RECESSION PROCESSES OF CUTTING SLOPES MADE OF LOOSELY CONSOLIDATED QUATERNARY DEPOSITS IN KANTO DISTRICT, JAPAN

by

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ABSTRACT

The purpose of this study is to investigate recession processes of cutting slopes made of loosely consolidated Quaternary deposits from the viewpoint of the rock control theory. Successive monitoring of recession distances, continual observations of recession mode and examination of slope-forming materials are performed.

Cutting slopes, composed mainly of the Kanto Loam, clayey beds and sandy beds, are located in the Kanto district, Japan. Of them several adjacent slopes with different aspects are selected from the northeastern part of this area. On the south-facing slopes which absorb much solar energy, a number of cracks are formed in the exposed part of the Kanto Loam and the clayey beds, but not found in the sandy beds. Rib-like relief is usually observed: the ridges of the relief are composed of the sandy beds and the furrows are made of the Kanto Loam and the clayey beds. On the north-facing slopes which receive less insolation, the cracks are little formed in the Kanto Loam, the clayey beds and the sandy beds. Rib-like relief is not observed.

On the south-facing slopes, the Kanto Loam and the clayey beds recede due to toppling failures, soilfalls and shallow slides caused by heavy rainfall, strong winds

and severe earthquakes. While, the failure of ridges accounts for the recession of the sandy beds. Recession rates of the Kanto Loam and the clayey beds are higher than that of the sandy beds in a short period of time. On the north-facing slopes, the slope recession takes place only in winter. Ice lenses are found to develop in the Kanto Loam, the clayey beds and the sandy beds. These beds recede mainly due to slumping caused by the freeze-thaw action and have similar recession rates (20 cm/year).

Results of physical, mechanical and mineralogical tests of slope-forming materials indicate that (1) each slope-forming bed is fully dried on the south-facing slopes, but has a high water-content on the north-facing slopes; (2) compressive, tensile and shear strengths of the Kanto Loam and the clayey beds are larger than those of the sandy beds, irrespective of the slope aspect; (3) as compared with the sandy beds, the Kanto Loam and the clayey beds are much more susceptible to shrinkage; and (4) clay minerals in the younger and older Kanto Loams are mostly allophane and hydrated halloysite respectively, and those in the clayey beds are composed of halloysite.

On the basis of laboratory measurements and experiments, it is found that (1) cracks are formed in the Kanto Loam and the calyey beds having a maximum shrinkage-ratio larger than 3.5 % and (2) shrinkage characteristics of the slope-forming beds is closely related to the clay content and/or the kind of clay minerals. On the south-facing slopes where the variation of water content is large, the strengths of the Kanto Loam and the clayey beds are markedly reduced by crack formation; this strength reduction process does not occur in the sandy beds. The Kanto Loam and the clayey beds recede due to the toppling failures, soilfalls and shallow slides and are eroded more severely than the sandy beds. As a result, the Kanto Loam and the clayey beds form the furrows and the sandy beds form the ridges, so that rib-like relief is formed. However, the sandy beds fail when the ridge attains a critical protruding length, and the rib-like relief disappears. (1) Reduction of water content due to much insolation and (2) shrinkage characteristics of the slope-forming materials are found to play a most important role in the crack formation, which in turn controls the recession of the south-facing cutting slopes.

On the north-facing slopes, the materials keep high water content because of being wet due to less insolation; so that the ice lenses are formed during winter in the Kanto Loam, the clayey beds and the sandy beds. These beds recede due mainly to slumping caused by freeze-thaw action. The depth of slumping is found to be determined by frost penetration depth, which is approximately the same in these beds. The slopes result in uniform recession with no distinct rib-like relief.

CHAPTER I

INTRODUCTION

Crucial factors determining earth-surface features are (1) geomorphic agents, (2) landform materials and (3) time. It has been considered for a long time that the properties of earth-surface materials control and condition the landforms (e.g., Davis, 1910, p.240; Thornbury, 1954, p.17-19).

Since Davis' work (1895, 1898, p.113-158, 1899), there have been many studies which treated the structural landforms, such as cuestas, hogbacks, homoclinal ridges and mesas (e.g., Gilbert and Gulliver, 1895; Grabau, 1920; Dicken, 1935; Woodridge and Linton, 1938; Lobeck, 1939, p.439-542; Sparks, 1949; Tohmpson, 1949; Monkhouse, 1954, p.90-94; Thornbury, 1954, p.130-134; Nakagawa, 1960; Trewartha et al., 1961, p.77-78; Gilliland, 1963; Twidale, 1966, 1976, p.101-123; Small, 1970, p.75-85). These studies have attempted to explain the relation between landforms and materials and have emphasized the difference in the material strength, permeability or solubility for the development of such landforms. However, the properties of the materials were not actually measured in these studies and such a qualitative explanation as "hard or resistant rocks form ridges" was only made.

Yatsu (1965, 1966, p.4-14, 1971) pointed out such qualitative state of researches and stressed the importance of quantitative study on landform materials. He proposed a "rock control theory" in which he mentioned that the investigation of the material properties from physical, chemical and mechanical viewpoints should be furthered.

On the basis of the rock control theory, quantitative studies were performed on the formation of a small-scale structual landform, i.e., washbord-like relief on the wave-cut benches at Arasaki, Miura Peninsura, Kanagawa Prefecture (Suzuki et al., 1970, 1972) and Aoshima island, Miyazaki Prefecture (Takahashi, 1975, 1976). Their studies were based on actual measurements of material properties such as compressive strength, abrasive hardness, swelling pressure, etc. Suzuki et al. (1970, 1972) emphasized the role of wet-dry weathering of the bench-forming rocks in the formation of such relief. Takahashi (1975, 1976) also pointed out the importance of weathering characteristics of the bench rocks.

As another case of similar work, Tanaka (1972) studied the recession of artificial cutting slopes located at an inland environment, i.e., the Chichibu Basin, Saitama Prefecture. His work was based on the measurements of (1) the recession distances and (2) physical and mechanical properties of slope-forming Tertiary rocks. Mechanical weathering due to (1) wet-dry and (2) freeze-thaw action was found to be of great significance in the slope recession.

All the recent studies by Suzuki et al. (1970, 1972), Tanaka (1972) and Takahashi (1975, 1976) have treated landforms made of consolidated materials. Even in these studies, thorough investigation of the process of landform changes have not been performed on the basis of continual observations.

The purpose of the present study is to investigate the recession process of slopes made of loosely consolidated Quaternary material through field obsrevation conducted on a weekly or biweekly basis during a two-year period. Artificially cut slopes located in the Kanto district, Japan were selected because the initial boundary condition is clear.

This study includes (1) the measurement of slope profiles, (2) the examination of geomorphic agents acting on the slope surfaces, (3) the observations of recessional features of the slopes, (4) the repeated measurements of the recession distances, (5) the investigation of physical, mechanical, mineralogical and thermal properties of the slope-forming materials, and (6) discussion on the recession process on the basis of these results.

CHAPTER II

STUDY AREAS

1. TOPOGRAPHY AND GEOLOGY

Two study areas are selected in the Kanto district: one is located at the northern part of Chiba Prefecture to the southwestern part of Ibaraki Prefecture, and the other at the northern part of Tochigi Prefecture (Figure 1). The former includes Shimousa and Tsukuba Uplands, and the latter includes Nasunogahara Fan. Average altitude of Shimousa and Tsukuba Uplands is about 20 to 30 m above sea level and that of Nasunogahara Fan is about 200 to 400 m. These uplands are dissected by many rivers and relative height between the upland surface and surrounding alluvial lowlands is about ten to several tens meters.

Topography and geology of the study areas have been investigated by many workers. The surface of Shimousa Upland is correlated to Shimosueyoshi terraces; the southern part of the Tsukuba Upland surface is Musashino terrace, and the northern part is Shimosueyoshi terrace; and the main part of Nasunogahara Fan surface is correlated to Nasuno terrace (Kanto Loam Research Group, 1961, 1965, p.169-174).

Shimousa Upland is composed of Pleistocene horizontal sedimentary beds on which late Pleistocene volcanic ashes are deposited (Kanto Loam Research Group, 1965, p.65-73; Sugihara, 1970). The sedimentary beds are made of sandy beds named Narita formation and pumiceous clayey-bed named Joso Clay in the order from the lower to the upper. The Narita formation and Joso Caly have been interpreted as marine deposits and flood-plain deposits, respectively. The volcanic ash layers, with a thickness of 3.5 to 4.5 m, are called the Kanto Loam which is explained as aeolian deposits. In the southern Kanto, the Kanto Loam is divided into four members which are in disconformable relation with one another. They are named Tachikawa, Musashino, Shimosueyoshi and Tama Loams from the younger to the older (Kanto Loam Research Group, 1956). The Kanto Loam of Shimousa Upland has been correlated to Shimosueyoshi Loam (Figure 2).

Tsukuba Upland is also composed of Pleistocene horizontal sedimentary beds of the Narita formation, Ryugasaki formation and Joso Clay in the order from the lower to the upper, and these beds are covered with the Kanto Loam (Kanto Loam Research Group, 1965, p.175-181; Sugihara, 1970). The Ryugasaki formation is considered to be flood-plain or delta deposits. The Narita formation, Ryugasaki formation, Joso Clay and the Kanto Loam have a thickness of 10 to 30 m, 2 to 6 m, 0.5 to 2 m, and 3 m, respectively. The Kanto Loam in the southern part of this upland is correlated to Musashino and Tachikawa Loams, and that in the northern part is correlated to Shimosueyoshi Loam (Figure 2). The Joso Clay also correlated to Shimosueyoshi Loam.

Nasunogahara Fan is composed of sand and gravel beds with a thickness of 5 to 20 m and the Kanto Loam having a thickness of 0.5 to 2.5 m. The Kanto Loam in the environs of Utsunomiya city has been divided into four members: A_1, A_2, A_3 and A_4 in descending order by Akutsu (1957). Kanto Loam Research Group (1965, p.157-165) called Akutsu's A_1, A_2, A_3 and A_4 members Tawara, Takaragi, Hoshakuji and Tomatsuri Loams, respectively. The Kanto Loam covered with Nasunogahara Fan is correlated to Tawara and Takaragi Loams (Figure 2).

The origin of Tachikawa, Musashino and Shimosueyoshi Loams has been attributed to volcanic ashes supplied from the Paleo-Fuji and the Hakone volcanos (Kanto Loam Research Group, 1965, p.194-197). Tawara, Takaragi and Hoshakuji Loams were originated respectively from the Nantai volcano, the Akagi volcano and the Nikko volcanic district (Akutsu, 1957). Tawara, Takaragi, Hoshakuji and Tomatsuri Loams have been correlated respectively to Tachikawa, Musashino, Shimosueyoshi and Tama Loams (Akutsu, 1957; Kanto Loam Research Group, 1961, 1965, p.187-203).

2. CLAY MINERALS IN THE KANTO LOAM

In the southern Kanto district, clay minerals (Tsuchiya and Kurahayashi, 1958; Kurahayashi and Tsuchiya, 1959, 1960; Kanto Loam Research Group, 1965, p.225-234) in the upper Kanto Loam are rich in allophane and those in the lower Loam are rich in hydrated halloysite. The clay minerals of Tachikawa Loam are mostly allophane, and sometimes the mixture of allophane and a small amount of hydrated halloysite is found. Musashino Loam has the principal clay mineral of hydrated halloysite, sometimes with a small amount of allophane. The clay minerals of Shimosueyoshi Loam are composed of (1) hydrated halloysite and (2) the random mixed-layer minerals of hydrated halloysite and halloysite. In Tama Loam, the constituent clay minerals are mainly a mixed type of halloysite clay minerals and similar to that of Shimosueyoshi Loam. Yoshinaga and Aomine (1962) found a fibrous clay mineral in volcanic ash distributed in Kyushu, and they named this clay mineral imogolite, which seems to be a transitional type between amorphous allophane and crystalline clay minerals. Weathering sequence of volcanic ash has been considered to be that allophane alters to halloysite (Fieldes, 1955; Kanto Loam Research Group, 1965, p.225-234; Wada and Harward, 1974). Such weathering sequence has been observed in the northern Kanto area. Namely, the dominant clay minerals of Tawara, Takaragi, Hoshakuji and Tomatsuri Loams are allophane, hydrated halloysite or a mixture of allophane and hydrated halloysite, hydrated halloysite, and hydrated halloysite of high crystallinity, respectively (Matsui, 1960; Kurahayashi and Tsuchiya, 1961; Kanto Loam Research Group, 1965, p.232). These clay minerals and weathering sequence have been observed in the Quaternary volcanic ash distributed in various parts of Japan (Kurahayashi and Tsuchiya, 1967; Kurahayashi, 1969; Kato, 1973), New Zealand (Fieldes, 1955), France (Eswaran, 1972) and Indonesia (Wesley, 1973).

3. GEOTECHNICAL PROPERTIES OF THE KANTO LOAM

Grain size distribution of the Kanto Loam has been studied by Nakao (1929, 1931a, b, 1932a, b, 1937, 1940), Kondo (1954), Tada and Yamazaki (1963) and Highway Research Group (1973, p.73-74). According to Tada and Yamazaki (1963), both Tachikawa and Tawara Loams have a clay (< 0.002 mm) content of about 40 %.

The following is a summary of physical properties of the Kanto Loam which were investigated by Kanto Loam Research Group (1965, p.340-345) and Highway Research Group (1973, p.65-77): Specific gravity is about 2.8, which is larger than that of alluvial soil. Porosity is about 75 to 80 %, which is markedly higher than that of alluvial soil and is approximately equal to the porosity of humus-rich clayey soil. Dry density is very small because of high porosity, and it is about 0.6 to 0.7 g/cm^3. Natural water content is almost always larger than 100 %. Consistency is similar to that of alluvial soil. Plastic and liquid limits decrease with decreasing water content: when the water content is 110 %, plastic and liquid limits are respectively 100 % and 160 %; when the water content becomes 15 %, they are respectively 80 % and 100 %.

The value of cohesion is about 0.3 to 0.5 kgf/cm^2, almost equal to that of alluvial clay, but its angle of internal friction is 25 to 30° (Kanto Loam Research Group, 1965, p.346). Unconfined compressive strength of the Kanto Loam is about 0.8 to 1 kgf/cm^2 at a water content of 100 to 120 % (Kanai, 1972; Highway Research Group, 1973, p.82). Shrinkage property has been studied by Takenaka (1965) using undisturbed specimens. Shrinkage-ratio of Tachikawa, Musashino and Tama Loams is 18.6, 2.5 and 10.5 %, respectively.

Kanai (1972) studied some physical and mechanical properties of the Joso Clay distributed in Shimousa and Omiya Uplands. The followings are his results. Clay content is 50 to 55 % and dry density is 1 g/cm^3. Cohesion and angle of internal friction are respectively 0.5 to 0.7 kgf/cm^2 and 5 to 6° when the water content is 55 to 60 %. Unconfined compressive strength is 1 to 1.5 kgf/cm^2 at the same water content.

4. METEOROLOGICAL CONDITIONS

Figures 3a and 3b show monthly averages of air-temperature and precipitation during the period of ten years from 1970 to 1979 using the data obtained at Tateno, Ibaraki Prefecture and at Otawara, Tochigi Prefecture (Figure 2) near the study areas. Mean annual temperature at Tateno and Otawara is found to be 13.6°C and 12.2°C, respectively. Annual precipitation at both locations is 1218 mm and 1349 mm, respectively. Mean monthly value of daily minimum temperature at both sites is lower than 0°C during the period from December to March and that of daily maximum temperature is higher than 8°C through the year. Mean monthly precipitation is about 50 mm during the interval from December to March, and is higher from April to November.

In the study areas, yearly average number of days giving a daily maximum wind speed higher than 10 m/s during the period of 1979 to 1981 is 22 days. Mean annual number of days having a snowfall during the same period is 5 days, and the average snow thickness is several centimeters. Mean annual number of felt earthquakes occurred during the period from 1970 to 1979 is 63, and the number of earthquakes with 3 and 4 in seismic intensity is 8.

CHAPTER III

DESCRIPTION OF CUTTING SLOPES

1. SELECTION OF CUTTING SLOPES

In the Kanto district, many cutting slopes have been artificially formed at the fringe of low uplands made of Quaternary deposits for the development of residential areas. These slopes are generally steep with a uniform gradient. After the cutting, ribbed ridges develop on the surface of most slopes (Photograph 1) and such relief is called rib-like relief; but it does not develop on some slopes (Photograph 2). Cutting slopes with different aspects were selected for the present study, because the rib-like relief development is considered different depending upon slope aspects. Sixteen locations including total twenty-three cutting slopes were chosen (Figure 2 and Table 1). They are six slopes at Shimousa Upland, eleven slopes at Tsukuba Upland and six slopes in the environs of Nasunogahara Fan. All study slopes are unvegetated.

In order to clarify the relation between the relief of the slope surface and the kind of slope-forming beds, slope profiles were measured in seventeen slopes located at Shimousa and Tsukuba Uplands. The measurements were carried out using a clinometer and a surveyor's tape. Data on the relative height of the slopes, their slope angle and aspect are listed in Table 1. Each study slope located at Shimousa and Tsukuba Uplands had been artificially cut one to two years before the slope profile measurements began in July or August of 1979. These slopes with a horizontal length of several tens meters have a relative height of 6 to 10 m and a slope angle of 40 to 80°.

Topographic maps around Slopes T2-SW, T2-N and T3-SW, where recession distances of the slope surface were measured, are shown in Figures 4 and 5. Dilluvial upland which has an altitude of about 20 to 30 m are distributed with a relative height of 10 m between the upland surface and surrounding alluvial lowlands. Slopes T2-SW and T3-SW receive the insolation in the daytime, whereas Slope T2-N seldom receive the insolation in the all day. A groundwater table lies near the alluvial lowland surface level and seldom rises up to the base of the cutting slopes during and after rainfall.

2. SLOPE-FORMING BEDS

The slope profiles and geologic sections are shown in Figures 6a through 6e. The study slopes are composed of several Pleistocene horizontal beds. At Shimousa and Tsukuba Uplands (Figures 6a, 6b and 6c), the upper part of each slope is composed of the Kanto Loam with a thickness of about 2 to 3 m, which is Tachikawa and Musashino Loams deposited in late Pleistocene (Kanto Loam Research Group, 1965, appendix; Sugihara, 1970). Tokyo Pumice, several to tens centimeters in thickness, is intercalated in the lower part of the Kanto Loam. in the northern part of Tsukuba Upland, Kanuma Pumice (KP) with a thickness of 30 cm is intercalated in the middle part (see Slope T1-W in Figure 6a).

The lower part of the slopes is composed of alternation of clayey and sandy beds (Nakamura and Fukuda, 1953; Sugihara, 1970; Kanno et al., 1976; Aoki and Baba, 1977) with a thickness of about 0.4 to 3 m. The most upper clayey bed i.e., the Joso Clay, is correlated to Shimosueyoshi Loam. Clayey and sandy beds of the lowest part in Tsukuba Upland and lowest sandy bed in Shimousa Upland are respectively correlated to Ryugasaki formation and Narita formation. The Joso Clay, Ryugasaki formation and Narita formation were deposited in late Pleistocene.

In the environs of Nasunogahara Fan (Figure 6d and 6e), the slopes are composed only of the Kanto Loam with a thickness of 5 to 10 m, which is correlated to Hoshakuji, Takaragi and Tawara Loams in the order from the lower to the upper (Kanto Loam Research Group, 1965, appendix). The Shichihonzakura Pumice (SP) and Imaichi Pumice (IP) are intercarated in the upper part of Tawara Loam. The Kanuma Pumice (KP) is intercalated in the middle part of Takaragi Loam. The Kataoka Scoria (KS) and Ogawa Scoria (OS) are found in Tawara Loam, and Mamiana Scoria (MaS) is recognized in Hoshakuji Loam.

As grain size distribution of slope-forming beds is mentioned in Chapter V, the volcanic ash layers having a clay content of about 30 % is called here "Kanto Loam", the Joso Clay and clayey beds of Ryugasaki formation which have a clay content of 60 to 70 % are expressed as "clayey beds", and Ryugasaki formation with a small amount of clay fractions and Narita formation are represented by "sandy beds".

3. CRACK DEVELOPMENT ON SLOPE SURFACE

On the surface of study slopes, cracks develop in the Kanto Loam and the clayey beds, but not in the sandy beds including pumice and scoria layers (Photographs 1 and 2, Figures 6a through 6e). The cracks notably develop on the slopes with a southern aspect. They are formed in exposed parts of the clayey beds and the Kanto Loam with some part having little crack-development. In the Kanto Loam, vertical cracks with a width of about one centimeter are spaced at intervals of 5 to 15 cm (Photograph 1). These cracks develop up to a depth of 4 to 10 cm from the slope surface and divide a soil mass into individual blocks called soil pillars with a width of 5 to 15 cm, a height of 10 to 30 cm and a thickness of 4 to 10 cm. Vertical cracks having a width of several millimeters are formed at intervals of about 10 to 20 cm in the Joso Clay; soil pillars develop with a width of 10 to 20 cm, a height of 20 to 40 cm and a thickness of 10 to 20 cm (Photograph 1). Cracks which have a width of several millimeters densely develop in the clayey beds of the Ryugasaki formation as compared with the Kanto Loam and the Joso Clay; soil pillars are formed with a width of 5 to 10 cm, a height of 4 to 13 cm and a thickness of 3 to 7 cm (Photograph 1). Such crack development on specified layers is found in various parts of the Kanto district.

4. RELATION BETWEEN SLOPE ASPECT AND RELIEF ON SLOPE SURFACE

A distinctive relief corresponding to the kind of the slope-forming beds is found on the southeast- to west-facing slopes (see Slopes T1-W, T2-S, T2-SW, T3-SW, T4-SW, S1-SE, S1-S, S1-W and S2-SE in Figures 6a, 6b and 6c), while, such a relation is not found on the northeastto northwest-facing slopes (see Slopes T2-N, T3-NW, T5-NW, T6-N, T7-NE, T7-NW, S1-N and S3-N in Figures 6a, 6b and 6c). The former slopes are expressed here in terms of "south-facing slopes", and the latter by "North-facing slopes". It should be noted that the relief formation is completely different depending upon the slope aspects. Similar phenomenon is found in the environs of Nasunogahara Fan and also in other parts of the Kanto district.

On the slopes of Shimousa and Tsukuba Uplands, the ridges are composed of the pumice and the sandy beds. In the environs of Nasunogahara Fan, scoria beds form the ridges. On the other hand, the furrows are always composed of the Kanto Loam and the clayey beds. Many cracks develop in these layers, forming a crack zone in the furrows. Kanto Loam Research Group (1965, p.68) reported that such a crack zone is found in the furrow part on the slopes located in various places of the Kanto district.

CHAPTER IV

RECESSION OF CUTTING SLOPES

1. GENERAL CONCEPT OF SLOPE RECESSION

The most important factors in recession of cutting slopes are the assailing force of geomorphic agents acting on the slope and the resisting force of the slope-forming materials. Similar to the relation which describes coastal cliff recession (Sunamura, 1973), the recession distance of cutting slopes can be expressed by the following relation:

$$D = \phi\ (G,\ t),\ G = f_a/f_r \qquad (1)$$

where D is the recession distance, f_a is the assailing force of the geomorphic agents, f_r is the resisting force of the slope-forming materials and t is the time. Erosion occurs when f_a exceeds f_r. It is absolutely necessary to elucidate f_a, f_r and t when we consider the recession of cutting slopes.

2. METHOD OF RECESSION DISTANCE MEASUREMENT

To measure the recession distance of the slopes, to observe erosional processes and to examine properties of the slope-forming materials, Slopes T2-SW (Figure 4 and Photograph 3) and T3-SW (Figure 5 and Photograph 4) located at Tsukuba Upland (Figure 2 and Table 1) were selected as a representative of the south-facing slopes. Slope T2-N at Tsukuba Upland was chosen as a representative of the north-facing slopes (Figure 4 and Photograph 5). On these slopes, the recession distance of the slope surface was measured using stainless steel stakes; their diameter and length were 3 mm and 50 cm, respectively. The measurement procedure was as follows:

(1) Two measurement lines at Slopes T2-SW (T2-SW(1) and T2-SW(2); Photographs 3 and 6) and T2-N (T2-N(1) and T2-N(2); Photograph 5 and 7), and one line at Slope T3-SW were established.

