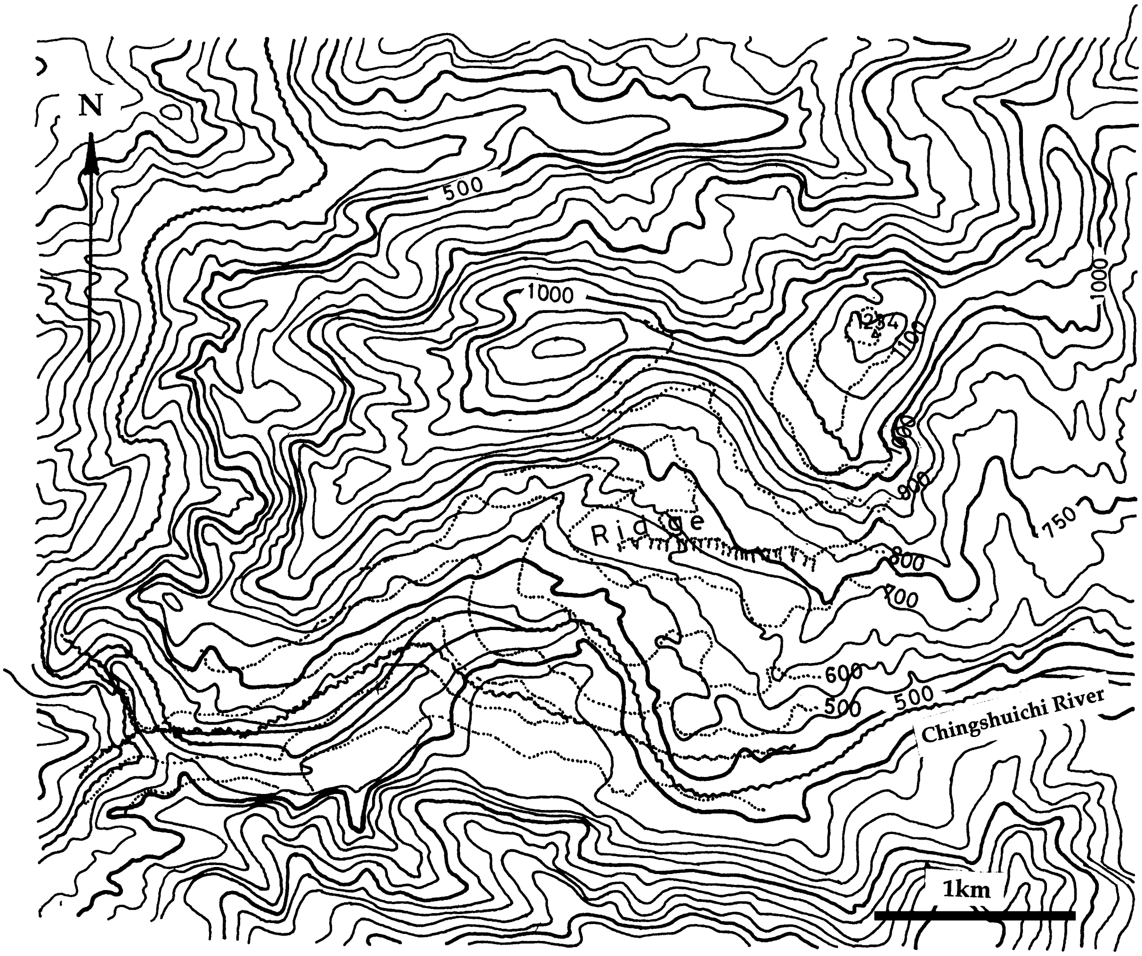


Fig. 6. The contour map of 1985 overlain by dotted contours from the 1930 map. The base maps are "Tsaoling" on a scale of 1:25,000, taken by the Combined Service Force, ROC (Taiwan), in 1985 and the "Takezaki", an ordnance map, on a scale of 1:50,000, made in 1930 by the former Japanese government.