(2) The stainless steel stakes were driven horizontally into each slope-forming material (Figure 7).

(3) Temporal changes in exposure length of each stake were measured. The measurement was repeatedly conducted at 2- to 5-week intervals. The measurement started from June 1980 to April 1982 on Slopes T2-SW and T2-N, from October 1979 to March 1982 on Slope T3-SW, respectively.

Observations were made at intervals of one or two weeks on (1) failure scars on the surface of each slope-forming bed and (2) soil blocks fallen from the slope and located at the slope foot were observed at intervals of one or two weeks.

Geomorphic agents acting on the slope are rainfall, winds and earthquakes. The data of daily amount of precipitation (mm) and daily maximum wind speed (m/s) measured at Shimotsuma Automated Meteorological Station (Figure 2) were used for the analysis of Slopes T2-SW and T2-N. Similar meteorological data obtained at Tateno Aerological Observatory (Figure 2) were used for T3-SW slope analysis. The data of seismic intensity observed at Mito Local Meteorological Observatory (Figure 2) were employed for these analyses. Daily amount of precipitation higher than 10 mm, daily maximum wind speed larger than 10 m/s and seismic intensity larger than 3 were taken into consideration.

3. SOUTH-FACING SLOPES

3.1 Recession distances and erosional processes

(a) Slope T2-SW

Temporal changes of the recession distance for each bed along the two measurement lines on Slope T2-SW (T2-SW(1) and T2-SW(2)) are shown in Figures 8a and 8b. The magnitude of geomorphic agents (rainfall, winds and earthquakes) is also illustrated in these figures. The recession distance was cumulated as shown by the dots (Figures 8a and 8b). On the both measurement lines of this slope, the cumulative recession distances of the Kanto Loam and the clayey beds are always greater than those of the sandy beds, except the case occurred from the latter stages of October to the early stages of November 1981 on the lower sandy bed (Figure 8a). The difference in the recession distance strongly suggests that the erosional processes on the Kanto Loam and the clayey beds greatly differ from those on the sandy beds.

The Kanto Loam and Clayey Beds 2, 4 and 6 on Slope T2-SW(1) receded respectively 12, 10, 3 and 4 cm from February 3 to April 23, 1981 (Figure 8a). During this period, (1) many cracks were found to develop in the exposed part of the Kanto Loam and of all clayey beds; these cracks form soil pillars which have a height of several to several tens centimeters, with width and thickness of similar sizes; and (2) needle ices and ice lenses were not found on each bed. On April 23, 1981, (1) soil blocks of the Kanto Loam and the clayey beds fallen from the slope were observed at the foot of the slope and (2) small horizontal failure-surfaces with a size of approximately 10 x 10 cm^2 in the Kanto Loam and of all clayey beds were seen. These observations indicate that the recession of the Kanto Loam and all clayey beds in this period would be caused by toppling failures (Photographs 8 and Figure 9) due to the rainfall and wind action on April 20, 1981, and the recession distance would abruptly increase on this day as shown by the broken line in Figure 8a.

During October 21 and November 11, 1981, the Kanto Loam and Clayey Bed 2 on Slope T2-SW(2) receded 10.5 and 8.5 cm, respectively (Figure 8b). Similar erosional features mentioned above were also observed on October 25, 1981. Therefore, the recession of the Kanto Loam and the clayey bed seems to be also caused by toppling failures due to the rainfall accompanied by Typhoon (8124). Clayey Bed 2 on Slope T2-SW(1) receded 7 cm during November 11 and December 9, 1981 (Figure 8a). This recession also is probably caused by toppling failures due to the rainfall on November 26 and 27.

Soilfalls due to strong wind were frequently observed on the Kanto Loam and all clayey beds. Because many fragments of the Kanto Loam and the clayey beds fallen from the slope were found at the foot of the slope after earthquakes with seismic intensity greater than 3, soilfalls can be related also to severe earthquakes. Slight recession of the Kanto Loam and Clayey Beds 2 and 4 on the both measurement lines (Figures 8a and 8b) is probably caused by soilfalls. For example, Clayey Bed 2 on Slope T2-SW(1) receded 1.5 cm during the period from August 6 to August 26, 1981; this recession seems to be caused by soilfalls due to strong wind.

At the observations after heavy rainfall, steeply inclined failure-surfaces were sometimes found in the Kanto Loam and all clayey beds (an example is shown in Photograph 9). This fact suggests that shallow slides in the both beds occurred due to rainfall (Figure 10).

From the recession measurement and observations the cause of major recession of the Kanto Loam and all clayey beds is toppling failures. Slight recession of these layers is caused by soilfalls and shallow slides.

On the other hand, the sandy beds on the two slopes (T2-SW(1) and T2-SW(2)) did not recede except Sandy Bed 5 on Slope T2-SW(1) (Figures 8a and 8b). This bed receded 30 cm during the period from October 21 to November 11, 1981. This recession was caused by the failure of a ridge due to a heavy rainfall accompanied by Typhoon (8124) on October 22, because blocks fallen from the bed were found at the slope foot on October 25. Other blocks fallen from the ridges except on the both measurement lines existed at the foot of the slope on this day. These facts suggest that the sandy beds recede due to the failure of ridges (Figure 11).

(b) Slope T3-SW

Cumulative recession distances of the Kanto Loam and a clayey bed are also larger than that of a sandy bed on Slope T3-SW (Figure 12). The clayey bed receded 5 cm during the period from April 29 to June 8, 1980, and 7.5 cm from January 21 to May 23, 1981. Blocks of the clayey bed fallen from the slope were found at the foot of the slope on June 8, 1980 and February 17, 1981. Moreover, small horizontal failure-surfaces in the clayey bed were observed on the slope surface on these days. Needle ices and ice lenses were not developed in this bed during winter. These facts suggest that the clayey-bed recession during the former period was caused by toppling failures due to the rainfall of May 1, 1980 and the recession for the latter period was induced by the earthquake of January 28, 1981. The recession distances at the both events are depicted by the dashed line in Figure 12.

Soilfalls due to strong winds were frequently observed in the Kanto Loam and the clayey bed; soilfalls are also closely related to earthquakes. Many small fragments of the Kanto Loam and the clayey bed fallen from the slope were found at the foot of the slope. Slight recession of the clayey bed during the period of October 4, 1979 and April 29, 1980 (Figure 12) seems to be caused by soilfalls. Figure 12 also shows that the

Kanto Loam receded a few centimeters during the period from August 25 to December 22, 1981; this recession would be due to also soilfalls.

Thus, the clayey bed mainly receded due to toppling failures caused by rainfall and earthquakes; this bed was slightly eroded due to soilfalls caused by winds and earthquakes. The slight recession of the Kanto Loam was also caused by the same process.

On the other hand, the sandy bed did not recede (Figure 12). However, blocks fallen from the sandy bed except on this measurement line were found at the foot of the slope. This fact suggests that the sandy bed of this slope also recedes due to the failure of ridges, as schematically illustrated in Figure 11.

(c) Summary of erosional processes on south-facing slopes

Consideration based on (1) measurement results of recession distance and (2) observations of erosional features leads to the following summary. Toppling failures and soilfalls due to rainfall, winds and earthquakes are found to be dominant erosional processes for the Kanto Loam and the clayey beds. While, the failure of ridges accounts for the recession of the sandy beds.

3.2 Recession rate

Average recession rate for each slope-forming bed during the measurement period (from June 8, 1980 to April 20, 1982 for Slope T2-SW; and from October 4, 1979 to March 25, 1982 for Slope T3-SW) was obtained by dividing the total recession distance by the length of the period (Tables 2a and 2b). The Kanto Loam receded at a rate of 1 to 7 cm/year on Slopes T2-SW and T3-SW. The annual rate for the clayey beds on the both slopes ranges from 0 to 12.2 cm/year. While, the value of the sandy beds on the both slopes is 0 cm/year except Sandy Bed 5 on Slope T2-SW(1). These results indicate that the Kanto Loam and the clayey beds are more susceptible to erosion as compared with the sandy beds, as for as the period not having the failure of the ridge of sandy beds is considered. If the failure of the ridge occurs, the recession rate of the sandy beds becomes equal to or slightly larger than that of the Kanto Loam and the clayey beds.

4. NORTH-FACING SLOPES

4.1 Recession distances and erosional processes

The measurement results of recession distance of each bed forming the north-facing slopes are shown in Figure 13a for the measuring line T2-N(1) and Figure 13b for T2-N(2). In these figures, the recession distance is cumulated and shown by the dots. The Kanto Loam, the clayey beds and the sandy beds show approximately equal cumulative recession distance, and it is found that they mainly receded during winter. Each bed was eroded about 20 cm during the period from late December 1980 to April 1981, and the recession with approximately same amount took place during the period from early December 1981 to late February 1982. Except these two periods, each bed was scarecely retreated.

Observations of erosional features indicate that slumping due to freeze-thaw action occurred in each bed during winter. Several freezing periods with ice lences were observed in each bed during the period from January to February 1981; three freezing periods were recorded from mid-December 1981 to late February 1982 (Figures 13a and 13b). Ice lenses were formed parallel to the slope surface (Photograph 10). These lenses had a thickness of several millimeters and were pure ices. In winter terms, some beds show the decrease in cumulative recession distance (Figures 13a and 13b). According to observations, the reason for this decrease is that the slope surface was slightly advanced due to frost heaving. Blocks with about 5- to 10 cm thickness fallen from the slope were found at the slope foot after each freezing period (Photograph 11), and slumping scars were observed on the slope surface. These facts strongly suggest that a recession distance of about 20 cm for each bed during one winter term was caused by slumping due to freeze-thaw action (Figure 14). The frost penetration depth was found approximately equal to the thickness of the fallen blocks. This finding indicates that slumping occurred at the boundary between frozen and unfrozen soil.

Erosional processes other than slumping were also observed. Soilfalls due to strong winds were observed on Clay Bed 2. Soilfalls due to the thawing of needle ices occurred on each bed in early- to mid-December, 1981, and in late February to mid-March, 1982. However, the recession of each bed was slight during these intervals.

It should be emphasized that each bed forming the north-facing slopes was mainly eroded by slumping due to freeze-thaw action and had an approximately equal recession distance.

4.2 Recession rate

Annual rate of recession of the slope-forming beds was calculated from the data of cumulative recession distance (Table 3). The Kanto Loam, the clayey beds and the sandy beds show a similar recession rate of about 20 cm/year. This value is several times larger than that of the Kanto Loam and the clayey beds on the south-facing slopes. It is found that the north-facing slopes much more uniformly receded with a larger rate as compared with the south-facing slopes.

CHAPTER V

PHYSICAL, MECHANICAL AND MINERALOGICAL PROPERTIES OF SLOPE-FORMING BEDS

1. INDEX OF RESISTING FORCE AGAINST SLOPE RECESSION

It was mentioned in Chapter IV that the Kanto Loam and the clayey beds on the south-facing slopes are eroded by toppling failures, soilfalls and shallow slides, and the recession rate of these two beds is larger than that of the sandy beds. To explain this larger recession rate, it is necessary to compare the resisting force of each bed against the three erosional processes: toppling failures, soilfalls and shallow slides. The kind of resisting force of slope-forming beds differs according to erosional processes (Yatsu, 1966, p.11). The resisting force against toppling failures is tensile strength and compressive strength (Nakayama, 1967, p.124-128). Crack formation (shrinkage characteristics) is closely related to the resistivity against soilfalls. Carson and Kirkby (1972, p.153) pointed out that the resisting force against shallow slides is shear strength.

These resisting forces of the slope-forming bed are greatly reduced by cracks. Therefore, it is necessary to examine the properties of the bed material which are favorable for crack formation. Cracks are usually formed by the shrinkage of material. Because physical and mineralogical properties relate to shrinkage characteristics (Yong and Warkentin, 1975, p.199; Mitchell, 1976, p.182), the investigation of these properties is requisite.

The Kanto Loam, the clayey beds and the sandy beds on the north-facing slopes are eroded by slumping due to freeze-thaw action, and these beds show an approximately equal recession rate, as mentioned in Chapter IV. Slumping occurs at the boundary between frozen and unfrozen soil: the frost penetration depth controls recession distance of the north-facing slope. Because physical and thermal properties relate to ice-lens formation and frost penetration depth (Casagrande, 1932; Aldrich, 1956; Linell et al., 1963), it is necessary to investigate these properties.

Physical, mechanical and mineralogical properties of the beds forming Slopes T2-SW and T3-SW (south-facing slopes) were tested. Using samples taken from Slopes N1 to N6, physical, mineralogical and shrinkage properties were examined. Physical and thermal properties of the material forming Slope T2-N (north-facing slope) were measured.

2. PHYSICAL PROPERTIES

2.1 Method

The following physical properties of the bed material were examined: grain size distribution (sand, silt and clay content), specific gravity, dry density, porosity, natural water content and consistency. Sampling points are shown in Figures 6d, 6e and 7.

Grain size distribution was investigated according to the Japanese Industrial Standard (JIS) A 1204, except for the Kanto Loam. The method of Tada and Yamazaki (1963) using HCl as a dispersing agent was adopted for the Kanto Loam test. Specific gravity was tested according to JIS A 1202. Dry density was determined using an 100-cc soil sampler and an oven in the laboratory. Porosity was calculated from the data of specific gravity and dry density. Natural water content was examined by the same method as the determination of dry density. Consistency (liquid limit, plastic limit and plasticity index) was tested for the Kanto Loam and the clayey bed material according to JIS A 1205 and JIS A 1206.

2.2 Results

Test results are listed in Tables 4 and 5. Both the Kanto Loam and the clayey beds are found to be composed of very fine grains such as silt (5-74 μm) and clay (< 5 μm). While, the sandy beds are mainly composed of sand (74-2000 μm). A clay content of the Kanto Loam is about 30 %, and that of the clayey beds ranges from 60 to 70 %. A clay content of the sandy beds is smaller than that of the Kanto Loam and the clayey beds. Specific gravity of material forming each bed is nearly equal (about 2.66). Dry density of the Kanto Loam is much smaller than that of the clayey beds and the sandy beds. Porosity of the Kanto Loam is larger than that of the clayey beds and the sandy beds. Liquid limit of the Kanto Loam and the clayey beds is about 110 %; however, the Kanto Loam of Slope T3-SW shows especially a higher value. Plastic limit of the Kanto Loam is larger than that of the clayey beds.

Natural water content of each bed ranges 6 to 70 %, and the value of Sandy Bed 2 of Slope T3-SW is especially small (Table 4b). Each slope-forming bed is fully dried in the south-facing slope, but have a high water content in the north-facing slope during winter (Table 5).

Measured values for the Kanto Loam and the clayey beds located upper part of the slope nearly agree with the values obtained by early workers (e.g., Tada and Yamazaki, 1963; Kanto Loam Research Group, 1965, p.340-345; Kanai, 1972; Highway Research Group, 1973, p.65-77) mentioned in Chapter II.

3. MECHANICAL PROPERTIES

3.1 Method

Unconfined compressive strength, tensile strength and shear strength were examined as mechanical properties of the bed-forming materials. Because these strengths vary with water contents (Terzaghi and Peck, 1948, p.31; Chorley, 1959, 1964; Kanto Loam Research Group, 1965, p.354-356), the test was performed under various water contents for the following representative materials: the Kanto Loam, clayey beds and sandy beds.

Three kinds of strengths were measured by using undisturbed specimens taken from Slope T2-SW (sampling points are shown in Figure 7). Because it was extremely difficult to make regular shaped specimens using samples including cracks, the specimens used here include no visible cracks. Shape of the specimens used for the compression test was cylinder; its diameter and height were 5 cm and 10 cm, respectively. Specially shaped specimens were made for the tension test (Photograph 12); the diameter of both ends was 5 cm and that of middle part was 3.5 cm, and the whole specimen height was about 10 cm. For the shear test, the specimens having a diameter of 6 cm and a height of 2 cm were used. Saturated specimens (after one week immersion) and air dried specimens were used for these tests.

Compressive strength was measured on the basis of JIS A 1216. For the tension test, a specially-built measurement apparatus was used (Photograph 13). A box shear apparatus with a single shear plane was used to perform Q-tests which were based on the method established by Japanese Society of Soil Mechanics and Foundation Engineering (1969., p.361-397).

3.2 Results

(a) Unconfined compressive strength

Test results are shown in Figure 15. Compressive strength of the Kanto Loam and the clayey bed material is nearly equal for any water content. The strength of each slope-forming material, irrespective of the Kanto Loam, the clayey beds and the sandy beds, decreases with an increase in the water content. However, the strength of the Kanto Loam and the clayey bed material is larger than that of the sandy beds. The strength of the Kanto Loam is about 0.8 kgf/cm^2 under fully saturated condition, namely, 100 % water content. The strength of the clayey beds is about 0.7 kgf/cm^2 under saturated conditions, i.e., about 80 % water content. The strength of the sandy beds is about 0.3 kgf/cm^2 under saturated conditions with a water content of about 65 %. Under such saturated conditions, compressive strength of the Kanto Loam and the clayey beds is about 2 to 3 times greater than that of the sandy beds. The Kanto Loam and the clayey bed material are "stronger" than the sandy beds.

The strength values of the Kanto Loam and the clayey beds obtained here are approximately similar to those obtained at other locations by Kanai (1972) and Highway Research Group (1973, p.82) (see Section 3 in Chapter II). This suggests that the test results can be extended to all study slopes.

(b) Tensile strength

The result of the tension test shows a similar tendency to that of the compression test (Figure 16). The tensile strength of the Kanto Loam is about 0.1 kgf/cm^2 under fully saturated conditions with a water content of about 100 %. The strength of the clayey beds is 0.04-0.2 kgf/cm^2 at a water content of about 80 %. The sandy beds have a strength of about 0.015 kgf/cm^2 when the water content is 70 %. Under these saturated conditions, tensile strength of the Kanto Loam and the clayey beds is about 7 times greater than that of the sandy beds.

(c) Shear strength

Because the depth of shallow slides is small, i.e., the normal stress is extremely small, cohesion of each slope-forming material should be compared. The result of the test shows a similar tendency to that of the compression and tension tests (Figure 17). Cohesion of the Kanto Loam is about 0.4 kgf/cm^2 under saturated conditions, namely, at a water content of about 95 %. The clayey beds have a cohesion of about 0.2 kgf/cm^2 under the water content is about 70 %. Cohesion of the sandy beds is about 0.2 kgf/cm^2 at a water content of about 60 %. Under such saturated conditions, cohesion of the clayey beds is nearly equal to that of the sandy beds. However, the value of the Kanto Loam is 2 times greater than that of the sandy beds and the clayey beds.

The Kanto Loam and the clayey beds have similar cohesion values to those obtained through tests conducted in other places by early workers (e.g., Kanto Loam Research Group, 1965, p.346; Kanai, 1972) (see Section 3 in Chapter II). Similar to compressive strength, the test results can be applied to all study slopes.

4. MINERALOGICAL PROPERTIES

4.1 Method

Clay minerals of the slope-forming material were examined. Samples were taken from Slopes T2-SW, T3-SW and N1 through N6. Sampling points are shown in Figures 6d, 6e and 7.

The type of clay minerals was detected on the basis of X-ray diffraction analysis for the samples after hydraulic elutriation. A color reaction method (Sudo, 1974, p.422) with sodium fluoride (NaF) and phenolphthalein ($C_{20}H_{14}O_4$) was used for the detection of allophane. Clay minerals were observed using a Transmission Electron Microscope (TEM). Clay mineral content was qualitatively examined according to color intensity in the color reaction method and through observations using TEM.

4.2 Results

X-ray diffractograms of clay fractions of the slope-forming beds of Slopes T2, T3, N1 and N4 are shown in Figures 18a and 18b, in which the Kanto Loam (T3-1, N4-1, N1-2 and N1-4) has a maximum located at around 25° (3.5 Å) suggesting the existence of allophane (Tsuchiya and Kurahayashi, 1958). Moreover, allophane was detected in the Kanto Loam by means of the color reaction method (Sudo, 1974, p.422). A diffraction peak appears at around 8.8° (10 Å) in Takaragi Loam (N1-2) and Hoshakuji Loam (N1-4) (see Figure 18b). This peak shifts to around 12° (7.4 Å) after 110°-C heat treatment (Figure 19). This suggests that the clay mineral is hydrated halloysite.

From Figure 18a, illite and halloysite are found to exist in the sandy bed (T3-2 and T2-3). In the clayey bed (T3-3), halloysite was detected. In the pumice bed (N1-1) and the scoria bed (N1-3), allophane was detected

(Figure 18b). Moreover, allophane was also detected in both beds by means of the color reaction method.

Clay minerals in the Kanto Loam, clayey beds, pumice beds and scoria beds are shown in electron-microscopic photographs (Photographs 14a and 14b). In the Kanto Loam (T3-1 and N2-1), fibrous clay minerals are found; these clay minerals are considered as imogolite. Halloysite and hydrated halloysite are found in the clayey beds (T3-3) and the Kanto Loam (N1-2, N2-1 and N1-4), respectively.

These results show that the clay minerals in the younger Kanto Loam are mostly allophane, and those in the older Kanto Loam are mainly composed of hydrated halloysite. In the pumice beds and the scoria beds, allophane is the principal constituent of the clay minerals. The clay minerals in the clayey beds are composed of halloysite. Sandy beds contain small amount of illite.

The results obtained in this study are similar to those of early workers (e.g., Tsuchiya and Kurahayashi, 1958; Kurahayashi and Tsuchiya, 1959, 1960, 1961; Matsui, 1960; Kanto Loam Research Group, 1965, p.225-234).

5. SHRINKAGE TEST

5.1 Method

Cracks are formed by shrinkage due to drying (Yong and Warkentin, 1975, p.197). A shrinkage test was performed using undisturbed samples taken from Slopes T2, T3 and N1 through N6 (the location is shown in Figure 2). The shape of specimens used for the test was cylinder; its diameter and height were 5 cm and 10 cm, respectively. The specimens submurged into distilled water for one week were naturally air-dried in the laboratory and shrinkage length was measured using a dial gauge (Photograph 15) at 12- to 24-hour intervals. Shrinkage ratio was obtained using

$$S = (1 - h_i/h_o) \times 100 \qquad (2)$$

where h_o is the initial height of the saturated specimens and h_i is the height of the dried specimens.

5.2 Results

The temporal change in shrinkage length is plotted in Figure 20. This figure shows that the Kanto Loam and the clayey bed samples are more susceptible to shrinkage with some exceptions as compared with the sandy bed, the pumice bed and the scoria bed samples. Most of specimens shrink at the early stage and then attain steady state. Maximum shrinkage-ratio S_{max} defined as the terminal value of the curves in Figure 20 was used as an index of shrinkage susceptibility. For the Kanto Loam, S_{max} ranges from 1.6 to 19.2 %. The clayey beds have S_{max} of 12.2 %. While, S_{max} of the sandy beds, the pumice beds and the scoria beds is about 1.4, 0.3 and 0.9-3.2 %, respectively. S_{max} of the Kanto Loam and the clayey beds is 3 to 14 times larger than that of the sandy beds. The values of S_{max} of the Kanto Loam obtained here approximately agree with Takenaka's (1965) values of Tachikawa and Musashino Loams.

During the shrinkage test, small cracks were formed in the Kanto Loam and the clayey bed samples, but not formed in the sandy, pumice and scoria bed samples.

6. THERMAL PROPERTIES

6.1 Method

On Slope T2-N, the ground temperature at a depth of 1 to 2 cm from the slope surface was measured in the Kanto Loam and Sandy Bed 3 (Figure 7) using a Bourdon tube-type earth thermometer. The continuous measurement was carried out during the period from November 1981 to March 1982.

The thermal conductivity varies with water and ice content (Kersten, 1952; Jumikis, 1977, p.73; Higashi, 1981, p.152-154). Increase in water content in the frozen soil is caused by the migration of the water from the unfrozen part toward the freezing plane (Taber, 1929, 1930; Nakaya, 1942; Nakaya and Sugaya, 1944; French, 1976, p.27; Ishii, 1976). Using undisturbed and saturated soil samples, the thermal conductivity was measured in the laboratory. A condition of –10°C was established for the test of frozen soil, while, 15°C was selected for the test of unfrozen soil.

6.2 Results

Data of the thermal conductivity are listed in Table 6. Frozen samples show values of $2x10^{-3}$ to $4x10^{-3}$ cal/cm·s·°C. The values of the unfrozen samples are generally smaller than those of the frozen samples. The average between the values of different states is shown for each bed.

CHAPTER VI

DISCUSSION

1. RECESSION PROCESS OF SOUTH-FACING SLOPES

On the south-facing slopes, the Kanto Loam and the clayey beds recede in a mode of toppling failures, soilfalls and shallow slides. Such recession is triggered by heavy rainfall, strong winds and severe earthquakes. The assailing force of rainfall, winds and earthquakes acts almost equally on the entire slope. Therefore, the formation of rib-like relief, i.e., the difference in recession rate of the slope-forming beds, is attributed to the difference in the resisting forces of the slope materials. The resisting forces against toppling failures and shallow slides can be represented by compressive strength, tensile strength and shear strength as described before. The Kanto Loam and the clayey beds have larger resisting force than the sandy beds (see Section 3 in Chapter V). Therefore, susceptibility of toppling failures and shallow slides in the Kanto Loam and the clayey beds can not be explained in terms of such mechanical strengths of the slope-forming beds. Such strengths were obtained through the tests using the specimens including no visible cracks, and the influence of cracks upon the decrease in these strengths was not taken into account.

The maximum shrinkage-ratio S_{max} of the Kanto Loam and the clayey beds is 3 to 14 times greater than that of the sandy beds (Figure 20). Because susceptibility of shrinkage is controlled by the clay content and the type of clay minerals (Yong and Warkentin, 1975, p.199; Mitchell, 1976, p.182), the relation among S_{max}, clay content and type of clay minerals was examined. The result is plotted in Figure 21. This figure clearly shows that, irrespective of clay content, cracks are formed both in the field and the laboratory shrinkage test for the Kanto Loam and the clayey beds having S_{max} larger than 3.5 %; and no cracks are formed in the Kanto Loam and the sandy beds having S_{max} smaller than 3.5 %. Kohno (1981) reported that cracks are formed for the compacted Musashino Loam with a maximum shrinkage-ratio of 8.4-12.6 %.

Bed-forming materials other than the Kanto Loam show that S_{max} increases with increasing clay content, as indicated by the dashed curve in Figure 21. But, S_{max} of the Kanto Loam is approximately independent of clay content. The shrinkage of the Kanto Loam seems to be related to the type and the amount of clay minerals.

The value of S_{max} of the Kanto Loam having allophane is generally smaller than that of the Kanto Loam with (1) hydrated halloysite or (2) imogolite and hydrated halloysite. Maekado et al. (1979) already pointed out that imogolite content has a close relation to the shrinkage of the Kanto Loam. These results strongly suggest that the type of clay minerals is an important factor controlling the shrinkage of the Kanto Loam.

Cracks are formed, when the Kanto Loam and the clayey beds having S_{max} larger than 3.5 % are dried. Cracks markedly reduce the strength of the slope-forming beds and cause instability of these beds. On the other hand, cracks are not formed in the sandy beds: no instability occurs.

Soil pillars are formed by the crack development in the Kanto Loam and the clayey beds. Toppling failures (Figure 9) occur in the beds with the soil pillars when heavy rainfall and severe earthquakes act on the slope, so that the beds recede. Moreover, the recession of such beds is caused by strong winds and earthquakes in a mode of soilfalls. Because cracks are not formed in the sandy beds, such soil pillars do not develop. Therefore, the recession of the sandy beds does not occur in such processes as mentioned above. As a result, the Kanto Loam and the clayey beds form the furrows, and the sandy beds form the ridges. However, the ridges have their critical length for protrusion (Figure 11). The recession rate of the sandy beds becomes equal to that of the Kanto Loam and the clayey beds when a long-term recession process is considered. In a short-term processes, however, the recession of the Kanto Loam and the clayey beds is much faster than that of the sandy beds, to form the rib-like relief on the slope. Such relief formation can be ascribed to the shrinkage characteristics of the slope-forming beds.

2. RECESSION PROCESS OF NORTH-FACING SLOPES

Freeze-thaw action takes place on the north-facing slopes. It has been reported that ice lenses can be formed in soil which contains more than 3 % of fine particles (<0.02 mm in diameter) (Casagrande, 1932; Linell et al., 1963). The grain size distribution of each bed fully satisfied this condition (Table 4a).

As mentioned in Section 1 in Chapter V, frost penetration depth controls the recession distance of slope-forming beds. One of the relationships giving frost penetration depth is a modified Berggren formula (Aldrich, 1956) which is given by

$$X = \lambda \sqrt{48kF / L} \qquad (3)$$

where X is the frost penetration depth (cm), k is the thermal conductivity of soil, generally taken as an average between values of the frozen and unfrozen states (cal/cm·s·°C), F is the freezing index (°C·days), L is the latent heat of soil (cal/cm^3), and λ is a dimentionless correction coeficient. The quantities L and F are given by Aldrich (1956):

$$L = 0.8\ w\ \gamma_d \qquad (4)$$

$$F = v_s\ t \qquad (5)$$

where w is the water content in soil (%), γ_d is the dry density of soil (g/cm^3), v_s is the mean ground surface temperature during a freezing period (°C), and t is the duration of the freezing period (days). Substitution of equation (4) into (3) yields

$$X = \lambda \sqrt{60kF\ /\ w\gamma_d} \qquad (6)$$

The coeficient λ is determined by the thermal ratio α and the fusion parameter μ. The thermal ratio is described by Aldrich (1956) as

$$\alpha = v_o/v_s = v_o t\ /\ F \qquad (7)$$

where v_o is the mean annual temperature of the ground surface (°C). The parameter μ can be written (Aldrich, 1956) as

$$\mu = Cv_s / L = CF / Lt \quad (8)$$

where C is the volumetric heat of soil (cal/cm^3·°C) which takes generally on an average of volumetric heat of frozen soil C_f and that of unfrozen soil C_u. The quantities C_f and C_u are given by Aldrich (1956):

$$C_f = \gamma_d(0.17 + w/200) \quad (9)$$

$$C_u = \gamma_d(0.17 + w/100) \quad (10)$$

Actual calculation of frost penetration depth using equation (6) requires the values of γ_d, w, k, F and λ. The values of γ_d, w and k are listed in Tables 4a, 5 and 6, respectively. Mean daily ground temperature is shown in the upper diagrams of Figures 13a and 13b. The freezing index F was obtained from the hatched area in these diagrams. Because the ground temperature of the clayey beds was not measured, F value for the Kanto Loam was substituted for that of the clayey beds. The mean annual air temperature recorded at Shimotsuma Automated Meteorological

Station (Figure 2) was 12.6°C, which was used for v_o. The coefficient λ was obtained from Fukuda's diagrams (Fukuda, 1981, Figures 3, 4 and 5).

In order to examine applicability of equation (6), the calculated and the measured frost penetration depths were compared. Actual frost penetration depths were measured in auger holes (10 cm in diameter) drilled into each bed by a chisel. Snow cover having more than 15-cm thickness influences the frost penetration depth (Higashi, 1954). Because the slope examined here was not covered with snow, such snow-cover influence has not been considered. The calculated depths approximately agree with the measured depths (Figure 22). This result indicates that equation (6) is applicable to the region where temperature varies above and below the freezing point a few times in a year. The modified Berggren formula seems to be applicable to the humid temperate areas.

The frost penetration depths calculated by equation (6) in each freezing period (the period having the hatched part in the upper diagrams of Figures 13a and 13b) were compared with recession distance. The calculated frost-penetration depths in each period are shown as the length of vertical solid lines (Figures 13a and 13b). Each frost penetration depth is cumulated: the cumulated result is shown by a step function. The cumulative values approximately agree with the actual recession distance with one exceptional case of Sandy Bed 3. For this case, the calculation is always overestimated. The reason for this is unknown at present.

The calculated frost-penetration depths of the each bed in a freezing period are approximately equal (see the solid line in Figures 13a and 13b). Because the frost penetration depth is identical with the recession distance in a freezing period, the recession rate of the each bed becomes equivalent; so that the north-facing slopes recede with no marked rib-like relief.

3. SUMMARY OF RECESSION PROCESSES

The results of the discussion is summarized in Figure 23. In the laboratory, mechanical strengths such as compressive strength, tensile strength and cohesion of the Kanto Loam and the clayey beds are larger than those of the sandy beds, irrespective of the slope aspect. On the actual south-facing slopes, many cracks develop in the Kanto Loam and the clayey beds. The cracks are produced by the shrinkage of these materials. The strength of the Kanto Loam and the clayey beds is notably reduced by the cracks. On the other hand, the sandy beds do not shrink, so that cracks are not formed. The

Kanto Loam and the clayey beds recede due to toppling failures, soilfalls and shallow slides caused by rainfall, winds and earthquakes, and are eroded more severely as compared with the sandy beds. As a result, the Kanto Loam and the clayey beds form the furrows and the sandy beds form the ridges, so that rib-like relief is formed. However, the sandy beds fail when the ridge attains a critical protruding length. Needle ices and ice lenses are not formed in the slope-forming materials. Thus, difference in shrinkage potential among the Kanto Loam, the clayey beds and the sandy beds causes different recession process on the south-facing slopes.

On the north-facing slopes, cracks are little formed in the Kanto Loam and the clayey beds. The Kanto Loam, the clayey beds and the sandy beds have high water content during winter; these beds are eroded by slumping due to freeze-thaw action during this period. The depth of slumping is determined by the depth of frost penetration. Because frost penetration depths are nearly the same in these beds, there exists little difference in recession rate among these beds. Rib-like relief is not formed on the north-facing slopes.

CHAPTER VII

CONCLUSIONS

On the basis of the rock control theory, the recession of cutting slopes made of loosely consolidated Quaternary deposits has been studied. The cutting slopes are composed mainly of the Kanto Loam, the clayey beds and the sandy beds. Rib-like relief is formed on the south-facing slopes and is not formed on the north-facing slopes.

As compared with the sandy beds, the Kanto Loam and the clayey beds are much more susceptible to shrinkage, and cracks are formed in these two beds which have a maximum shrinkage-ratio larger than 3.5 %. Cracks are not formed in the sandy beds which have a maximum shrinkage-ratio smaller than 3.5 %. The Kanto Loam composed mainly of hydrated halloysite is susceptible to shrinkage as compared with the Kanto Loam composed mainly of allophane. Shrinkage characteristics of the slope-forming beds is closely related to the clay content and/or the kind of clay minerals.

On south-facing slopes where the variation of water content is large, the strength of the Kanto Loam and the clayey bed material is markdly reduced by crack formation. These two beds recede due to toppling failures and soilfalls caused by heavy rainfall, strong winds and severe earthquakes. The recession rate of the Kanto Loam and the clayey beds is higher than that of the sandy beds in a short-term. The former constitute the furrows and the latter form the ridges to develop the rib-like relief. When the ridges fall, the rib-like relief disappears. Shrinkage characteristics of the slope-forming materials are found to play a most important role in the recession of the south-facing slopes.

On north-facing slopes where the variation of water content is small, the Kanto Loam, the clayey beds and the sandy beds recede mainly due to slumping caused by freeze-thaw action. The depth of slumping is found to be determined by frost penetration depths, which are approximately the same in these three beds. As a result, the slope uniformly recede with no distinct rib-like relief.

At the adjacent locations, the variation of water content in the slope-forming material is differnt according to the slope aspect even if the same material is exposed. On the south-facing slopes, (1) reduction of water content due to much insolation plus (2) shrinkage characteristics of slope material cause the crack formation in the Kanto Loam and the clayey beds, but such cracks are not formed in the sandy beds. These slopes recede forming the rib-like relief. On the other hand, the materials forming the north-facing slopes keep high water content because of being wet due to less insolation; so that the ice lenses are formed during winter in the Kanto Loam, the clayey beds and the sandy beds. These slopes uniformly recede, with no distinct rib-like relief. Thus, two kinds of recession processes are found on the slopes with completely different aspects.

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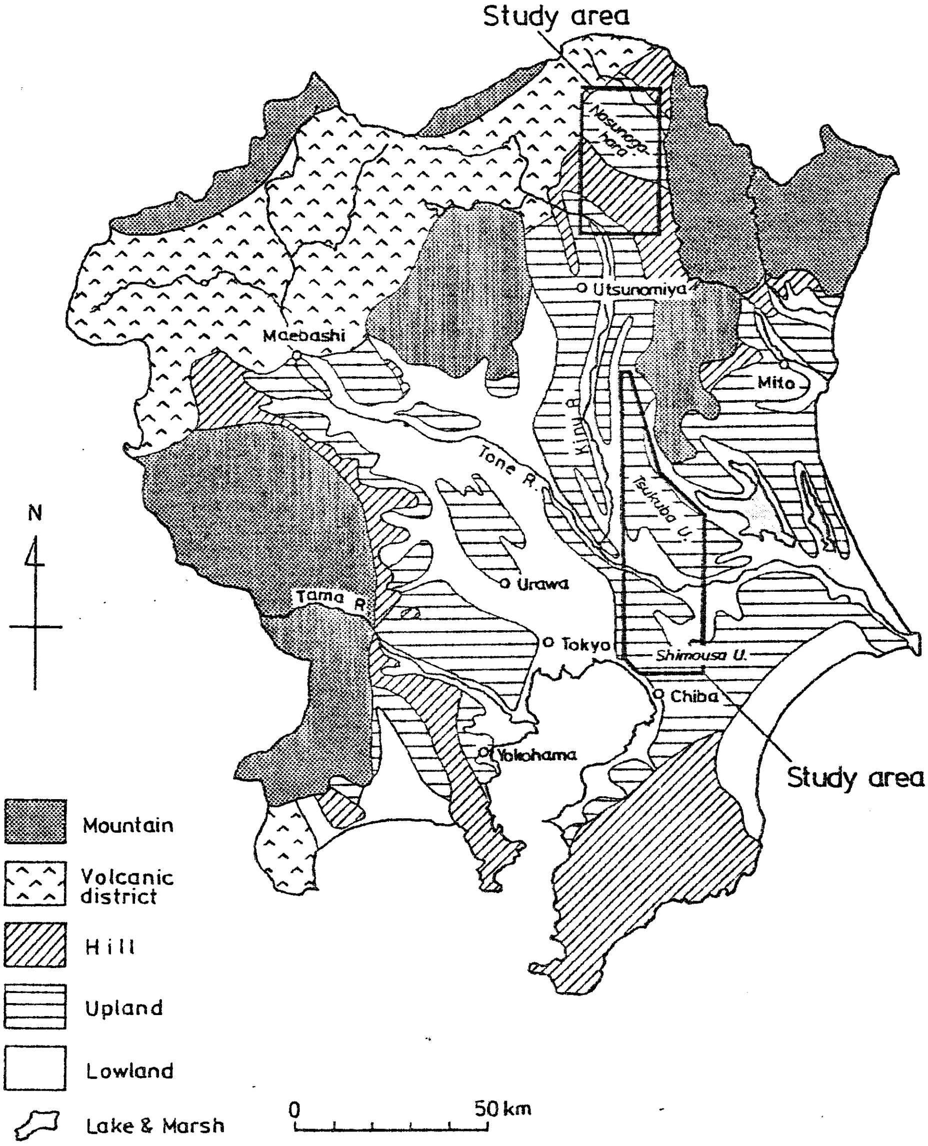


Figure 1 Topographical regions of the Kanto district and locations of the study areas. (Modified after Machida, 1968)

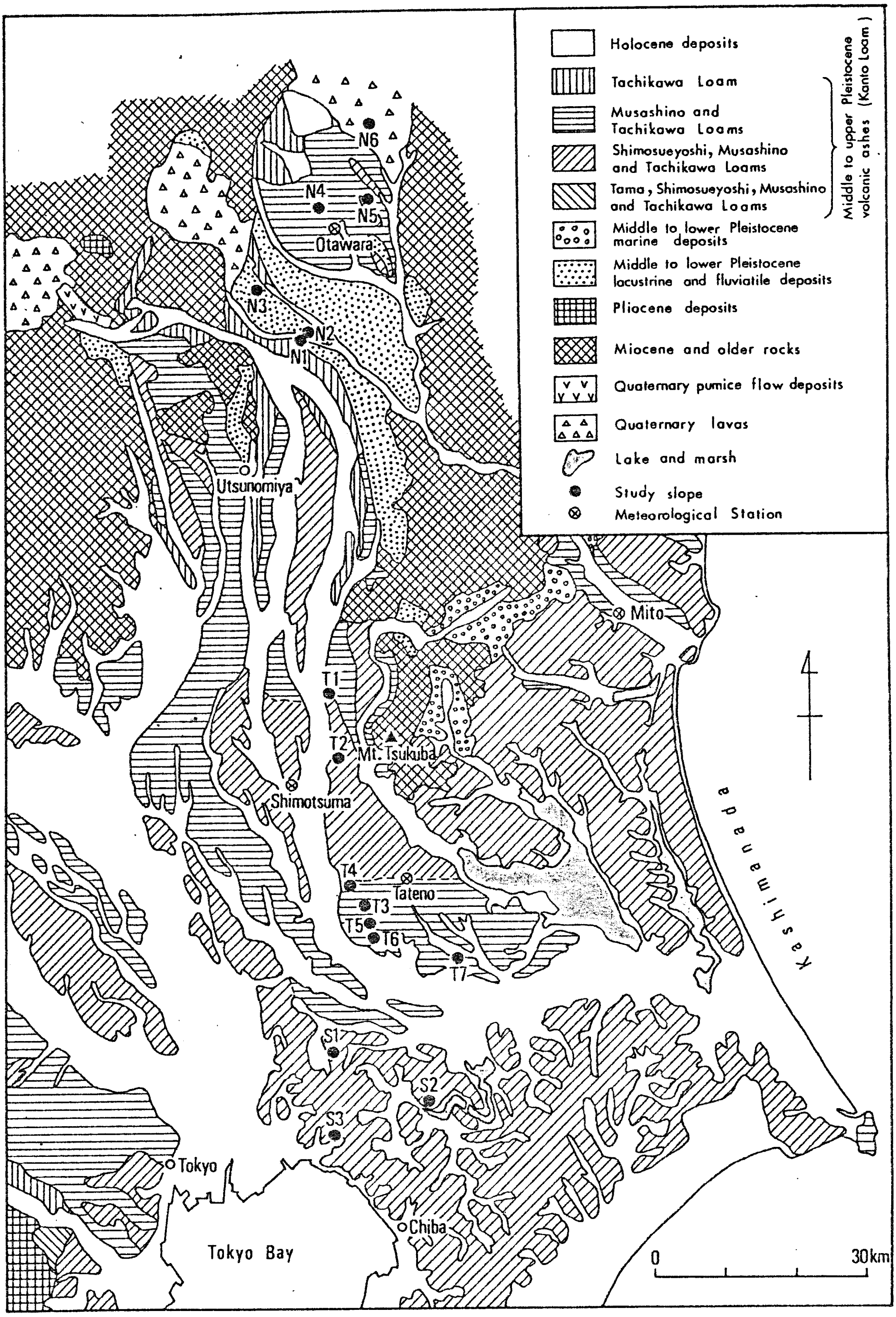


Figure 2 Geologic map of the study areas and locations of the study cutting slopes. (Geologic map is modified after Kanto Loam Research Group, 1965)

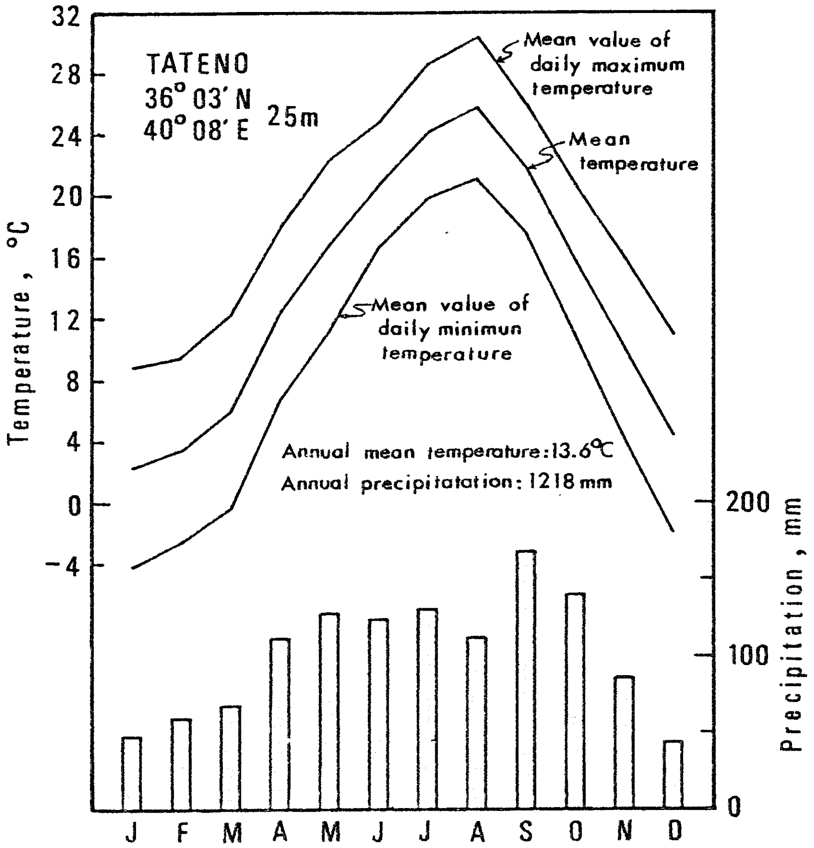


Figure 3a Mean monthly air temperature and precipitation at Tateno, 1970-1979. (Data from Tateno Meteorological Station)

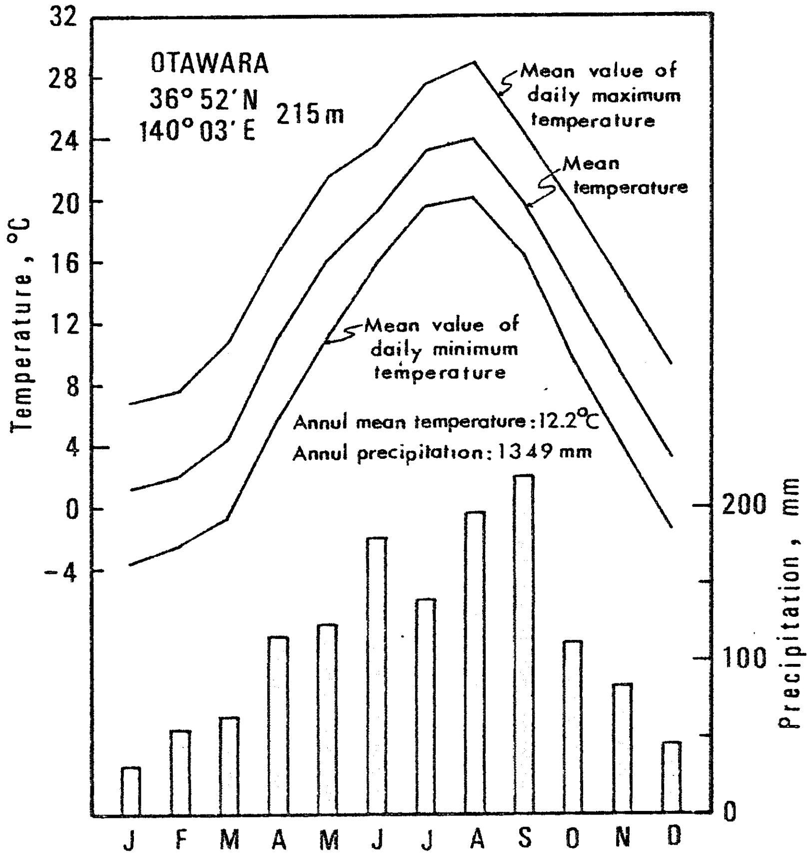


Figure 3b Mean monthly air temperature and precipitation at Otawara, 1970-1979. (Data from Otawara Meteorological Station)