## 3. Geomorphology of the landslide area

We studied the geomorphology of the Tsaoling landslide area by means of topographic maps and aerial photographs. The "Takezaki" topographic map (scale 1:50,000), an ordnance map of the former Japanese government in 1930, and the "Tsaoling" topographic map (scale 1:25,000) made by the Combined Service Force, ROC (Taiwan) in 1985 were employed for this study, and we analyzed aerial photographs (scale 1:17,000) taken by the Forestry Bureau, Taiwan Provincial Government, ROC (Taiwan), in 1990 and 1999. The map of 1985 overlain by dotted contours from the 1930 map, as shown in Fig. 6, illustrates that the Chingshuichi River was located about 500 m south of the present river before 1930 and that a small ridge with an elevation of 800 m was seated between its northern bank and the 1234-m peak. This ridge was not shown on the 1985 map, and Kawada (1942) reported that the ridge was within the landslide area of 1941 and 1942. In addition, Huang et al. (1983) described that the highest scarp, more than 50 m high, formed by the 1941 landslide was at an elevation of 950 m. Therefore, the ridge is known to have slid down during the event of 1941, leaving scarps near an elevation of 950 m. The slope higher than 950 m was outside the slide area of

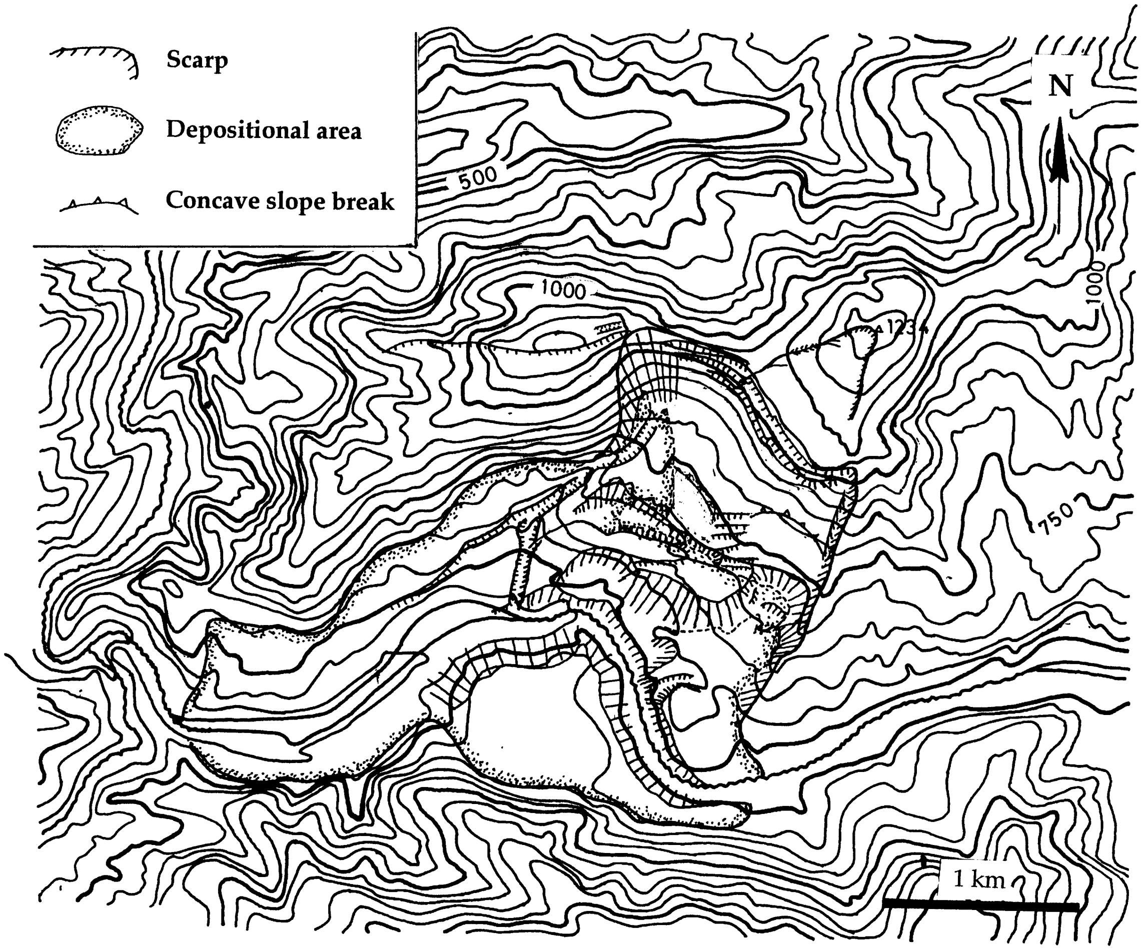


Fig. 7. Landslide outline observed from the aerial photographs taken in 1990–1999. The base map is the "Tsaoling" topographic map on a scale of 1:25,000 published in 1985.

the 1941 event, which is demonstrated by the contours of the two maps we studied. The geometry of the 1942 landslide is not yet understood.

The geomorphological features, which were interpreted from the aerial photographs taken in 1990–1999, show morphological conditions after the 1979 landslide and just before the 1999 landslides (Fig. 7). According to the description of Huang et al. (1983), the 1979 landslide occurred in the lower part of the landslide scar of the 1941 and 1942 landslides, and left a scarp at elevations approximately 600–750 m in the white sandstone and the Chinshui shale. The scarp of the white sandstone is clearly observable on the photographs of Plate II of their paper. The scar above these scarps was somewhat planar and parallel to the bedding surface and probably was the exposed slip surface. The 1979 landslide stripped most of the strata from the slope below these scarps.

A V-shaped scarplet can be clearly recognized from the aerial photographs taken in 1990–1999 to be convex upslope to the northeast near the top of the 1234-m peak (Fig. 7). This scarplet was outside the scar of the 1941, 1942, and 1979 landslides, and it precisely coincided with the upper boundary scarp of the 1999 landslide (Figs. 1 and 7). The northern edge of the V-shaped scarplet, 700 m long, connected to the scarp of the 1941 landslide at an elevation of 1100 m. The eastern edge, 300 m long, disappeared before connecting to the scarp, but it was on the extension of the southeastern margin of the 1941 landslide. Such a V-shaped scarplet does not occur as a result of gully erosion; it must be due to movement before the 1999 landslide.