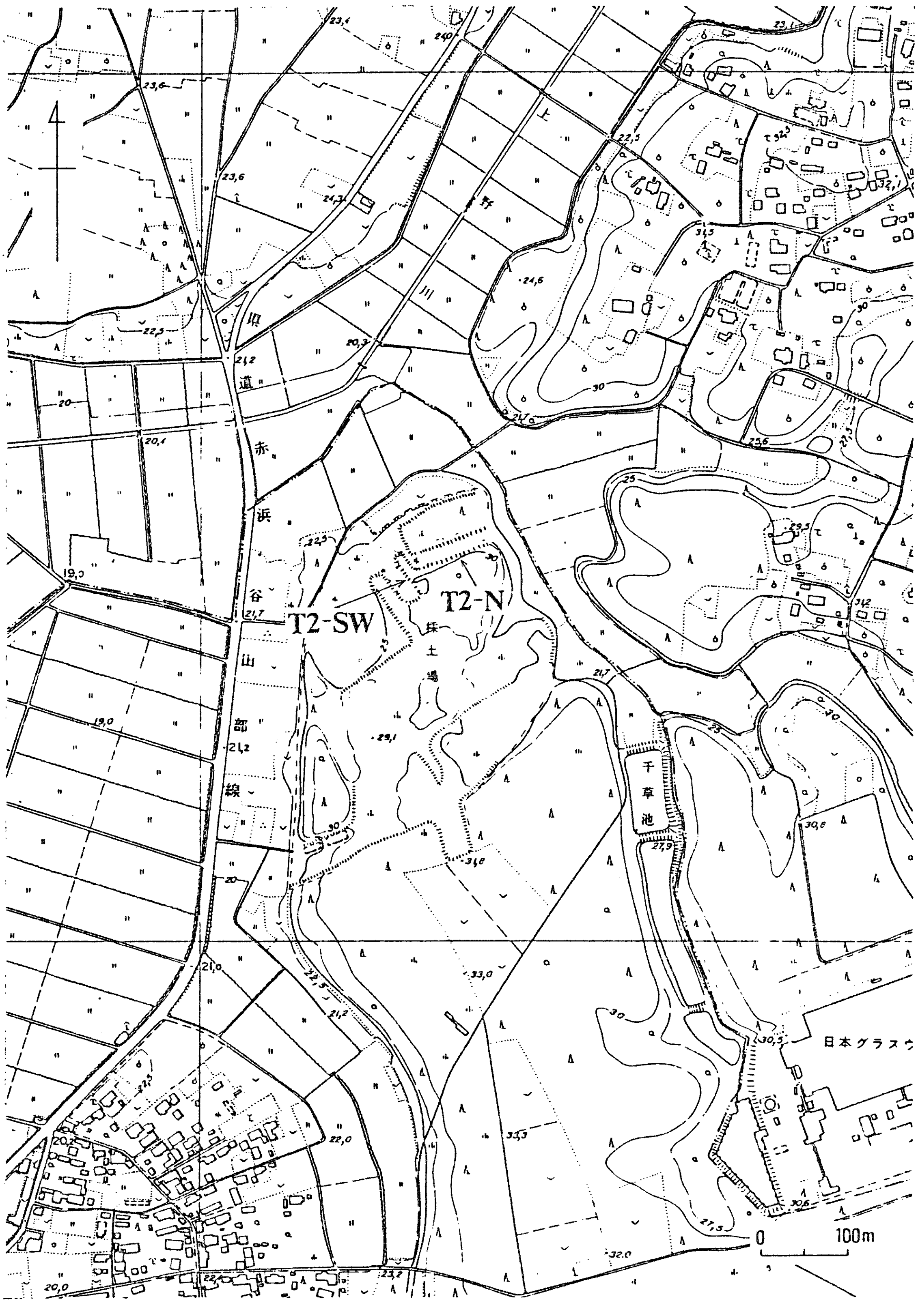


Figure 4 Topographic map around Slopes T2-SW and T2-N. See Figure 2 for location. Topogtaphic map is a part of the 1/5,000 quadrangle "IX-JE-24" published by Geographical Survey Institute of Japan.

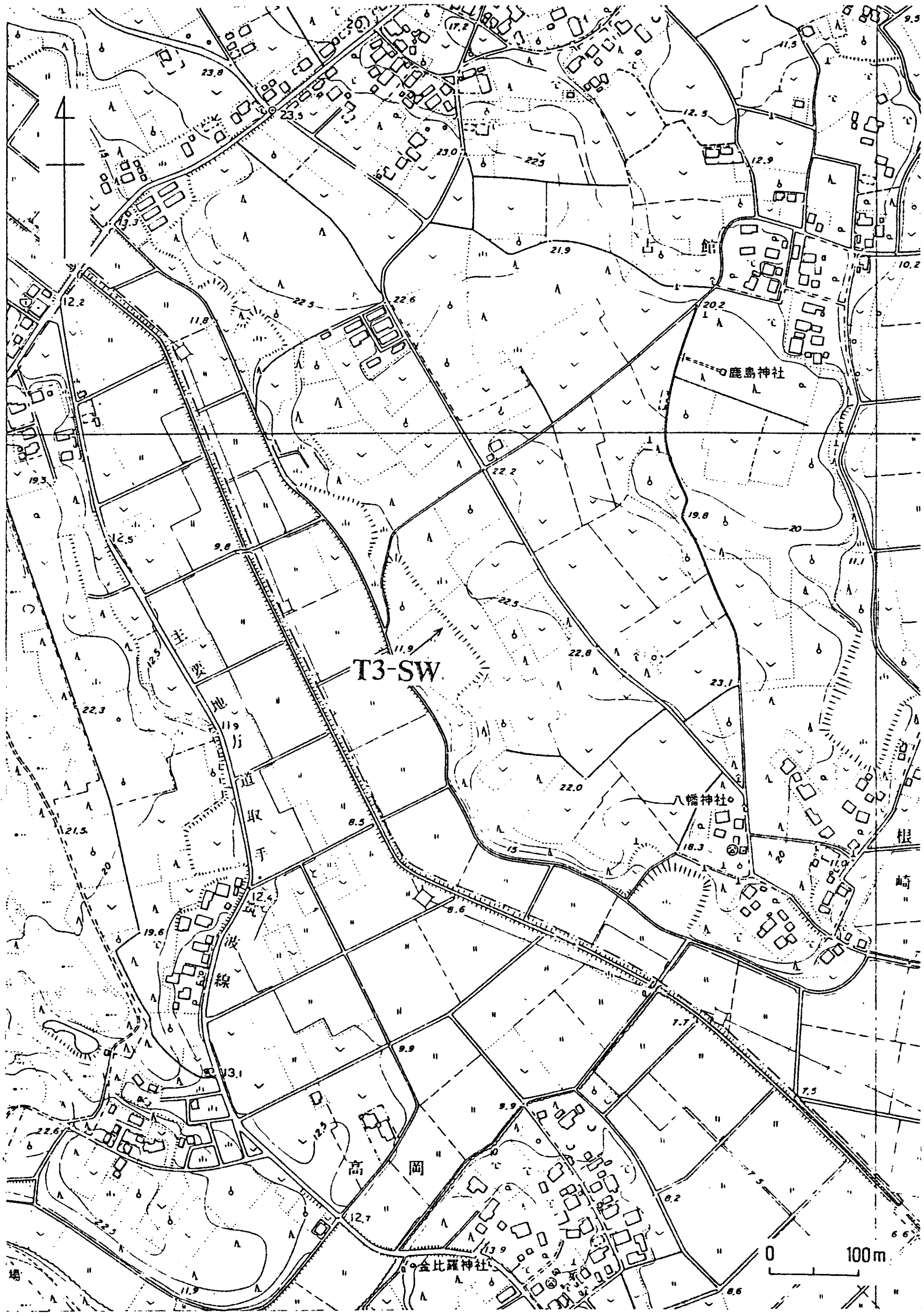


Figure 5 Topographic map around Slope T3-SW. See Figure 2 for location. Topographic map is a part of the 1/5,000 quadrangle "IX-JE-95" published by Geographical Survey Institute of Japan.

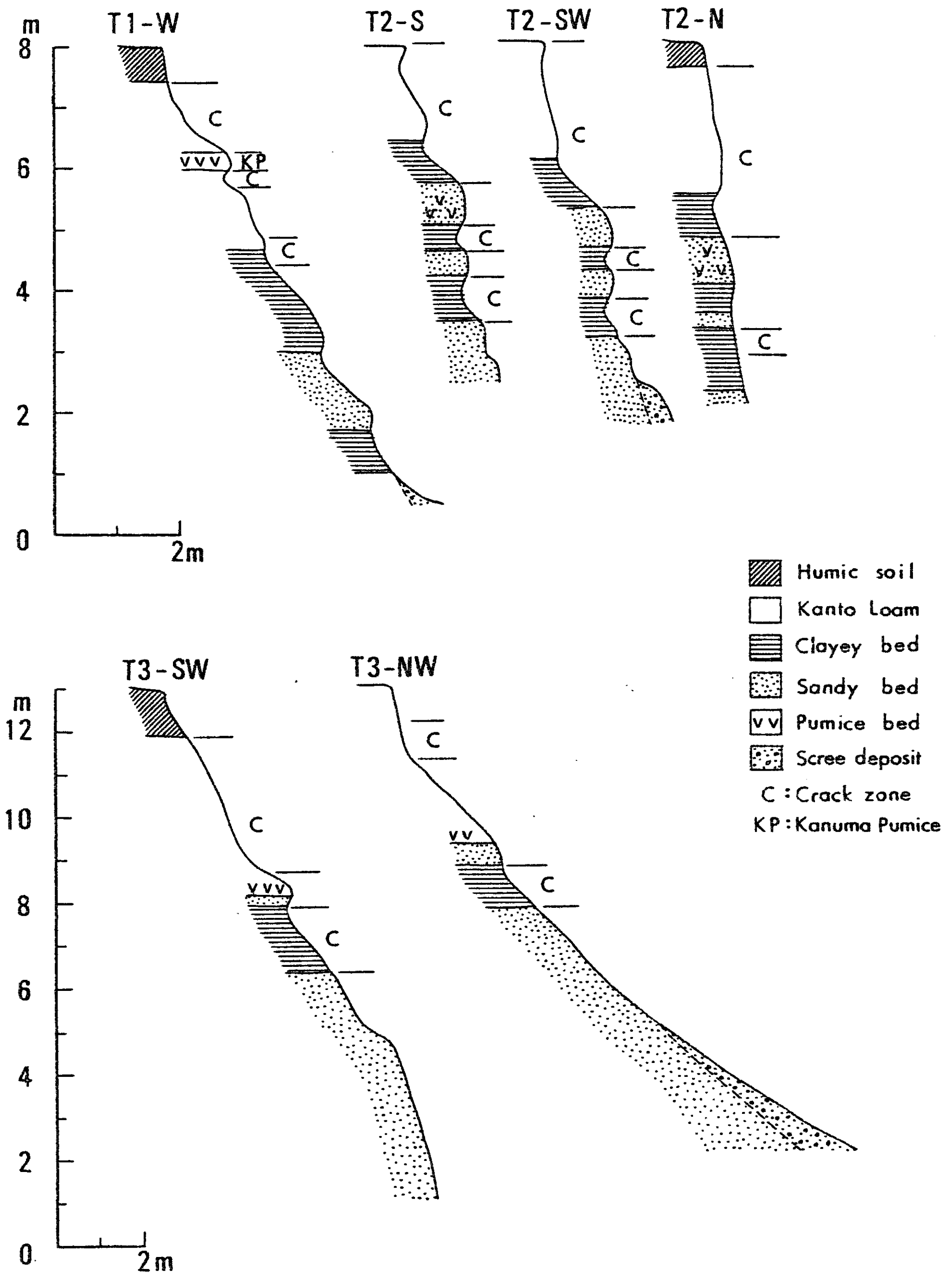


Figure 6a Slope profiles and geologic sections in Tsukuba Upland.

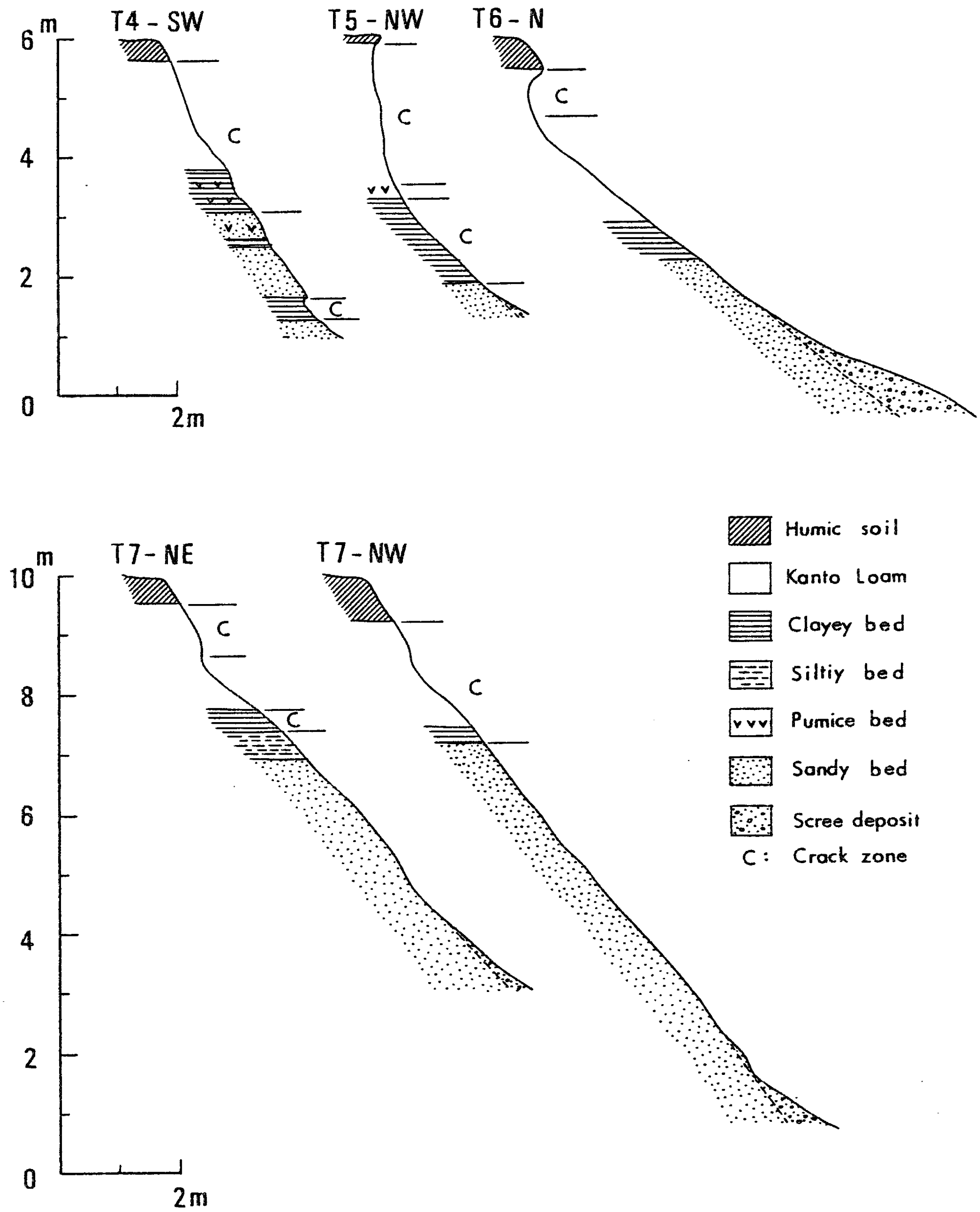


Figure 6b Slope profiles and geologic sections in Tsukuba Upland.

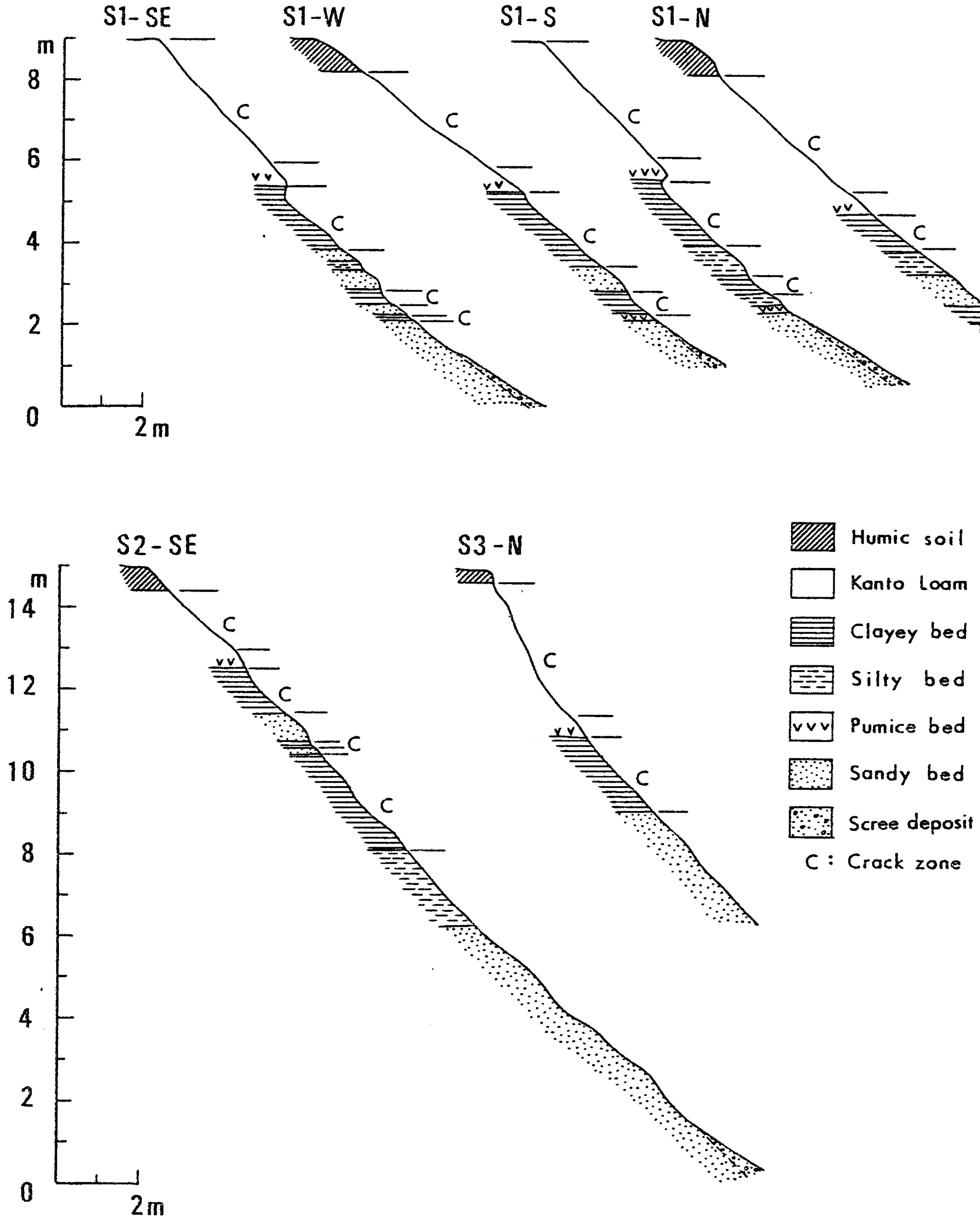


Figure 6c Slope profiles and geologic sections in Shimousa Upland.

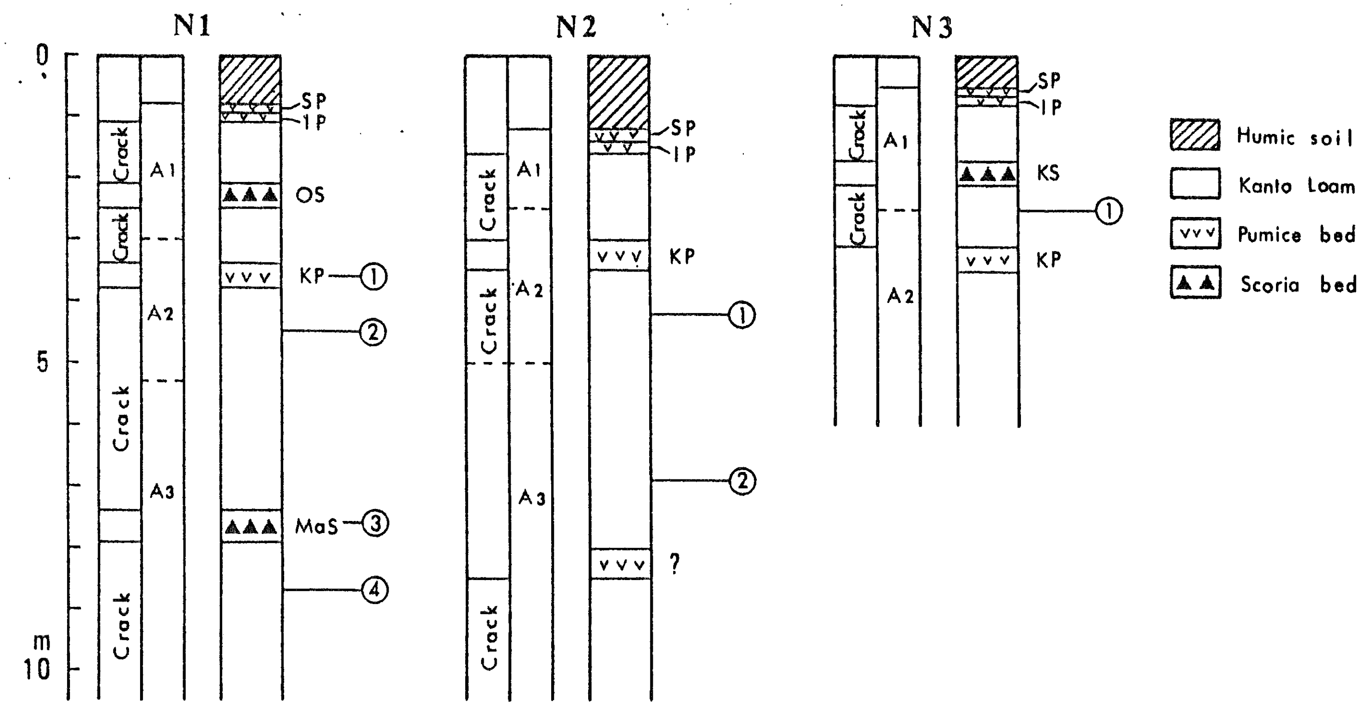


Figure 6d Columnar sections in the environs of Nasunogahara Fan. ①-④: Soil sampling points.

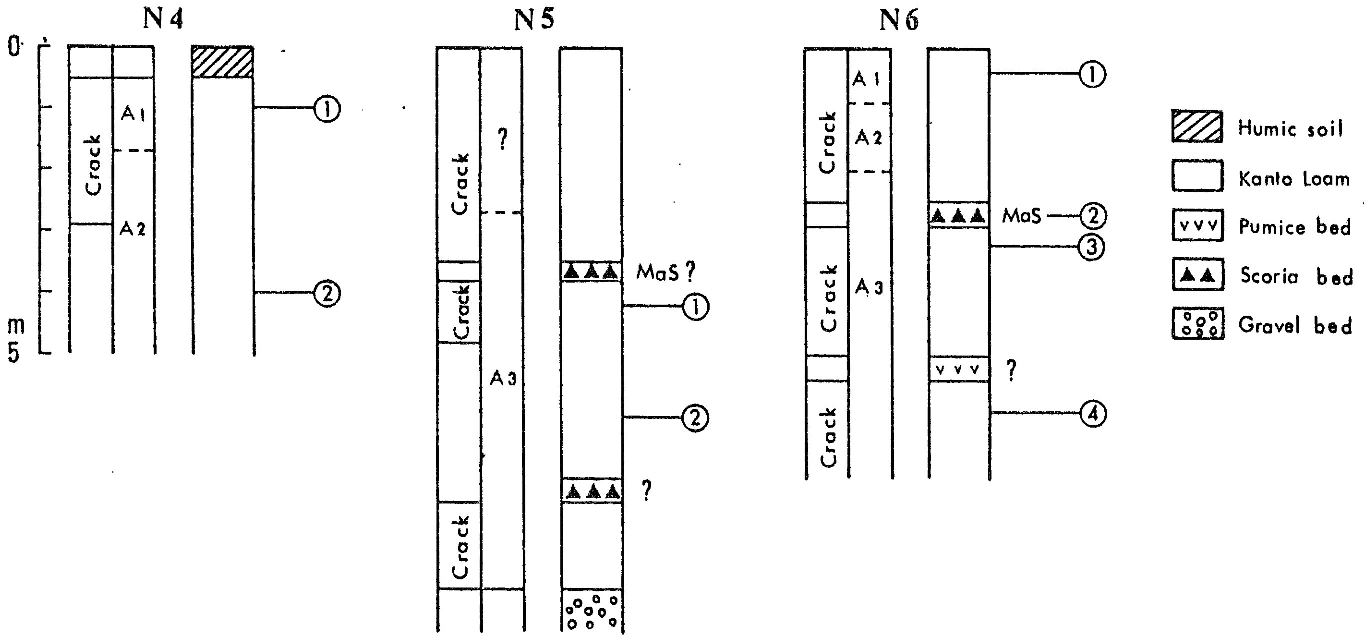


Figure 6e Columnar sections in the environs of Nasunogahara Fan.

① - ④ : Soil sampling points.

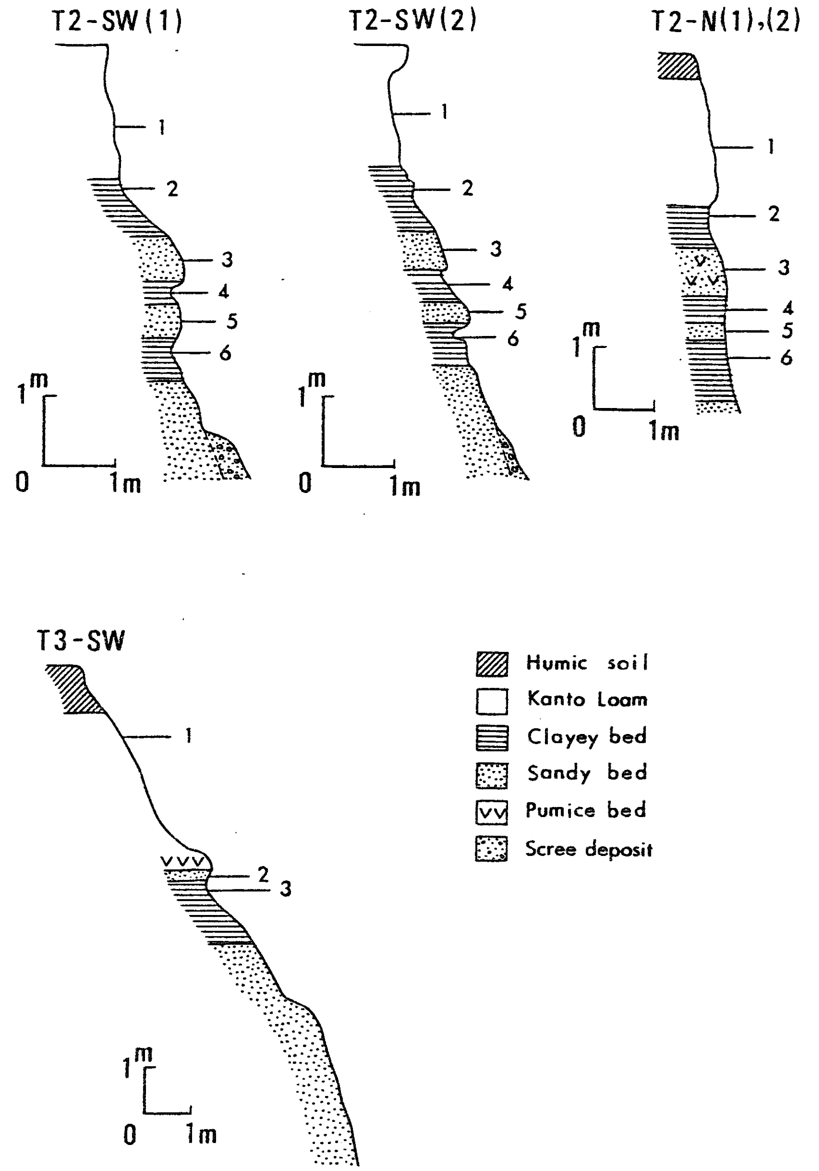


Figure 7 Measuring points of soil properties and recession distances.

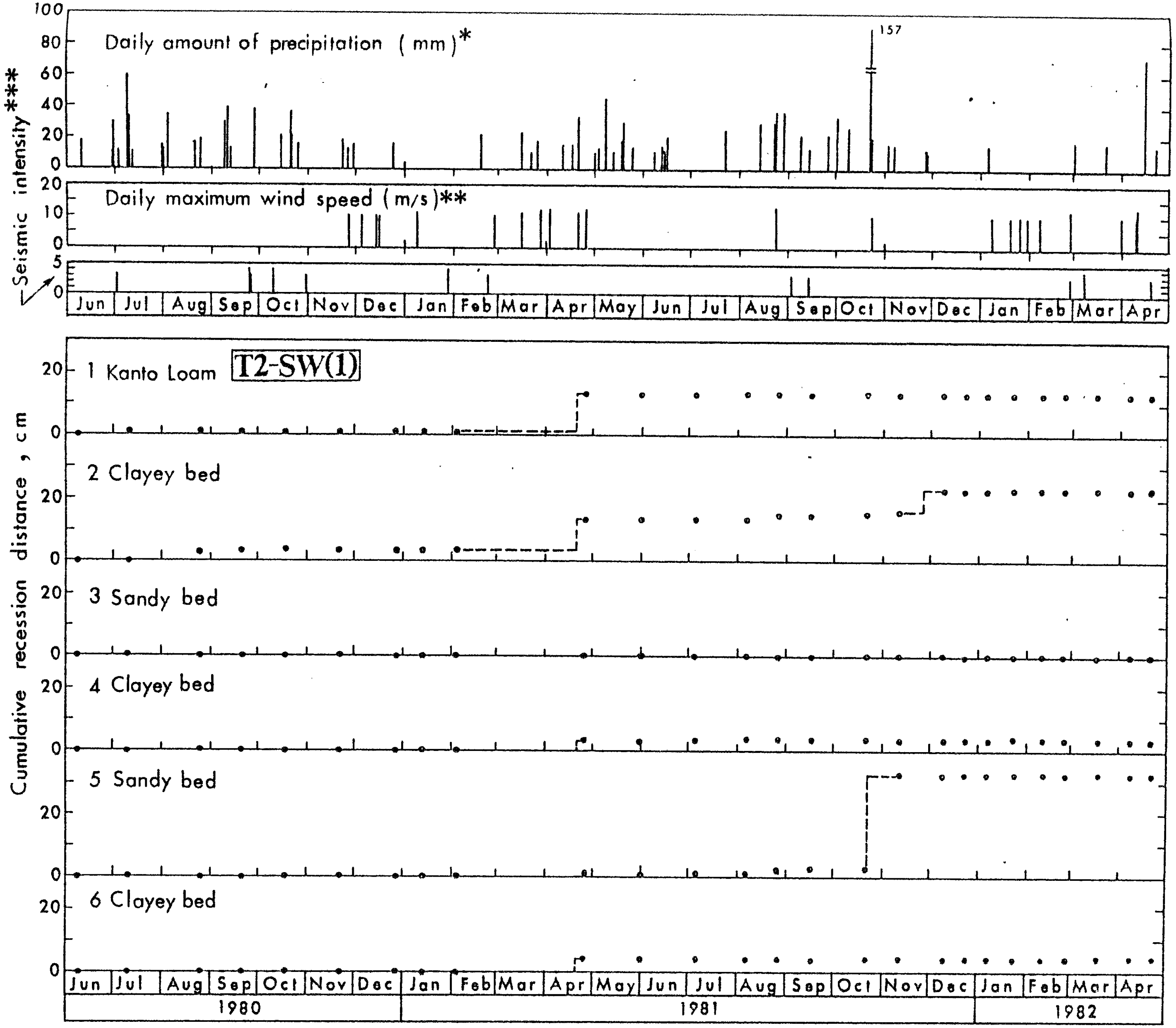


Figure 8a Temporal changes of geomorphic agents and cumulative recession distance at Slope T2-SW(1). *: >10 mm at Shimotsuma, ** : >10 m/s at Shimotsuma, ***: >3 at Mito.

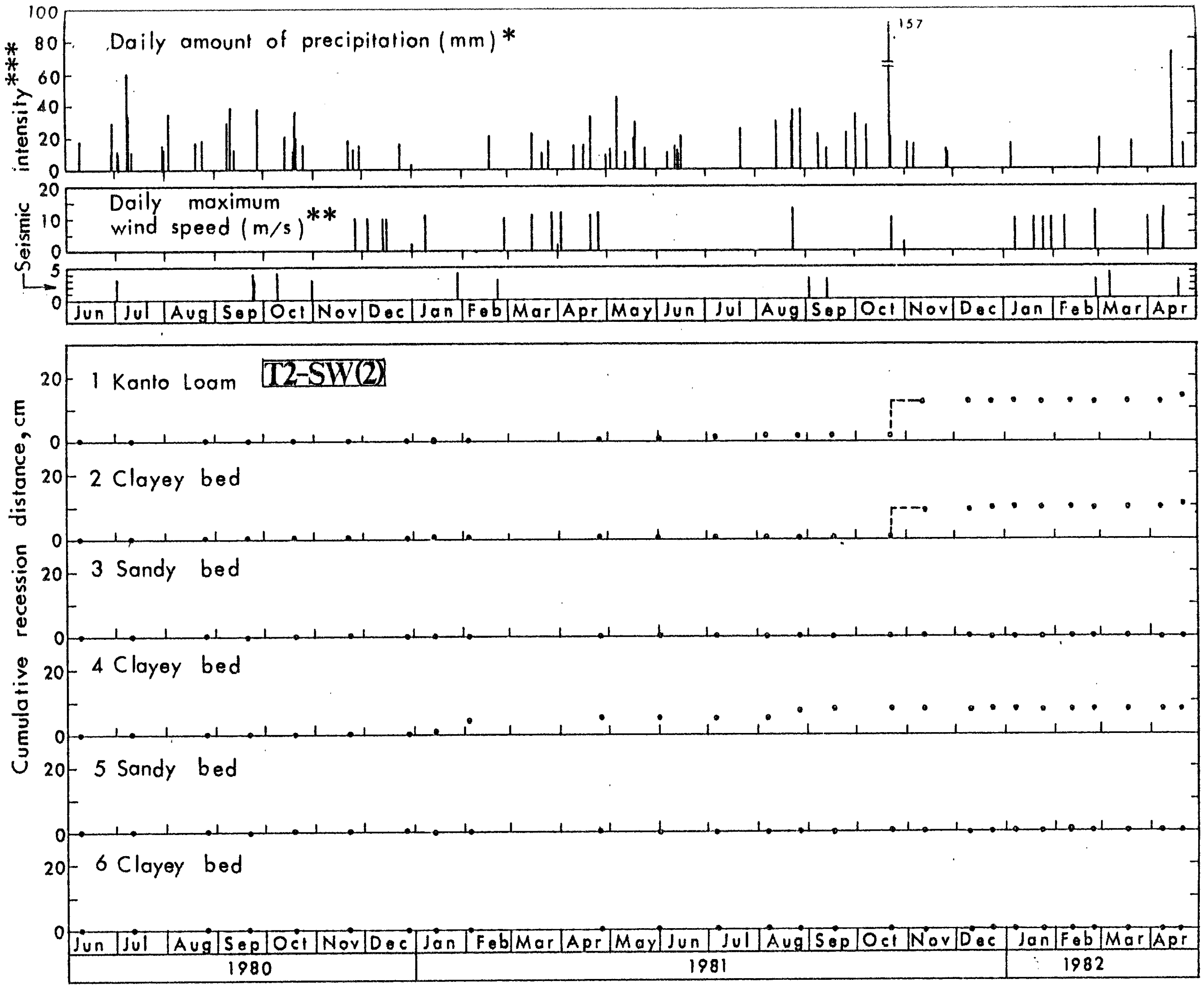


Figure 8b Temporal changes of geomorphic agents and cumulative recession distance at Slope T2-SW(2). *: >10 mm at Shimotsuma, **: >10 m/s at Shimotsuma, ***: >3 at Mito.

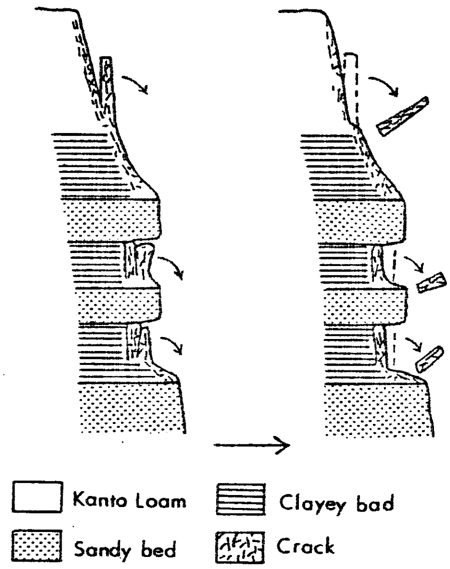


Figure 9 Schematic diagrams illustrating toppling failura.

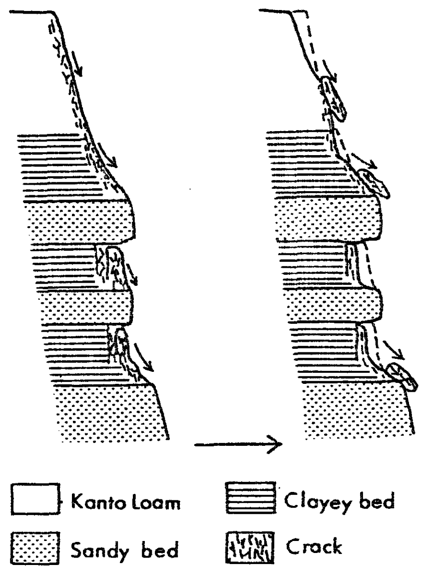


Figure 10 Schematic diagrams illustrating shallow slide.

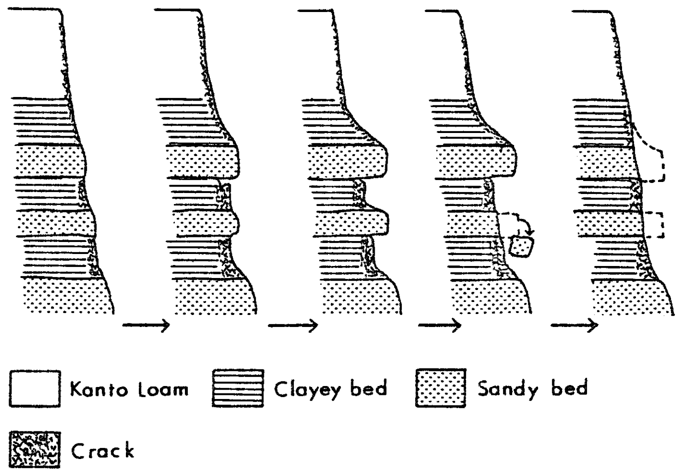


Figure 11 Schematic diagrams illustrating failure process of sandy bed ridge.

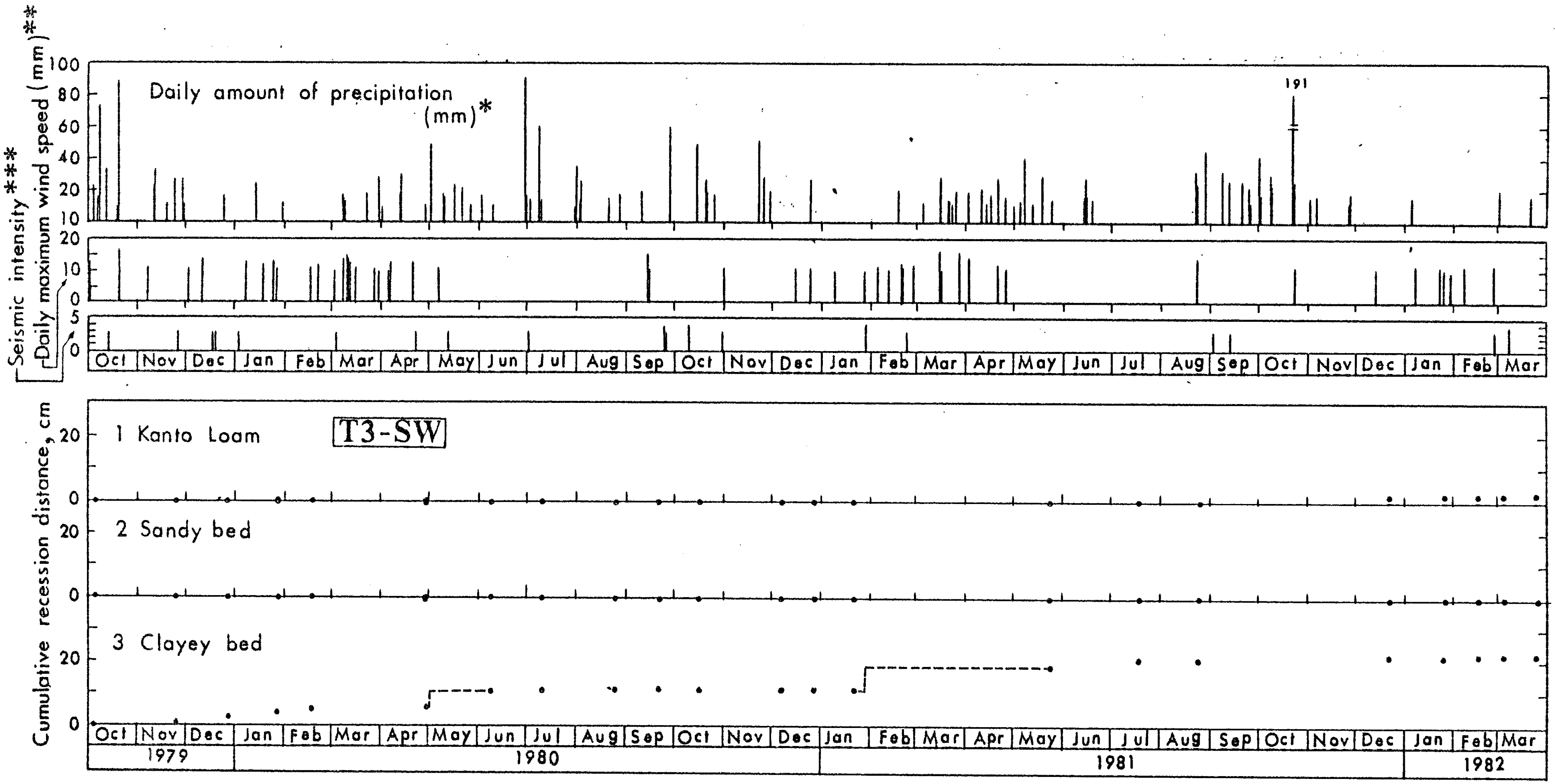


Figure 12 Temporal changes of geomorphic agents and cumulative recession distance at Slope T3-SW. *: >10 mm at Tateno, **: >10 m/s at Tateno, ***: >3 at Mito.

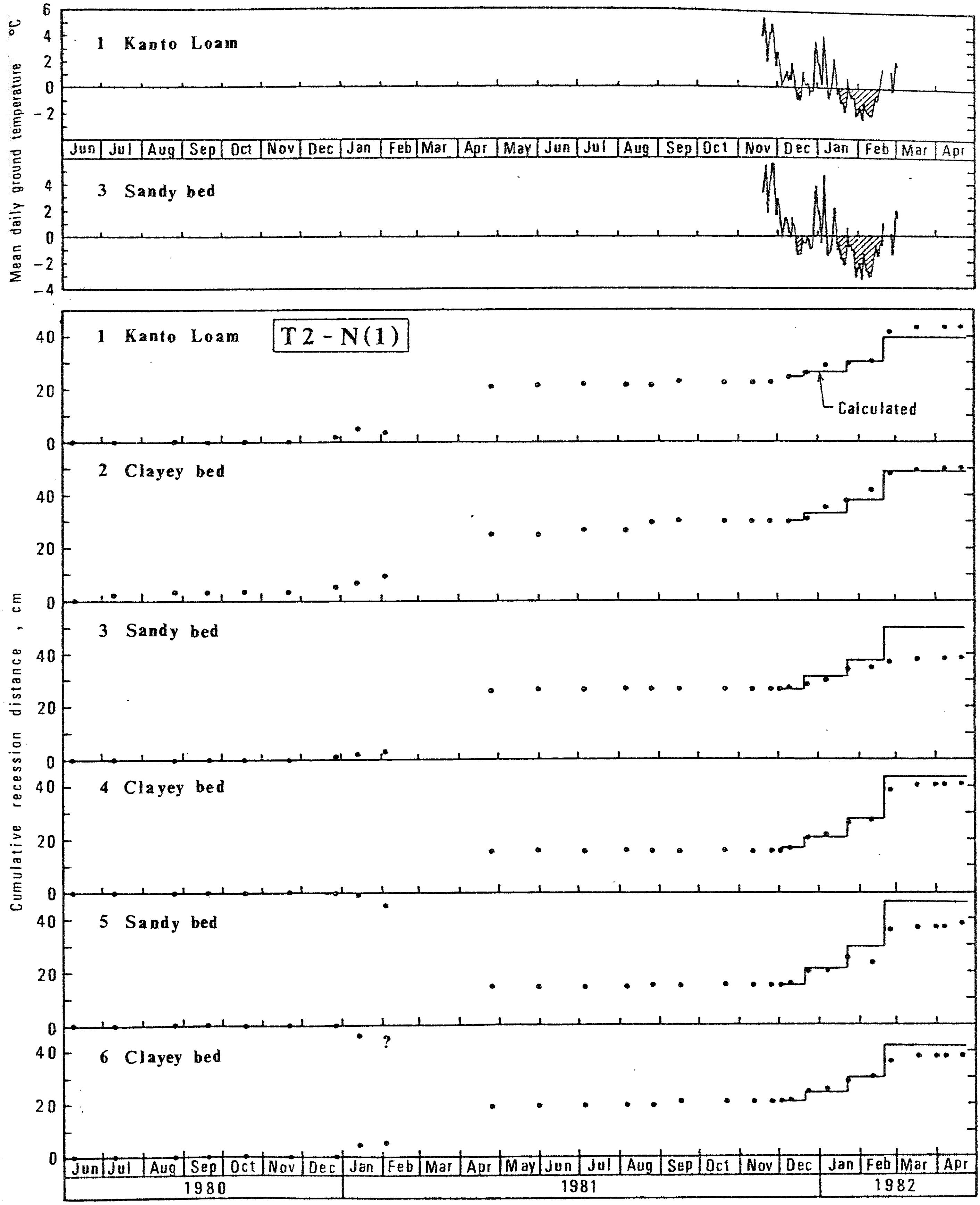


Figure 13a Temporal changes of daily ground-temperature and cumulative recession distance on Slope T2-N(1).