## 4. Slip surface

As can be seen in the photographs and the descriptions of Huang et al. (1983) and in the aerial photographs, the slip surfaces of the 1941, 1942, and 1979 landslides were partially exposed before the 1999 landslide (Fig. 8A). Among these sporadic exposures, one slip surface, located between convex slope breaks and the white sandstone scarp at an approximate elevation of 700 m, was in the alternating beds of sandstone and shale on top of the white sandstone. The other slip surface was within the Chinshui shale and was exposed in a narrow gap between the white sandstone scarp and a detached white sandstone block downslope (Fig. 8A).

Planar slip surfaces were widely exposed after the 1999 landslide. Slip surfaces within three horizons formed a stepped, but continuous, slip surface. One was within the shale in the middle of the Chinshui shale, another in the alternating beds of shale and fine sandstone with ripples just beneath the white sandstone of the Cholan Formation, and the other in the alternating beds of sandstone and shale just above the white sandstone. Each slip surface is parallel to the bedding plane, which trends NW and consistently dips 14° SW.

The landslide of 1999 is characterized by the development of slip surfaces just above and below the white sandstone, as indicated in Fig. 8 and in the cross-section in Fig. 5. The scarp of the white sandstone retrogressed about 300 m as a result of the 1999 landslide, exposing the slip surface beneath it. This retrogressed interval corresponds to the interval between the white sandstone scarp made by the 1941–1942 landslides and the upslope convex slope break made by the same landslides. This coincidence means that the slip surface beneath the white sandstone bed appeared where the top surface of the white sandstone bed had been exposed for 57 years, from 1942 to 1999. During this period, the alternating beds beneath the white sandstone must have been affected by weathering because water could move through the permeable white sandstone. The previous convex slope break also retrogressed 750 m, exposing a slip surface in the alternating beds of sandstone and shale on the white sandstone. A cross-section before the 1999 landslide shows that the lower half of this newly exposed slip surface had been unloaded by the 1941 and 1942 landslides, which supports the idea that at least this half of the future slip surface could have been affected by the unloading and subsequent weathering and had deteriorated before the 1999 landslide.