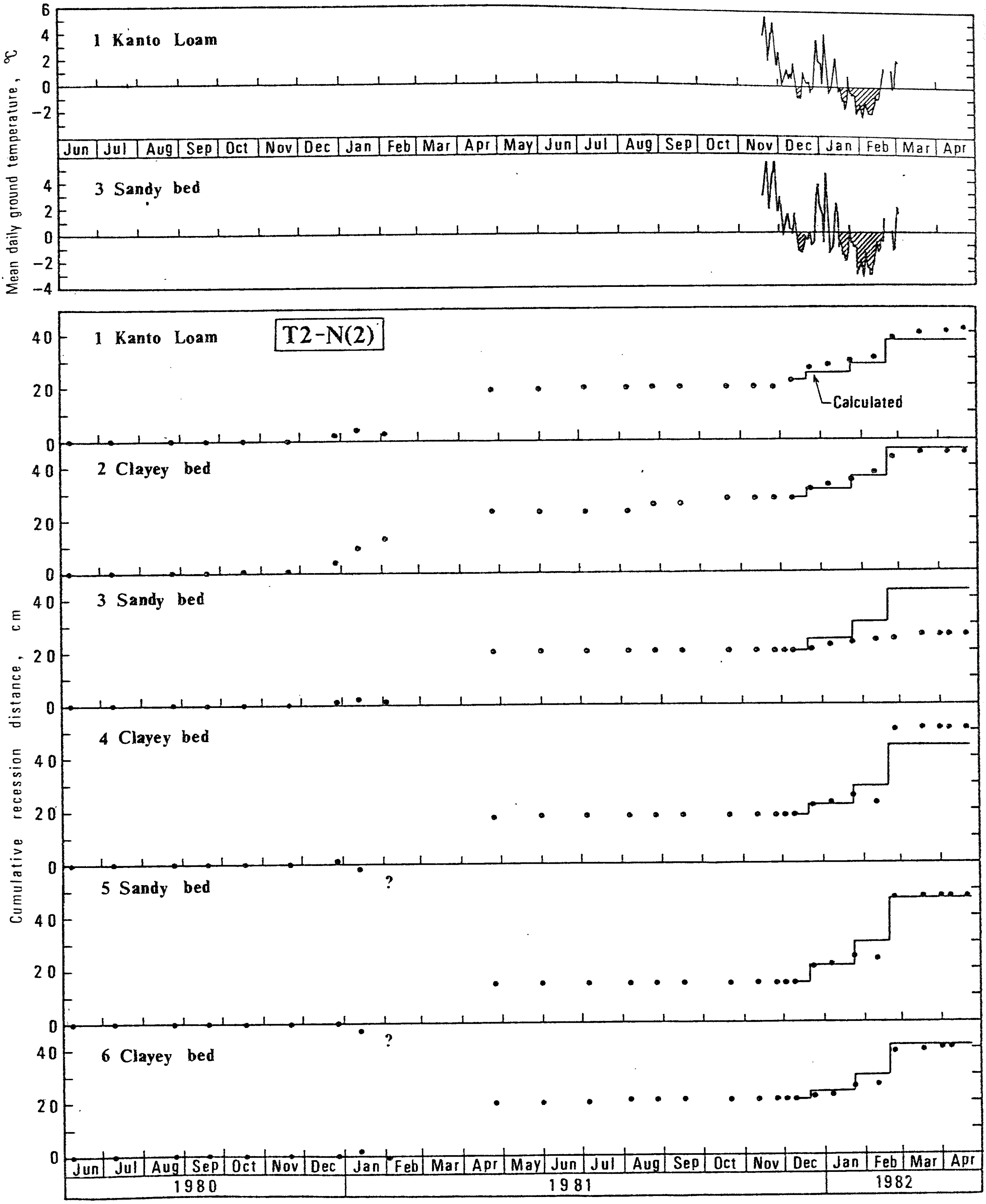


Figure 13b Temporal changes of daily ground-temperature and cumulative recession distance on Slope T2-N(2).

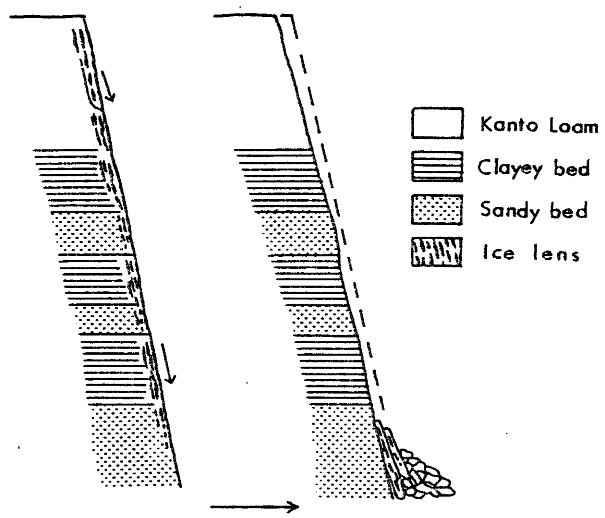


Figure 14 Schematic diagrams illustrating slumping.

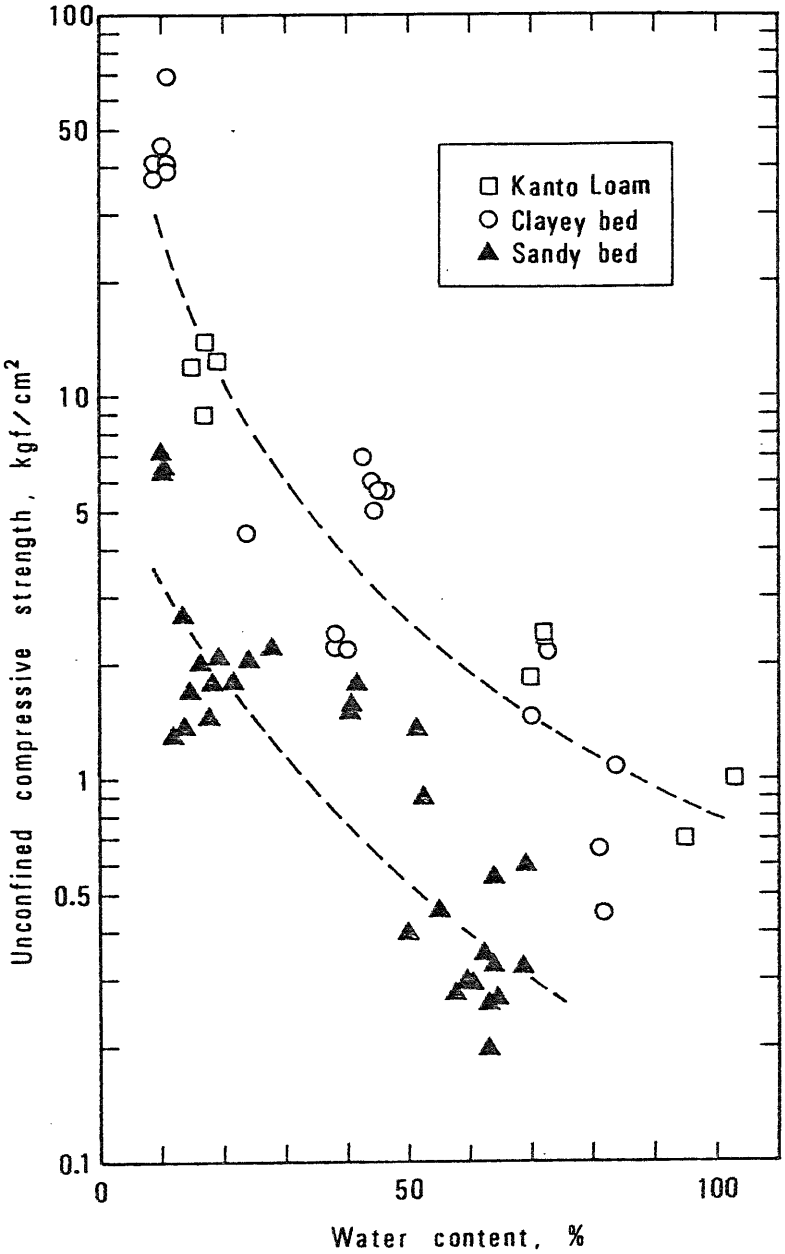


Figure 15 Relation between unconfined compressive strength and water content.

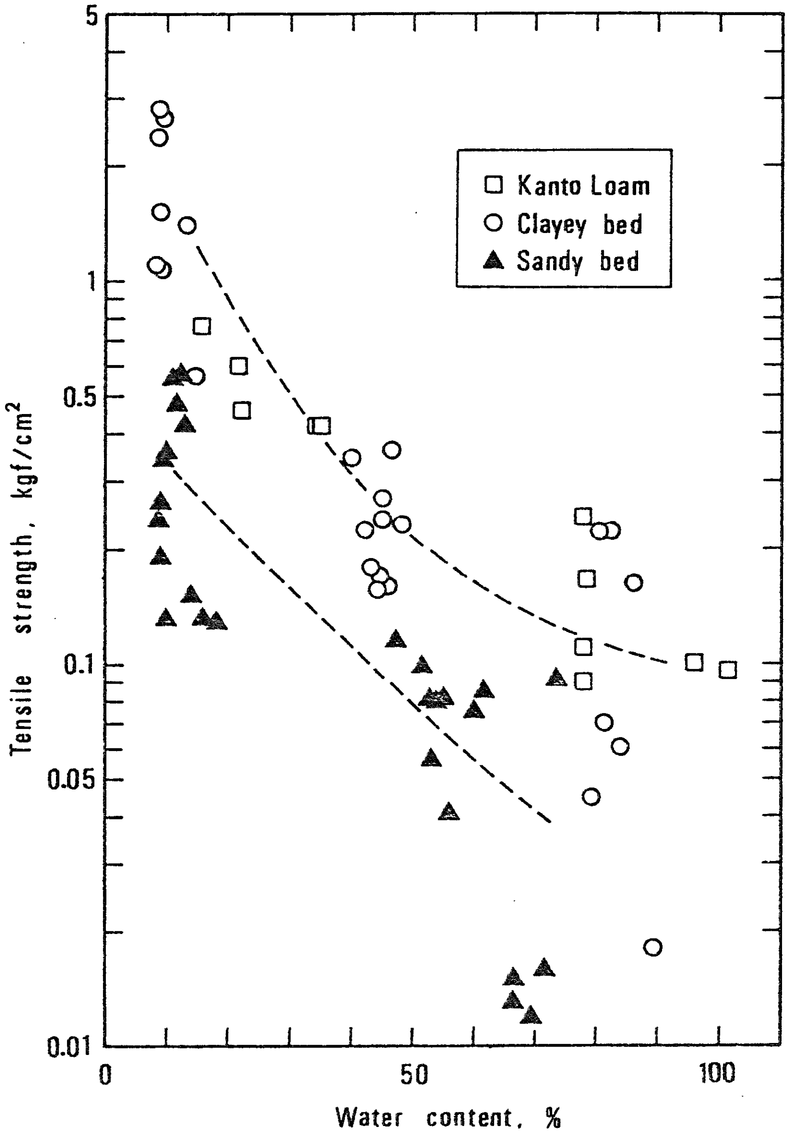


Figure 16 Relation between tensile strength and water content.

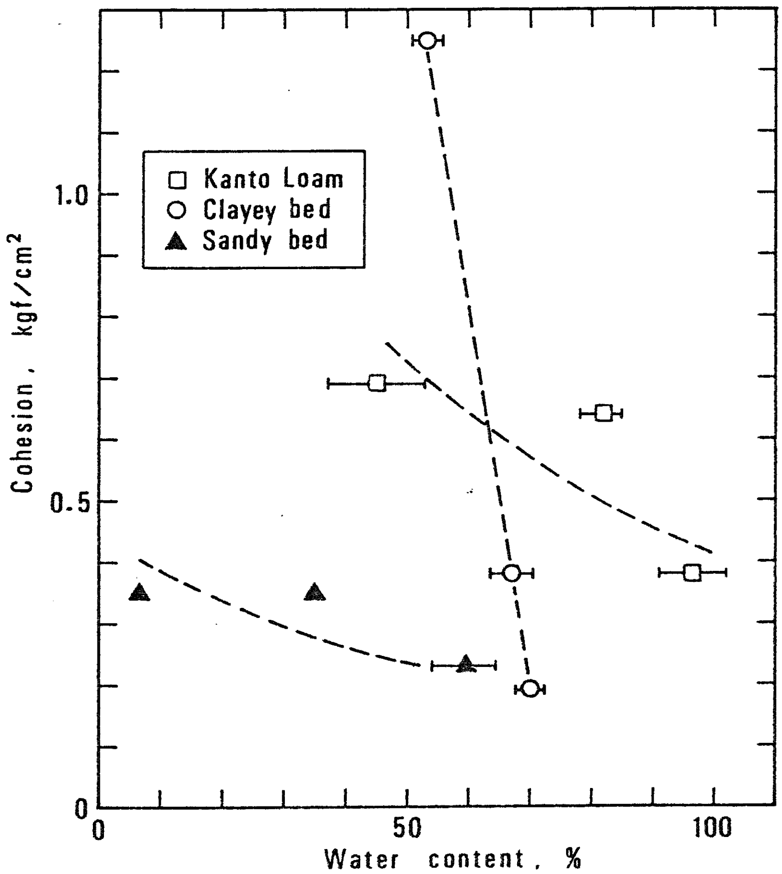


Figure 17 Relation between cohesion and water content.

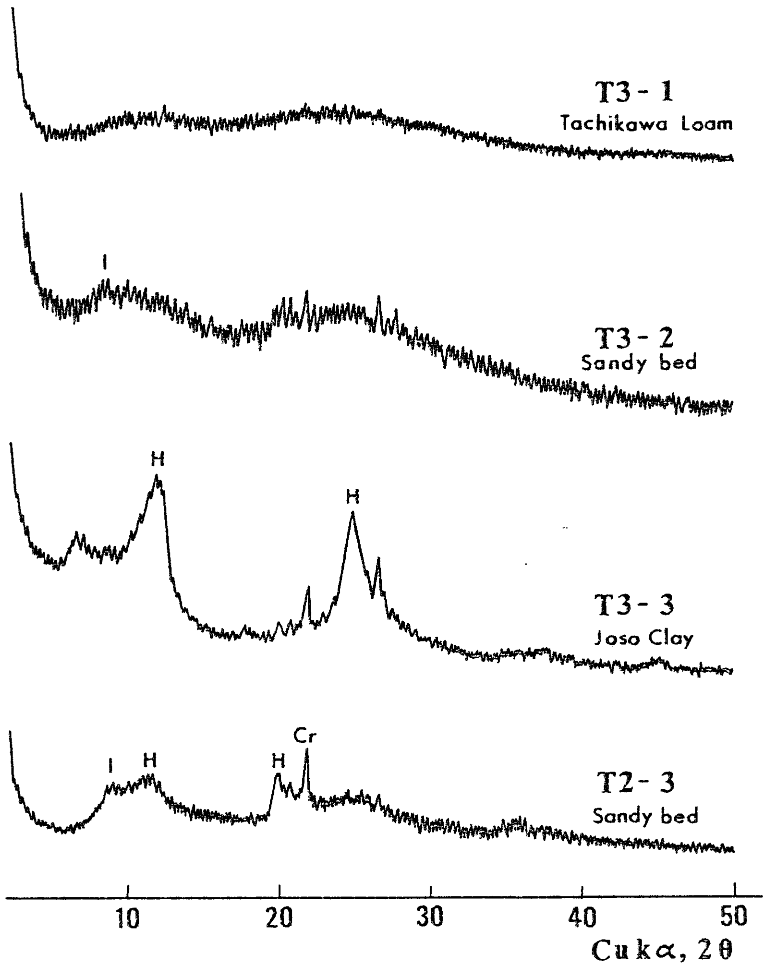


Figure 18a X-ray diffraction diagrams of clay fractions. The number after the hyphen means the soil sampling point. I: illite, H: halloysite, Cr: cristobalite.

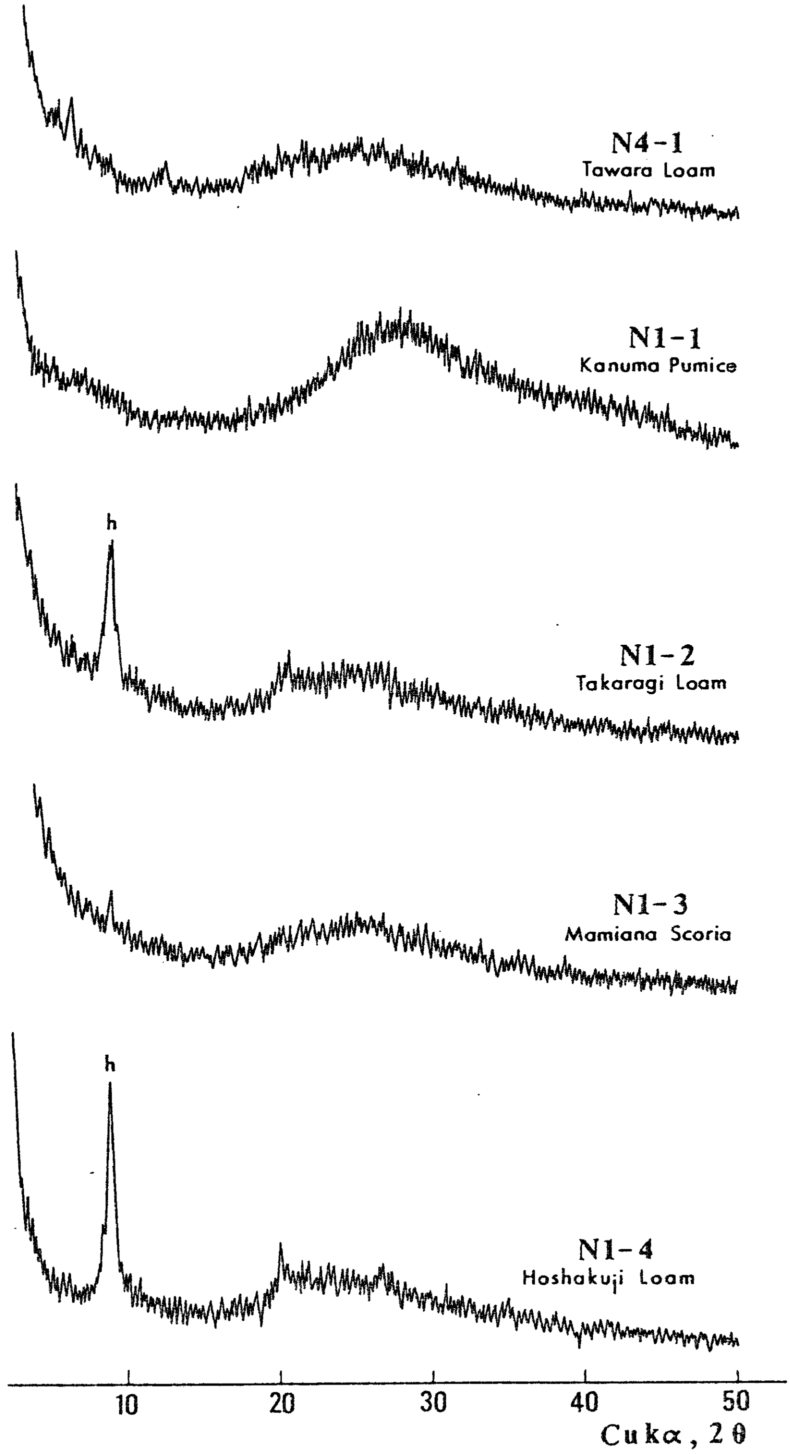


Figure 18b X-ray diffraction diagrams of clay fractions. The number after the hyphen means the soil sampling point. h: hydrated halloysite.

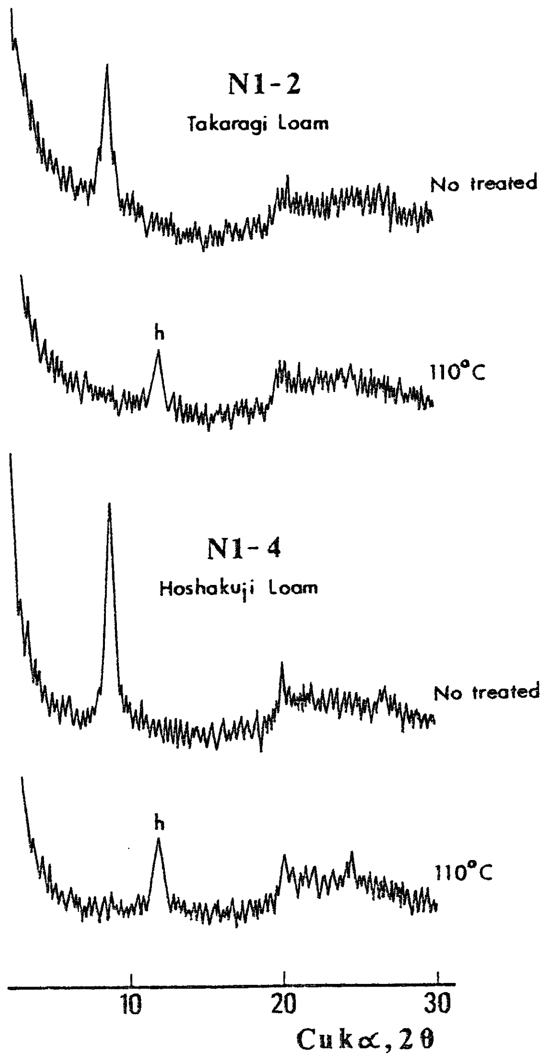


Figure 19 X-ray diffraction diagrams of clay fractions after heat treatment. The number after the hyphen means the soil sampling point. h: hydrated halloysite.

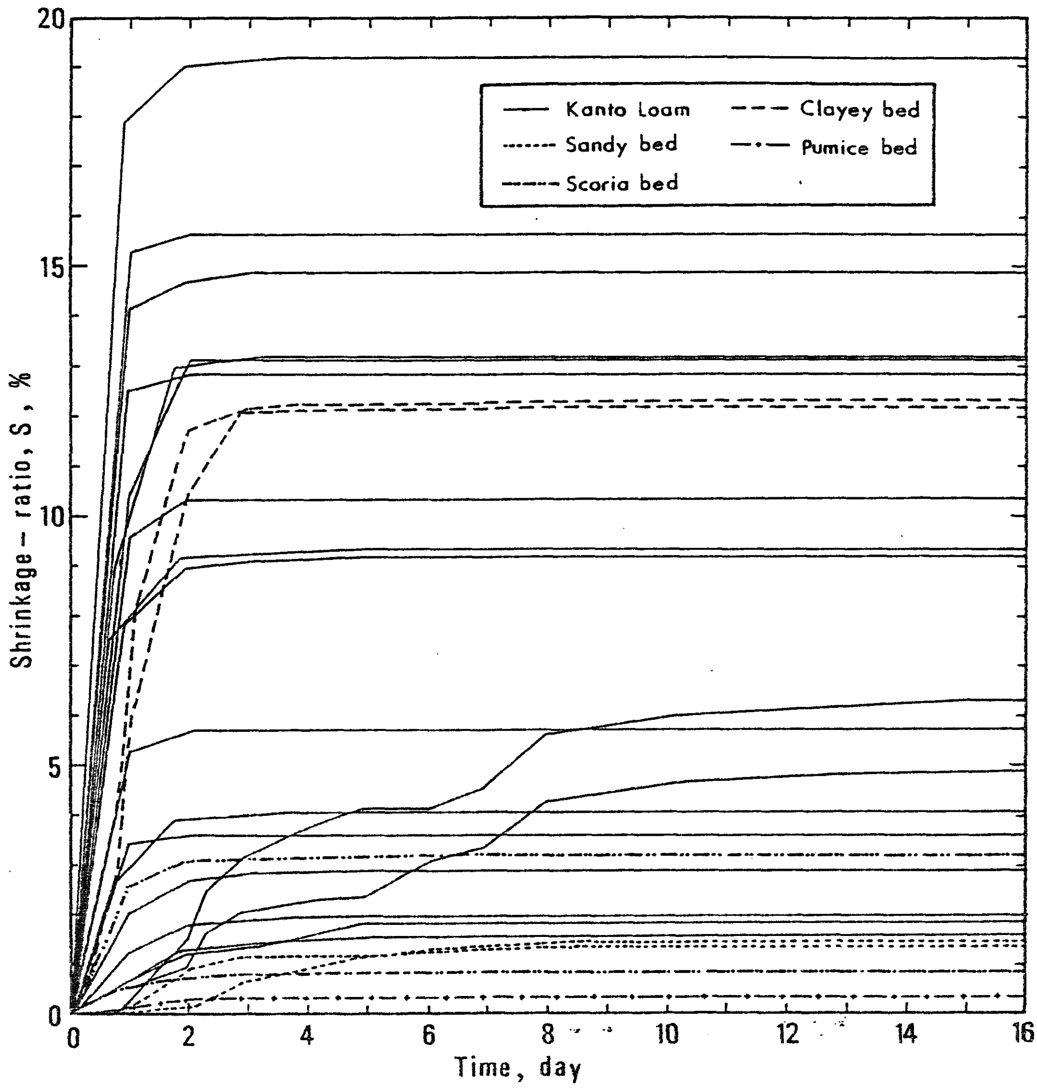


Figure 20 Temporal changes of shrinkage ratio in the Kanto Loam, clayey, sandy, pumice and scoria beds.