After the 1999 landslide, alternating beds of sandstone and shale just beneath the slip surfaces slid in many places for less than 100 cm and made small chevron folds (Fig. 9). The folds were made by the buckling of the 10–30-cm-thick surface strata with slip surfaces within clay layers, which were originally shale beds and disintegrated probably by slaking. The clay layers were very soft and without distinct slickensides even along the contacts with sandstone beds, indicating that they did not originate in flexural slip faults. The

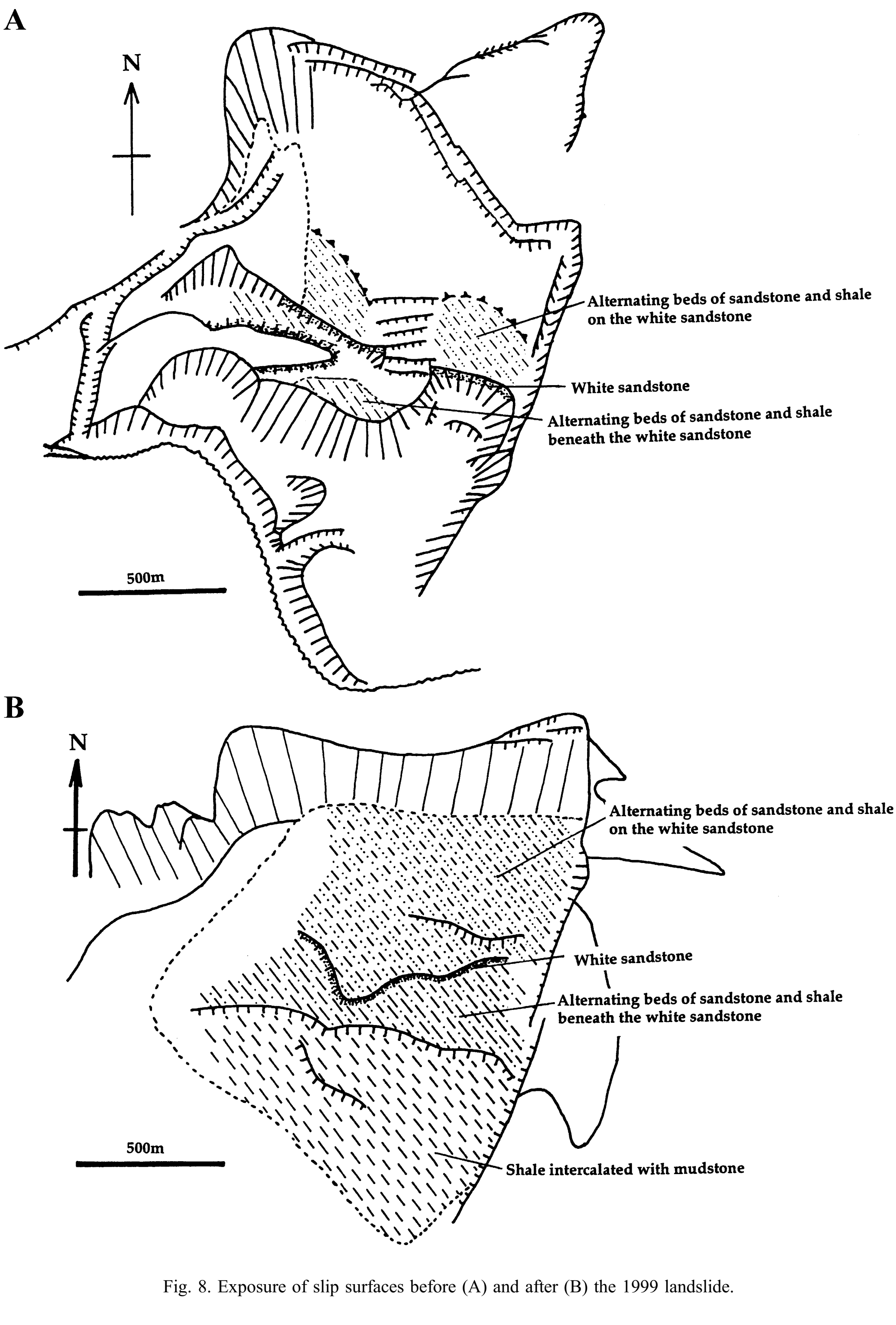


Fig. 8. Exposure of slip surfaces before (A) and after (B) the 1999 landslide.