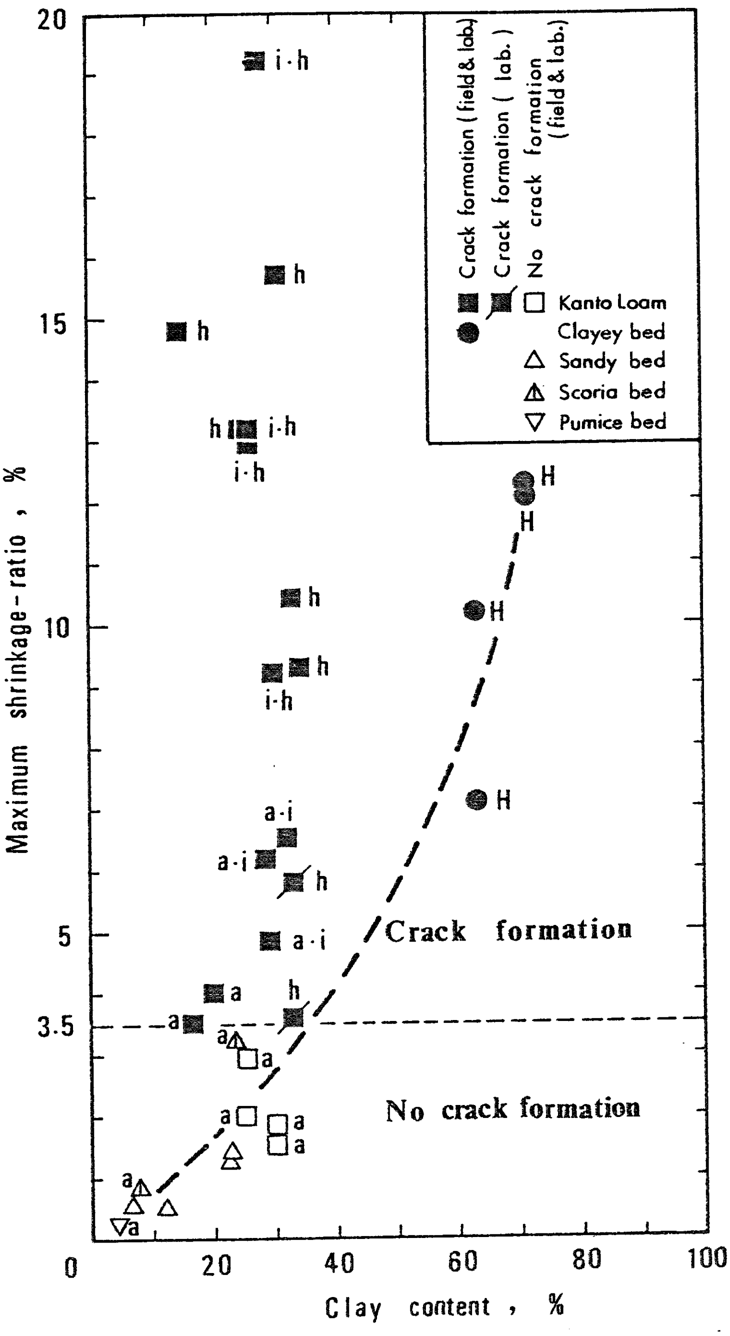


Figure 21 Relation between maximum shrinkage-ratio, clay content and major clay minerals. a: allophane, i: imogolite, h: hydrated halloysite, H: halloysite.

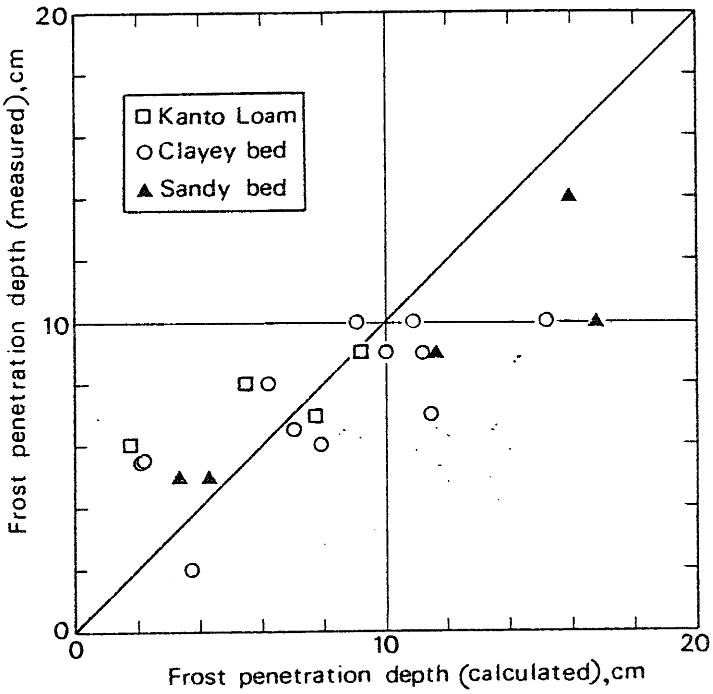


Figure 22 Relation between measured and calculated depth of frost penetration.

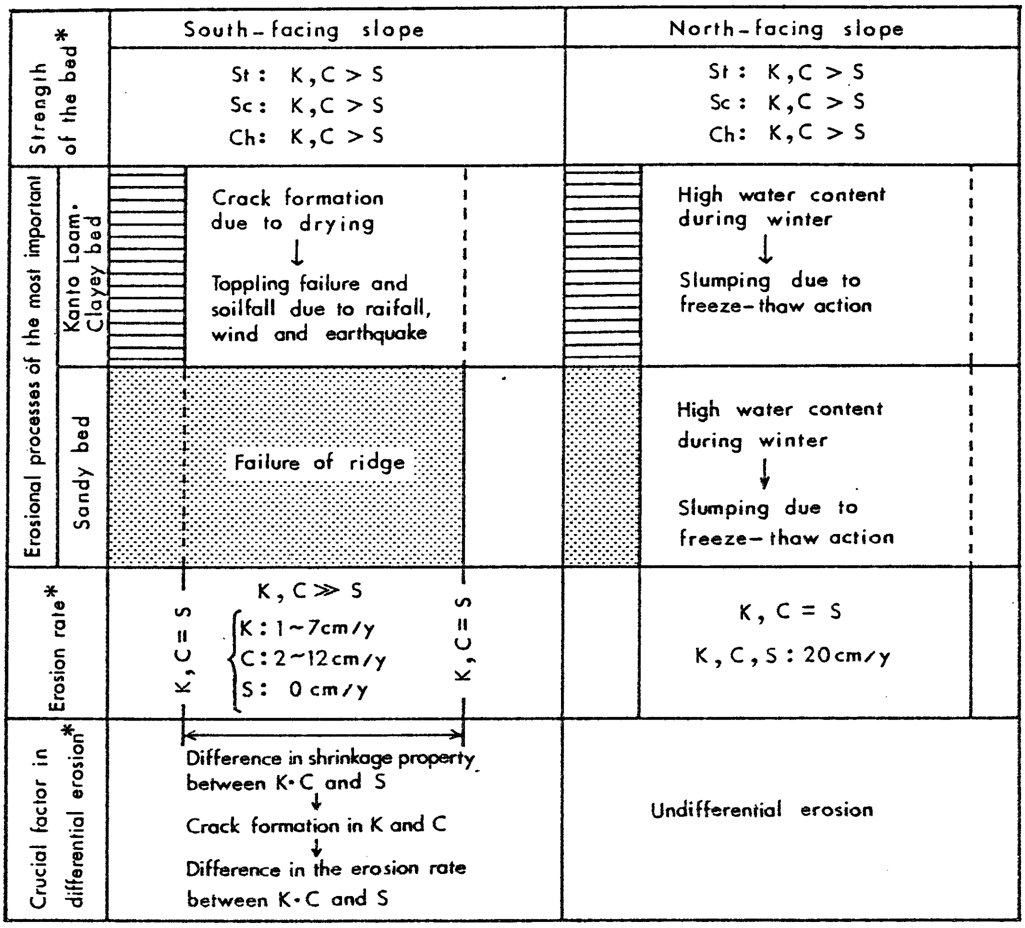


Figure 23 Mechanisms of slope recession. * K: Kanto Loam, C: Clayey bed, S: Sandy bed, St: Tensile strength, Sc: Compressive strength, Ch: Cohesion.

Table 1 Location, relative height, slope angle and aspect of cutting slopes studied

Cutting slope number*	Location**	Relative height (m)	Slope angle (degrees)
T1-W	Akeno, Makabe-gun, Ibaraki Pref.	7.5	62-65
T2-S	Shimotsuma, Ibaraki Pref.	5.5	75-80
T2-SW	Shimotsuma, Ibaraki Pref.	6.0	72-80
T2-N	Shimotsuma, Ibaraki Pref.	6.0	85
T3-SW	Yatabe, Tsukuba-gun, Ibaraki Pref.	10.0	60-63
T3-NW	Yatabe, Tsukuba-gun, Ibaraki Pref.	9.0	45-50
T4-SW	Yatabe, Tsukuba-gun, Ibaraki Pref.	5.0	55-60
T5-NW	Ina, Tsukuba-gun, Ibaraki Pref.	4.5	50-80
T6-N	Ina, Tsukuba-gun, Ibaraki Pref.	6.5	40
T7-NE	Ryugasaki, Ibaraki Pref.	7.0	45
T7-NW	Ryugasaki, Ibaraki Pref.	9.0	50
S1-SE	Shonan, Higashikatsushika-gun, Chiba Pref.	9.0	43-45
S1-W	Shonan, Higashikatsushika-gun, Chiba Pref.	8.0	40
S1-S	Shonan, Higashikatsushika-gun, Chiba Pref.	8.0	40-45
S1-N	Shonan, Higashikatsushika-gun, Chiba Pref.	8.0	40
S2-SE	Inba, Inba-gun, Chiba Pref.	16.0	45-50
S3-N	Funabashi, Chiba Pref.	8.0	45-60
N1-SE	Kitsuregawa, Shioya-gun, Tochigi Pref.	-	-
N2-SE	Ujiie, Shioya-gun, Tochigi Pref.	-	-
N3-S	Yaita, Tochigi Pref.	-	-
N4-S	Nishinasuno, Nasu-gun, Tochigi Pref.	-	-
N5-SW	Otawara, Tochigi Pref.	-	-
N6-SW	Nasu, Nasu-gun, Tochigi Pref.	-	-

* "T" represents Tsukuba Upland, "S" Shimousa Upland, and "N" Nasunogahara Fan. The abbreviation after the hyphen means the slope aspect. ** See also Figure 2.

Table 2a Recession rates of the slope-forming beds of Slope T2-SW

	Recession rate (cm/y) T2-SW(1)	T2-SW(2)	Period
1 Kanto Loam	6.9	7.3	June 8, 1980-April 20, 1982
2 Clayey bed	12.2	5.5	June 8, 1980-April 20, 1982
3 Sandy bed	0.0	0.0	June 8, 1980-April 20, 1982
4 Clayey bed	1.8	3.9	June 8, 1980-April 20, 1982
5 Sandy bed	17.3	0.0	June 8, 1980-April 20, 1982
6 Clayey bed	1.7	0.0	June 8, 1980-April 20, 1982

Table 2b Recession rates of the slope-forming beds of Slope T3-SW

	Recession rate (cm/y)	Period
1 Kanto Loam	0.9	Oct. 4, 1979-Mar. 25, 1982
2 Sandy bed	0.0	Oct. 4, 1979-Mar. 25, 1982
3 Calyey bed	8.8	Oct. 4, 1979-Mar. 25, 1982

Table 3 Recession rates of the slope-forming beds of the Slope T2-N

	Recession rate (cm/y)		Period
	T2-N(1)	T2-N(2)	
1 Kanto Loam	23.3	22.1	June 8, 1980-April 20, 1982
2 Clayey bed	26.6	23.8	June 8, 1980-April 20, 1982
3 Sandy bed	20.5	13.5	June 8, 1980-April 20, 1982
4 Calyey bed	21.7	27.1	June 8, 1980-April 20, 1982
5 Sandy bed	20.3	25.3	June 8, 1980-April 20, 1982
6 Calyey bed	20.2	21.6	June 8, 1980-April 20, 1982

Table 4a Some physical properties of material forming Slope T2-SW

Sampling point	Grain size distribution Clay(%) (< 5μm)	Silt(%) (5-74μm)	Sand(%) (74-2000μm)	G_s	γ_d (g/cm^3)	n (%)	w_n (%)	w_L (%)	w_P (%)	I_P
1 Kanto Loam	30.0	41.9	28.1	2.72	0.69	75	65.1	115.0	64.6	50.4
2 Clayey bed	71.0	26.5	2.5	2.66	1.20	55	45.1	107.8	35.9	71.9
3 Sandy bed	22.5	37.9	39.6	2.67	0.86	68	46.9	-	-	-
4 Clayey bed	70.0	26.1	3.9	2.67	0.89	67	72.6	125.0	42.1	82.9
5 Sandy bed	12.0	54.4	33.6	2.66	0.85	68	52.3	-	-	-
6 Clayey bed	62.0	29.7	8.3	2.67	1.19	55	53.2	-	-	-

G_s: Specific gravity, γ_d: Dry density, n: Porosity, w_n: Natural water content,
w_L: Liquid limit, w_P: Plastic limit, I_P: Plasticity index.

Table 4b Some physical properties of material forming Slope T3-SW

Sampling point	Grain size distribution Clay(%) (< 5μm)	Silt(%) (5-74μm)	Sand(%) (74-2000μm)	G_s	γ_d (g/cm^3)	n (%)	w_n (%)	w_L (%)	w_p (%)	I_p (%)
1 Kanto Loam	32.0	35.3	32.7	2.66	0.46	83	51.4	167.5	105.5	62.0
2 Sandy bed	6.5	8.1	85.4	2.64	1.25	53	6.3	-	-	-
3 Clayey bed	63.0	28.5	8.5	2.64	1.02	61	30.3	103.0	30.5	72.5

G_s: Specific gravity, γ_d: Dry density, n: Porosity, w_n: Natural water content,
w_L: Liquid limit, w_p: Plastic limit, I_p: Plasticity index.

Table 5 Water content (%) of Slopes T2-SW and T2-N

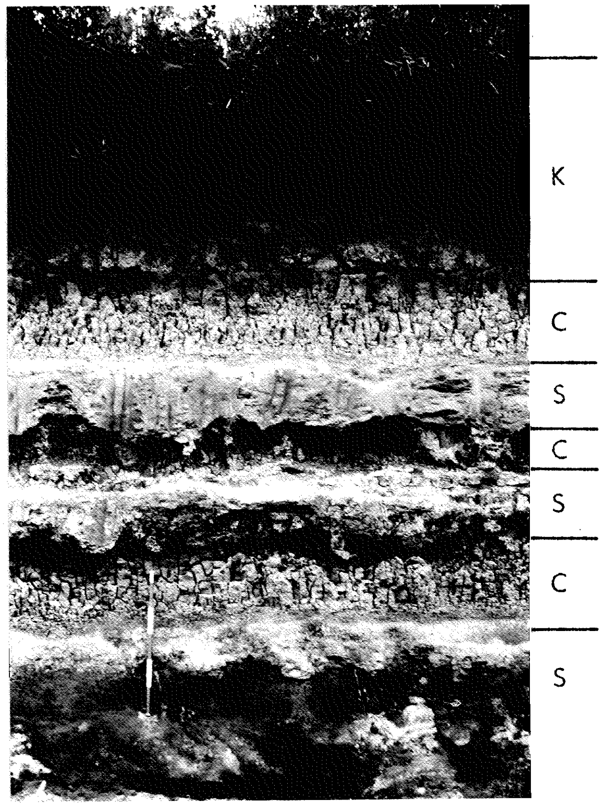
Slope-forming beds	T2-SW*	T2-N*
1 Kanto Loam	19.8	85.0
2 Clayey bed	9.3	65.9
3 Sandy bed	26.0	39.5
4 Clayey bed	17.6	96.2
5 Sandy bed	12.3	44.1
6 Clayey bed	9.1	47.2

* : Sampled on Jan. 13, 1981.

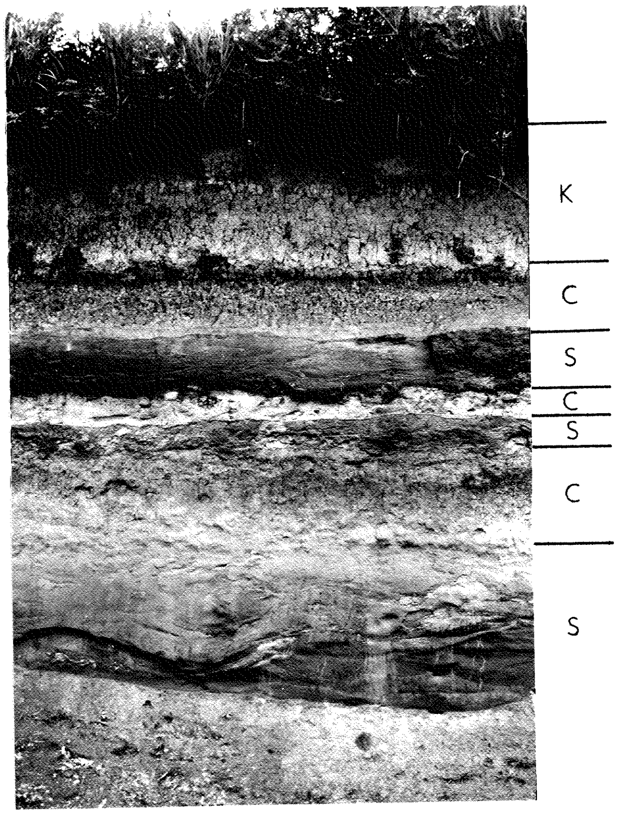
Table 6 Thermal properties of material forming Slope T2-N

	k_f ($\times 10^{-3}$cal/cm·s·°C)	k_u ($\times 10^{-3}$cal/cm·s·°C)	Average ($\times 10^{-3}$cal/cm·s·°C)
1 Kanto Loam	1.91	1.84	1.86
2 Clayey bed	4.21	3.22	3.72
4 Clayey bed	4.21	3.22	3.72
6 Clayey bed	4.21	3.22	3.72
3 Sandy bed	1.80	2.20	2.00
5 Sandy bed	3.55	2.57	3.06

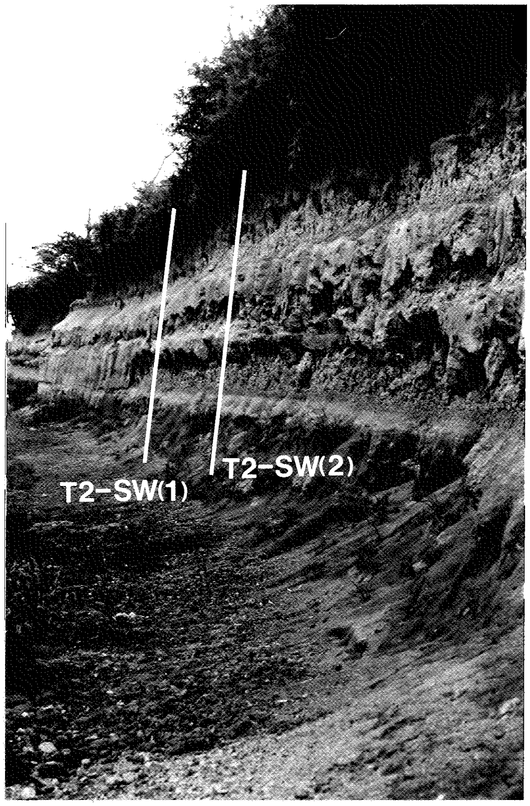
k_f: Thermal conductivity of frozen soil, k_u: Thermal conductivity of unfrozen soil.



Photograph 1 Rib-like relief on the surface of a cutting slope located in Tsukuba Upland. A measure is 1.1 m long. K: Kanto Loam, C: Clayey bed, S: Sandy bed.

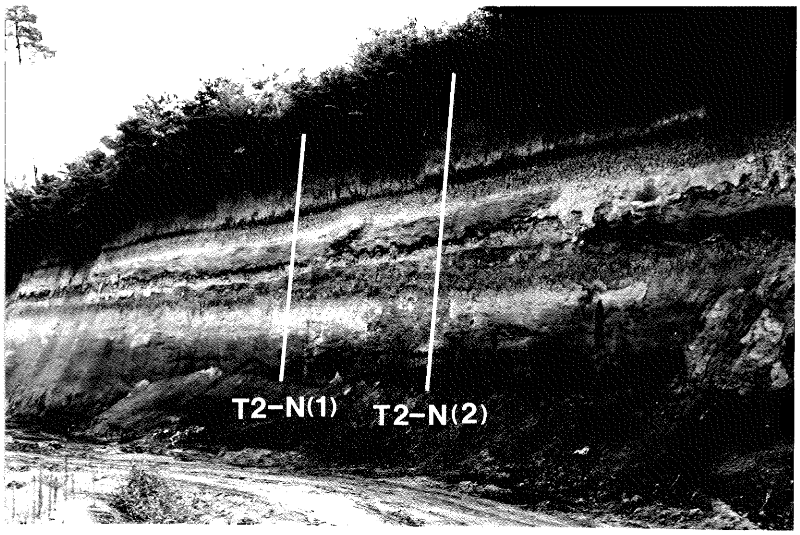


Photograph 2 No rib-like relief on the surface of a cutting slope located in Tsukuba Upland. Relative height of the slope is about 6 m. K: Kanto Loam, C: Clayey bed S: Sandy bed.

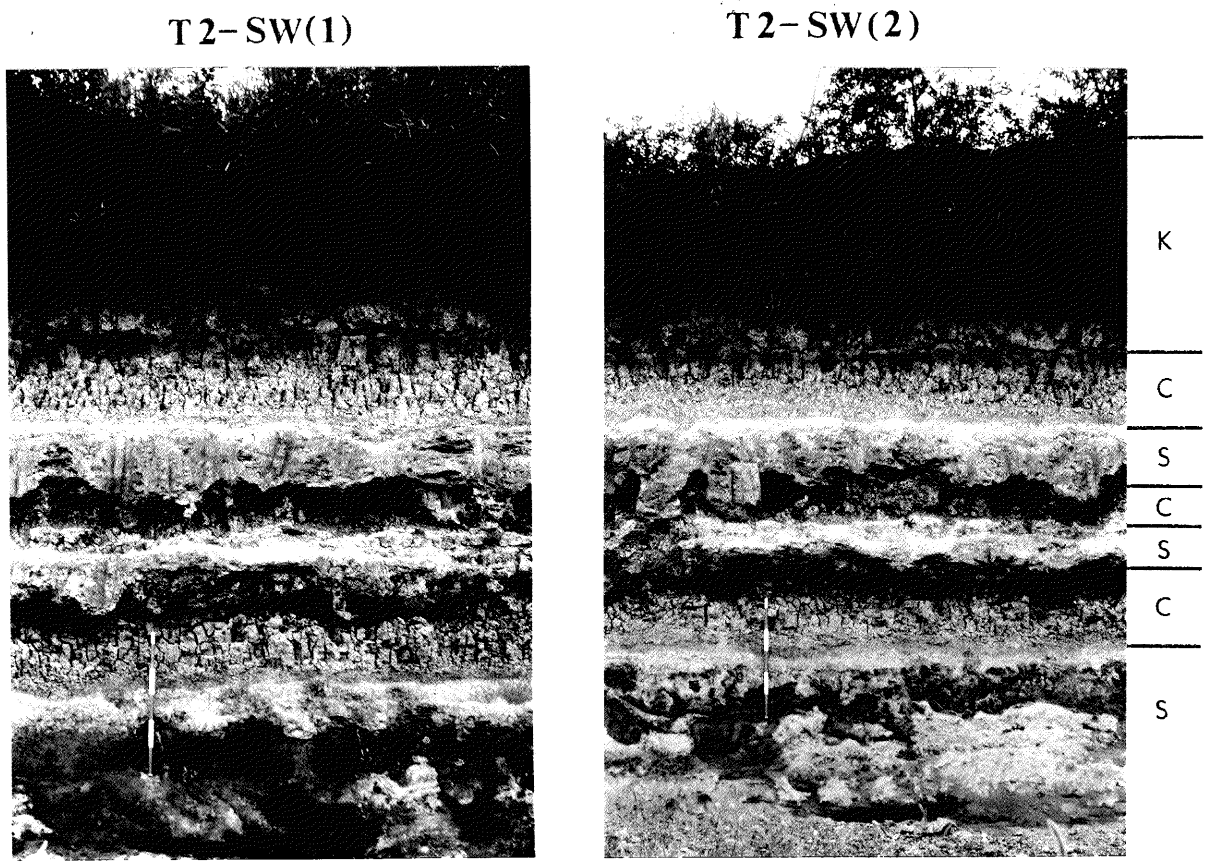


Photograph 3 Slope T2-SW viewed from the south. T2-SW(1) and T2-SW(2): Measurement lines of recession distance. September 1981.

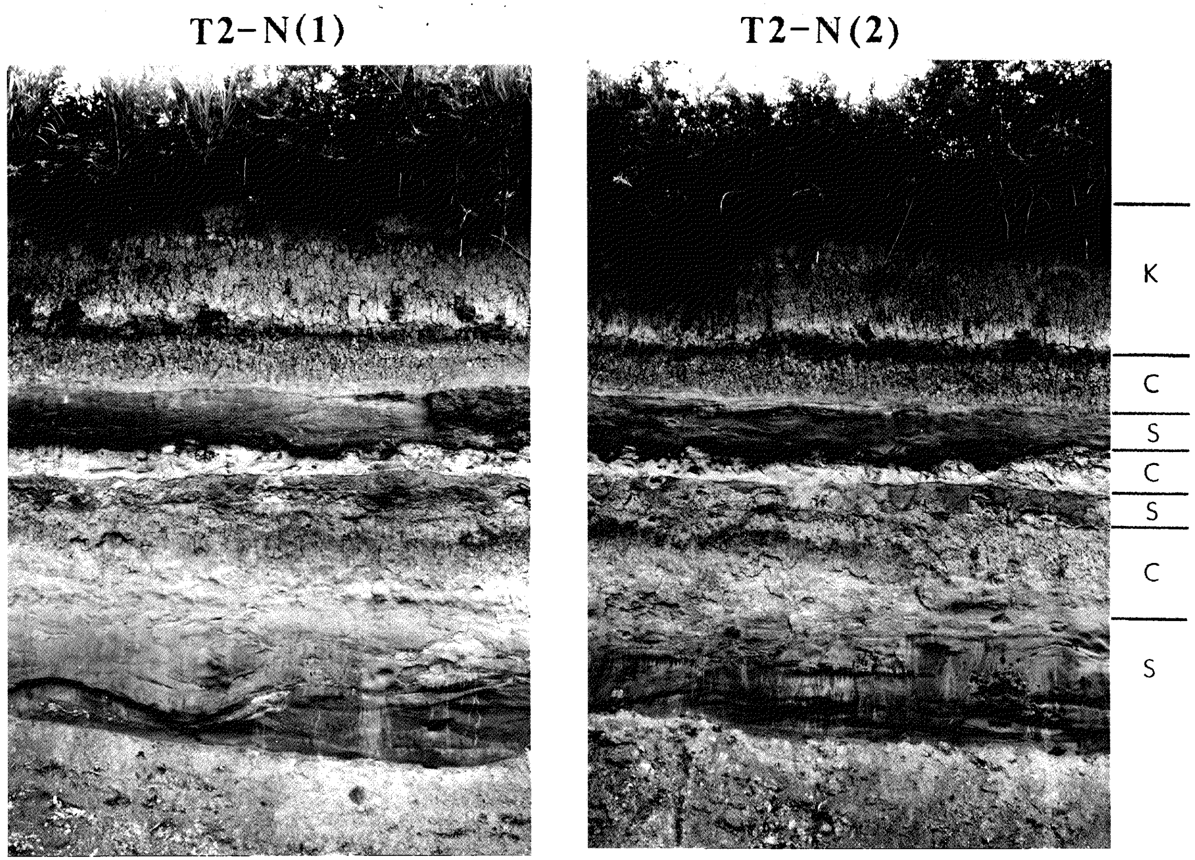
Photograph 4 Slope T3-SW viewed from the southwest. A measure at middle of bottom is 80 cm long. August 1981. K: Kanto Loam, S: Sandy bed, C: Clayey bed.



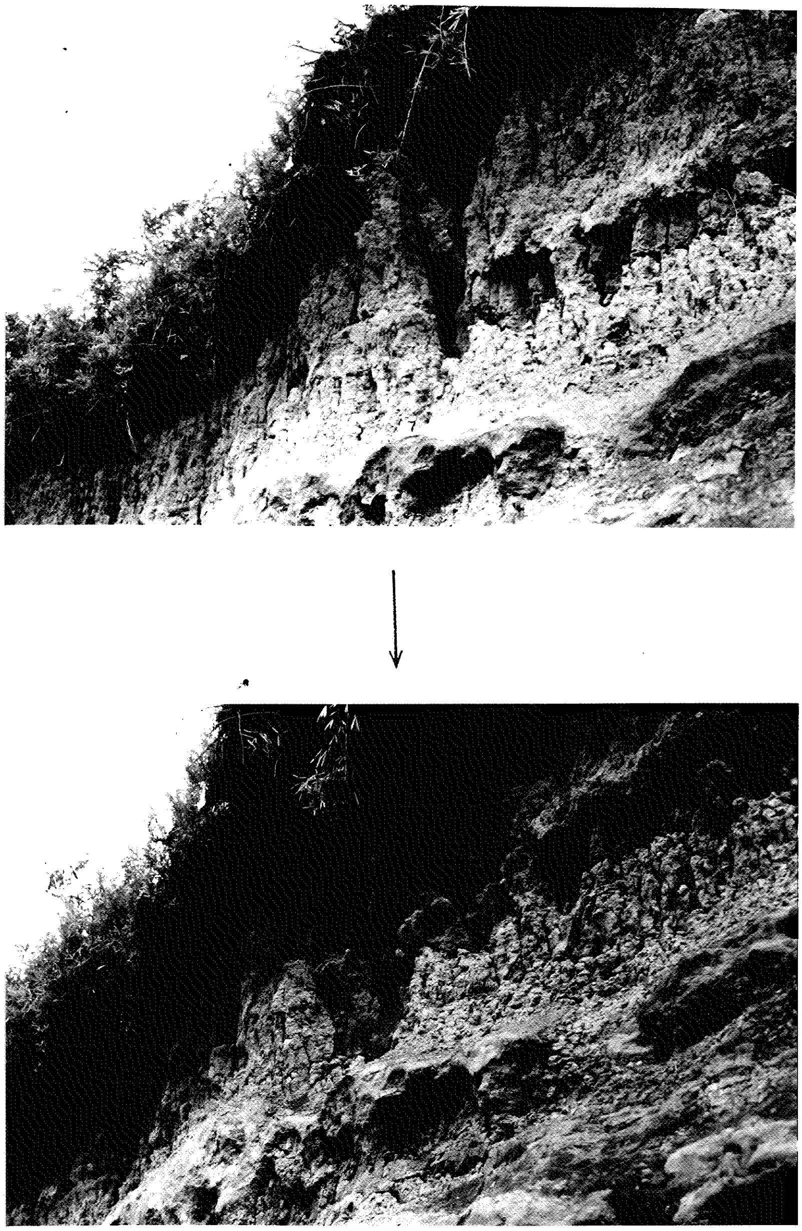
Photograph 5 Slope T2-N viewed from the northwest. T2-N(1) and T2-N(2): Measurement lines of recession distance. July 1981.



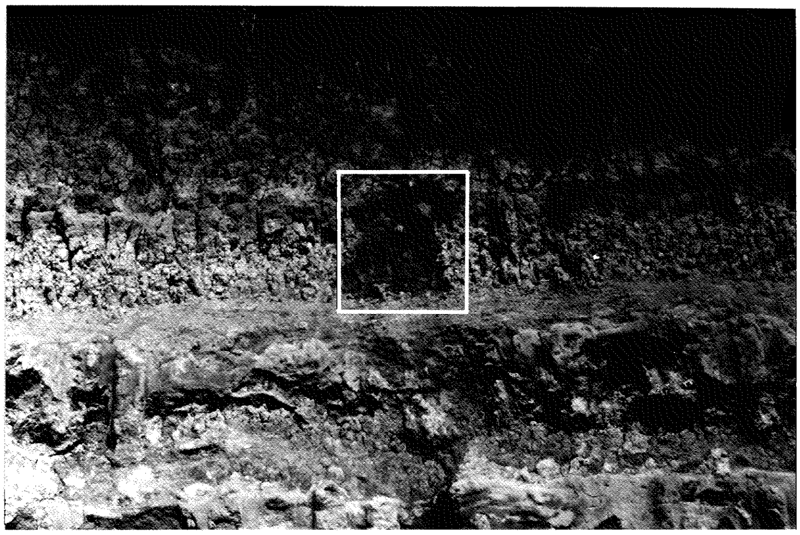
Photograph 6 Slopes T2-SW(1) and T2-SW(2) viewed from the southwest. A measure is 1.1 m long. October 1981.
K: Kanto Loam, C: Clayey bed, S: Sandy bed.



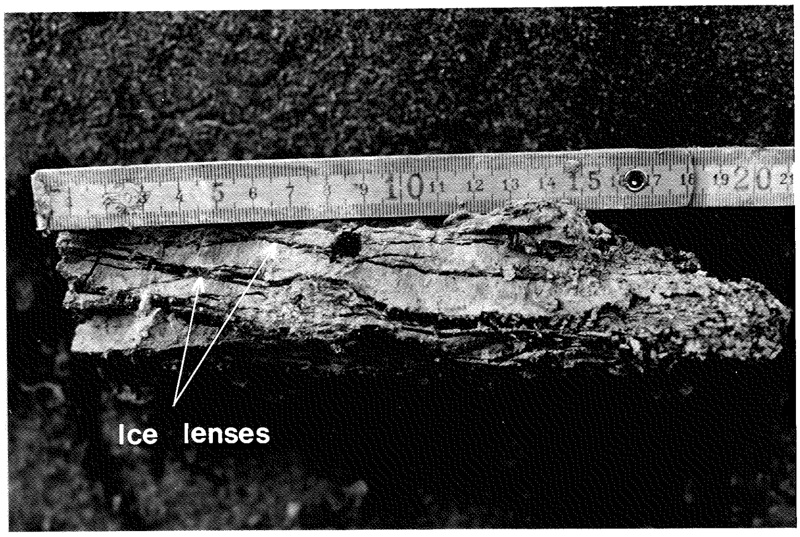
Photograph 7 Slopes T2-N(1) and T2-N(2) viewed from the north. October 1981. K: Kanto Loam, C: Clayey bed, S: Sandy bed.



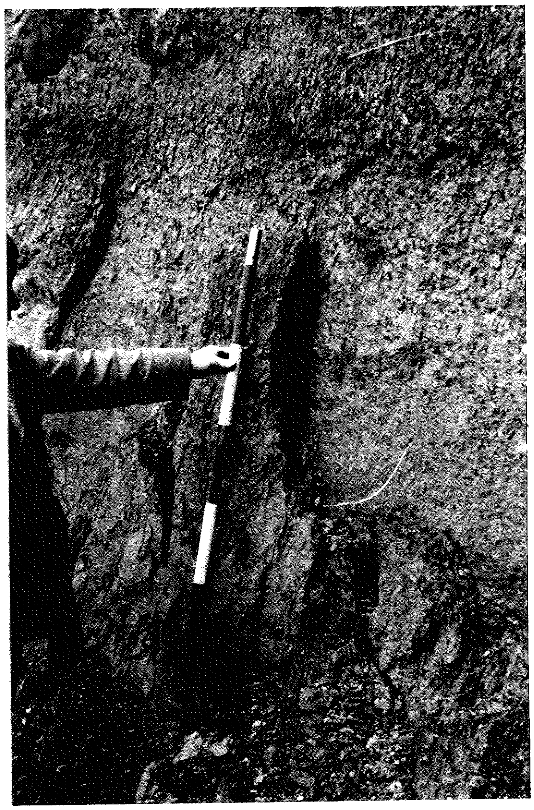
Photograph 8 Toppling failure in the Kanto Loam.



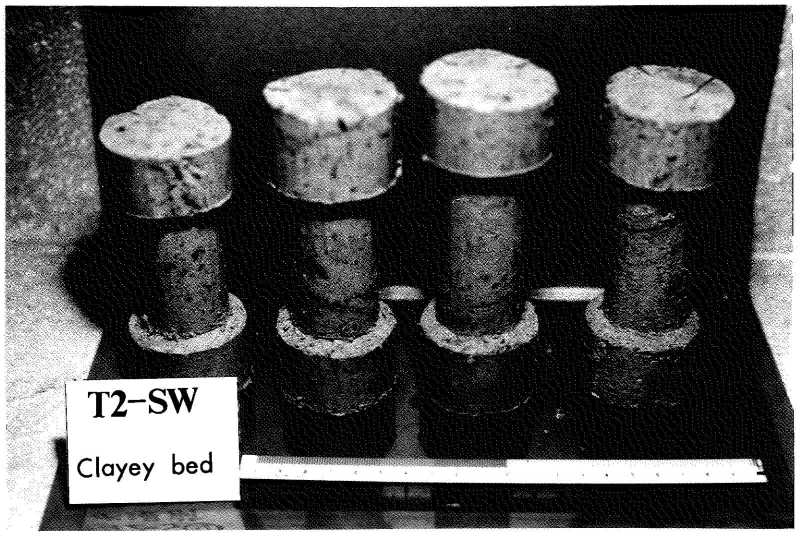
Photograph 9 Steep failure-surface caused by shallow slide in the clayey bed. September 15, 1980.



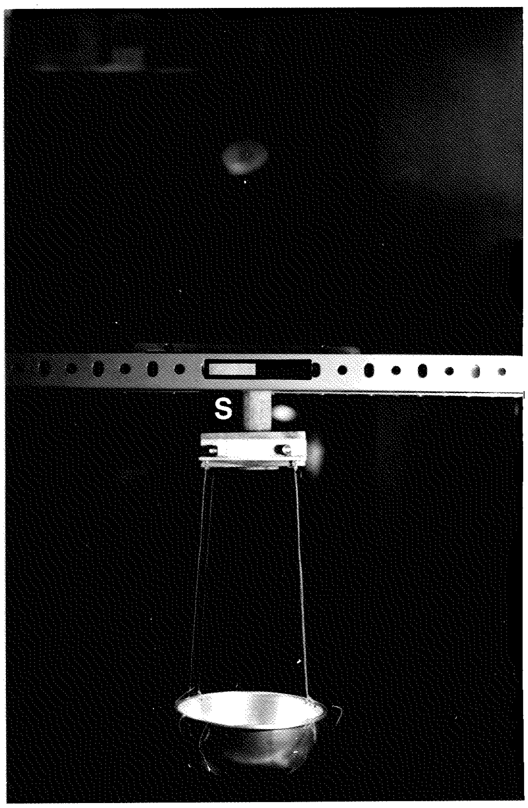
Photograph 10 Ice lenses formed in the clayey bed. These lenses grow parallel to the slope surface.



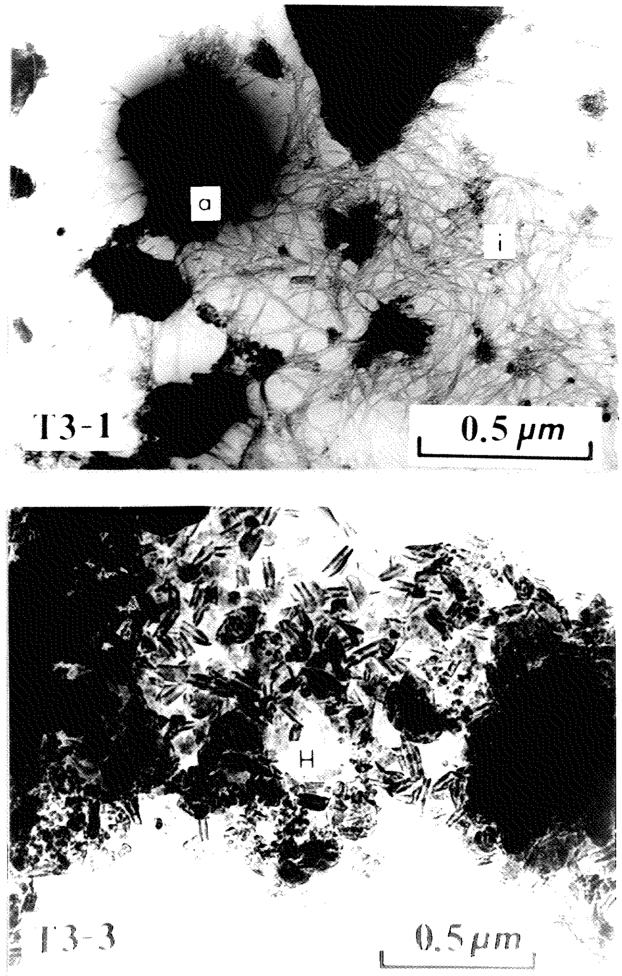
Photograph 11 Slumping on Slope T2-N. A measure is 1.1 m long. February 23, 1982.



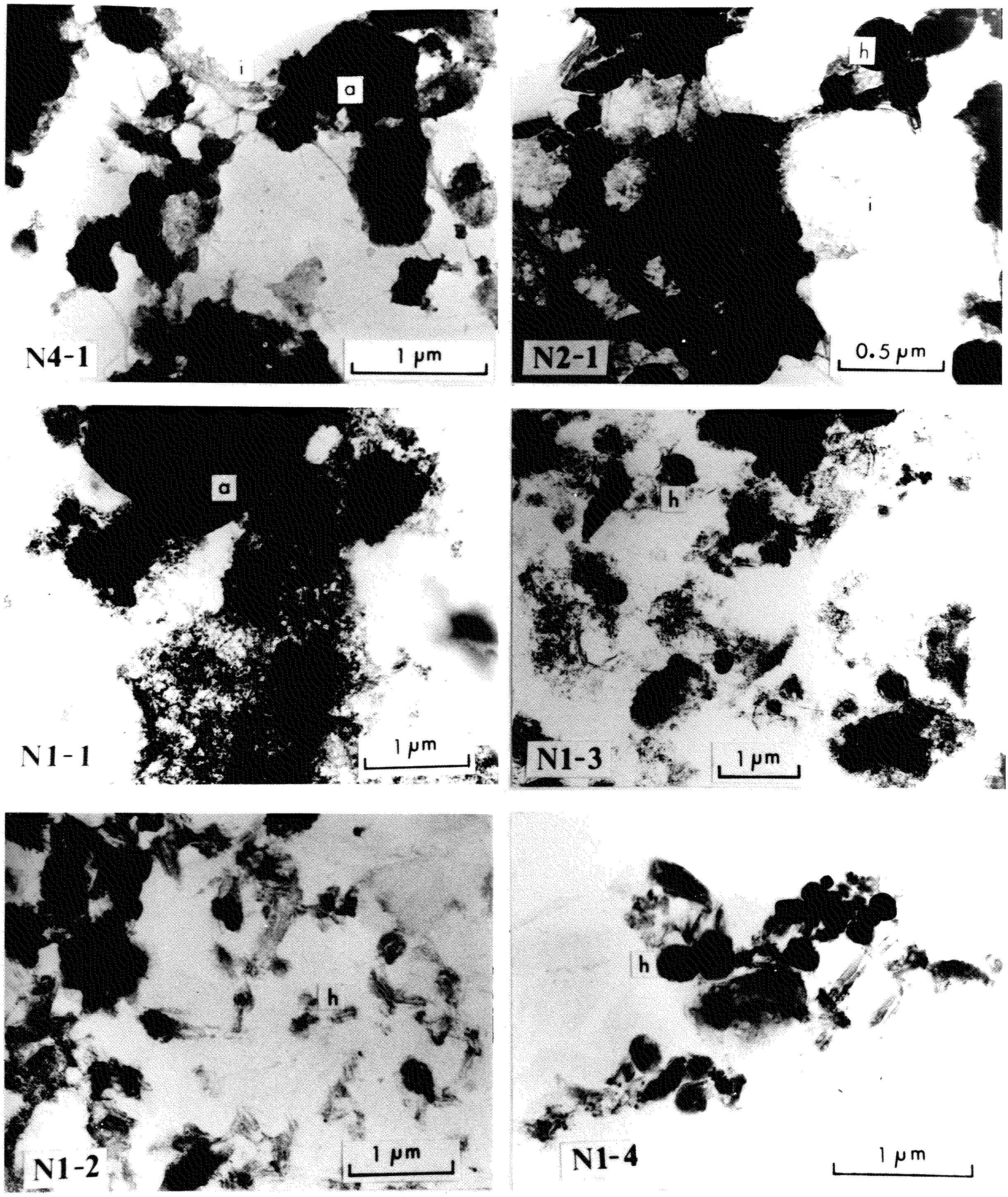
Photograph 12 Specimens for tension test. 3.5 ϕ in the middle part, condition of natural water content. A measure is 20 cm long.



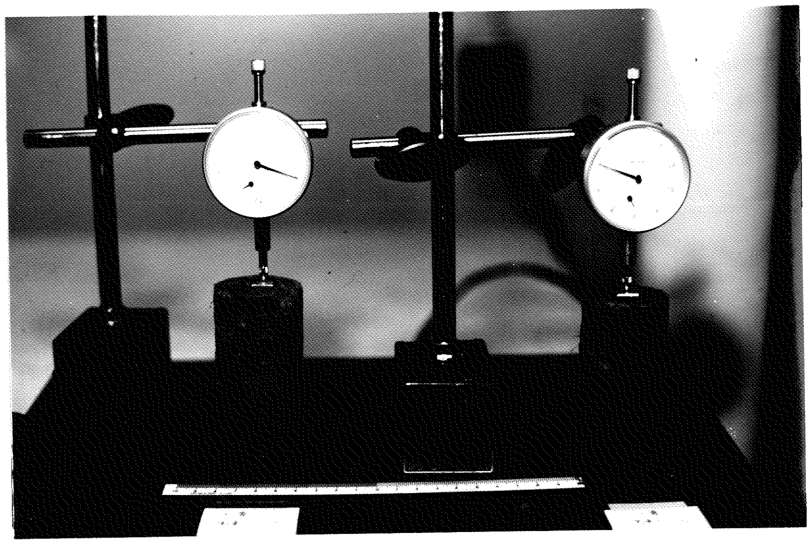
Photograph 13 Apparatus for tension test. A measure is 10 cm long. S: Specimen.



Photograph 14a Clay minerals under an electoron-microscope. The number after the hyphen means the soil sampling point. a: allophane, i: imogolite, H: halloysite.



Photograph 14b Clay minerals under an electoron-microscope.
The number after the hyphen means the soil sampling point.
a: allophane, i: imogolite, h: hydrated halloysite.



Photograph 15 Apparatus for shrinkage test.
Size of specimens is 5 ϕ x 4 cm^3.
A measure is 20 cm long.