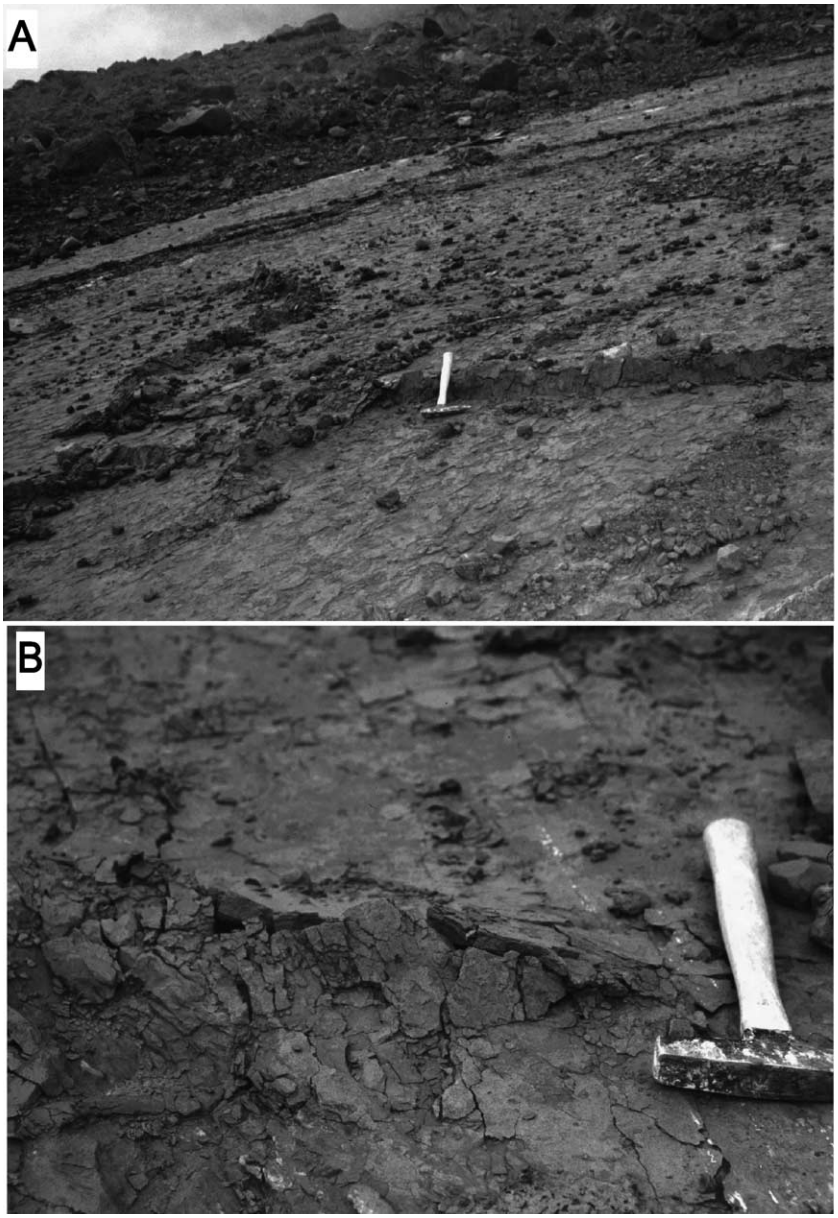


Fig. 9. Chevron fold of alternating beds of sandstone and shale beneath the slip surface. (A) Chevron folds similar to small mole tracks. (B) Close-up of the chevron fold. Such folds were made by sliding of the strata at a depth of 10–30 cm after the 1999 landslide.

folded beds were broken into small pieces with jagged outlines (Fig. 9B), indicating that they postdated the 1999 landslide. The chevron folds were observed in March 2000 and November 2000. So, the weathering that occurred during the 6 months following the 1999 event might have deteriorated the shale enough to allow it to be sheared, even though the shale had been affected by the landslide itself. The stress release by the 1999 landslide probably affected the weathering process also. Stress release can accelerate weathering and decrease the shear strength of mudstone significantly (Chigira, 1993).

## 5. Precursory phenomena of the Tsaoling landslide

The history of the Tsaoling landslide area indicates that chemical and physical weathering of shale provided the conditions that promoted landslide activity. The 1999 slip surface beneath the white sandstone was likely affected by the infiltrating groundwater through the white sandstone after the 1942 landslide, as stated before. In addition, the groundwater in this area is of the sodium-sulphate type, with the sulphate probably due to oxidation of pyrite, which indicates that sulfuric acid could have dissolved acid-fragile minerals, such as carbonates (Russell and Parker, 1979; Chigira, 1990; Chigira and Sone, 1991; Chigira and Oyama, 1999). Magnesium sulphate precipitating on the scarp, and dolomite ($MgCa(CO_3)_2$) being contained in the surrounding rocks, also demonstrate this dissolution. This chemical process and slaking of shale, as well as stress release, are inferred to be the basic causes of the formation of the slip surfaces on and beneath the white sandstone and their intermittent retrogression. The slip surface within the Chinshui shale could also have been formed as a result of the same mechanism, but this is not clear because the landform made by the 1942 landslide was modified by the 1979 landslide, particularly on the lower part of the slope. The slip surface within the Chinshui shale was widely exposed by the 1999 landslide.

The dip of 14° for the slip surfaces is too gentle to generate a landslide, even if there were an earthquake tremor, because the internal friction angle of the peak strength of shale and sandstone is too large to generate the landslide (Towhata et al., 2002). This also suggests the role of deterioration by the weathering process in generating landslides, as discussed above, even though detailed geotechnical investigation has not yet been performed.

Information about the geomorphological conditions before the 1941 landslide, which is the first major event that was well-documented at this site, is only available from the topographic map made in 1930 and the description by Kawada (1942). However, a small ridge at an elevation of 800 m seems to have already been detached from the main mountain behind it, because there was a small stream, which appears as a gap between the ridge and the main mountain on the map.

Before the 1999 landslide, the slide mass had already started to move, which is known from the fact that the upper peripheral boundary of the 1999 landslide had been clearly shown by the V-shaped scarplet upslope before this event. This previous movement could be attributed to the deterioration of the lower half of the future slip surface in the alternated bed of sandstone and shale on the white sandstone as described above. This deterioration might have propagated upslope and possibly led to a deep-seated mass rock creep and formed the V-shaped scarplet.

The presence of the V-shaped scarplet is the only clear geomorphological precursory phenomenon, and the other deteriorating factors, such as stress release and weathering, represent geological interpretation. However, the coincidence of the exposed areas of the new 1999 slip surface with the previously unloaded areas strongly suggests that these factors provided the preferable conditions for the 1999 landslide. Such a sequential mechanism, consisting of unloading, weathering, and landslide, has not been documented previously, but it may be common for retrogressive rockslide-avalanches in alternating beds of soft sandstone and mudstone or shale.

## 6. Conclusions

(1) The 1999 Chi-Chi earthquake triggered the Tsaoling landslide on a dip slope of Pliocene sandstone and shale dipping uniformly at 14°.

(2) The slip surfaces were made within thinly alternating beds of fine sandstone and shale with ripple lamination and also in shale beds.

(3) Weathering of shale by the iteration of drying and wetting and probably sulfuric acid is inferred to be one of the major causes of the intermittent retrogressive development of landslides.

(4) The weathering was likely accelerated by the removal of overlying beds during the landslides of 1941 and 1942.

(5) The top margin of the 1999 landslide was along a scarplet with a V shape in plan view, which can be clearly recognized on aerial photographs taken before the landslide. This geomorphological feature indicates that this landslide had already moved slightly before the 1999 slide, providing precursory characteristics.

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