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SLOPE FAILURE IN A HYDROTHERMAL ALTERATION AREA: A CASE STUDY ON THE IZU PENINSULA, CENTRAL JAPAN

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ABSTRACT

Two heavy rainfalls in August of 1982 caused about two thousand failed slopes that seriously damaged to transportation networks on the Izu Peninsula in central Japan. About half of the failed slopes took place in hydrothermal alteration areas. Details of the mode, volume, and frequency of slope failure differed among the alteration zones. In general, slope failure was more frequent in low grade zones such as those made up of smectite and halloysite, probably because of the extreme decrease of the strength of the parent rock in the course of alteration. The change in rock strength seems to be related to the amount, mode of occurrence and mineralogical properties of the authigenic minerals.

1. INTRODUCTION

In the past several decades, the Izu Peninsula in central Japan has suffered major damage from slope failures related to heavy rainfall and to earthquakes that have taken place at intervals of up to ten years. The Izu-Hanto-Oki Earthquake in 1974, for instance, rtiggered a number of slope failures in the southern part of the peninsula. Otsuka and Kimiya [1] reported that most of the slope failures were concentrated in "intensely altered areas". In paticuler, a large scale slope failure occurred in halloysitized tuffs and struck the fishing port of Nakagi. It killed 27 peoples and demolished more than 90 buildings. Heavy rainfall in the summer of 1976 caused serious damage to humans, domestic animals, farm products, buildings and transportation networks. The total number of slope failures was about 500 and most concentrated in "hydrothermal alteration areas" [2]. The largest slope failure took place along a coastal cliff near Shirata where the rocks had been smectitized [3]; it struck a hamlet and killed 6 persons.

Rock alteration, especially hydrothermal alteration, has been speculated to be closely related to slope failure in this peninsula. Hydrothermally altered rocks are distributed over fairly wide areas throughout Japan Archipelago and many reports have pointed out that large scale slope failures have been frequent, for these types of rocks; but, the genetic relation between rock alteration and slope failure has yet to be clarified.

Twice in August of 1982, heavy rainfall caused a large number of slope failures on the Izu Peninsula. The writer made field survey of nearly two thousands of these failed slopes, and mineralogical and rock strength analyses of rock samples gathered from these failed slopes and the surrounding areas.

The writer here describes the distribution, occurrence, and frequency of failed slopes in hydrothermally altered areas and on the Izu Peninsula and discuss the genetic relation between slope failure and hydrothermal alteration.

KEY WORDS: Slope failure, Rock alteration, Rock strength, Hydrothermal alteration, Rainfall.
Note: Discussion open until 1 September, 1990

2. GEOMORPHOLOGY, GEOLOGY AND ROCK ALTERATION IN THE IZU PENINSULA

2.1. *Geomorphology and Slope*

The Izu Peninsula, located on the Pacific Coast of central Honshu (Fig. 1), is a narrow mountainous peninsula that extends about 50 km in the N-S direction. Its maximum width is 30 km east to west. The peninsula is divided into two areas by the Amagi-Mountains that run the NEE-SWW, the highest point in this range being more than 1,400 m above sea level. The central part of the northern area is dissected by the Kano River along which there are an alluvial plain and terraces. Volcanic ranges stretch north and south on both coasts of the Peninsula. Many parts of the coastline are surmounted by steep cliffs, the southern area being wholly mountainous except

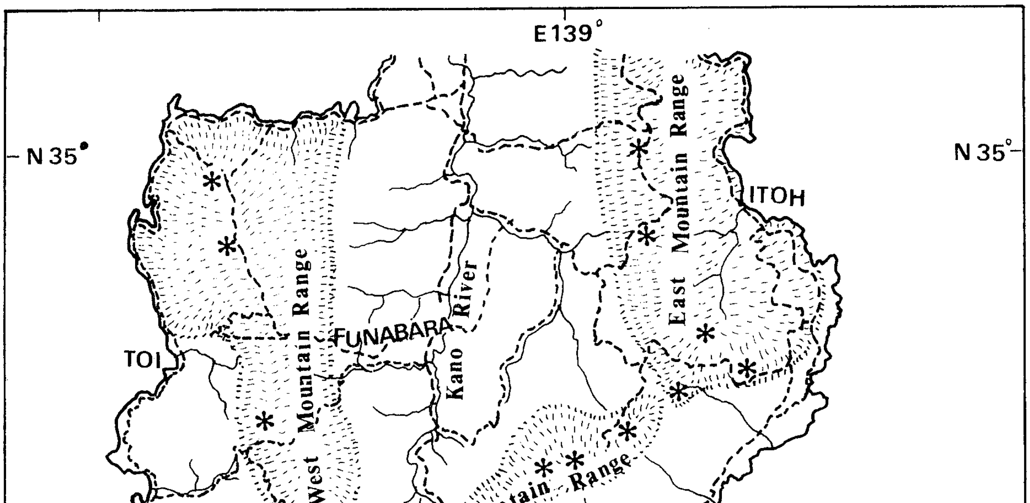


Fig. 1 Map of the area surveyed on the Izu Peninsula.

for some very narrow coastal plains. Although all the rivers are small, they have intensely dissected the mountain slopes, producing many riverside cliffs.

On the whole, the morphology of the peninsula is very steep, there being many mountain, riverside, and coastal slopes throughout the peninsula. Many artificial slopes also have been created along roads that cut through mountains.

2.2. *Geology*

The Izu Peninsula is made up of four stratigraphic units that are Miocene to Quaternary in age. The lowest unit, the Yugashima Group, is composed mainly of felsic to intermediate lava flows, volcaniclastics, dikes and small amounts of clastic sediments; the age of its rocks may range from early to late Miocene. The second unit, the Shirahama Group, overlies the former unconformably. It is composed mainly of andesitic lava flows, volcanic breccias, felsic tuffs, and tuffaceous sediments. It occasionally intercalates thin layers of limestone containing *Miogypsina-opaculina* fauna. Its strata are intruded by comparatively large felsic to intermediate intrusive masses of the same age. The age of the rocks in this group may range from the latest Miocene to Pliocene [4]. The Shirahama Group is unconformably covered by a third unit of Pleistocene strativolcanoes and monogenic volcanoes.

This unit is composed mainly of andesitic lava flows, volcaniclastics, debris, loam and lacustrine sediments. The fourth and uppermost, unit is made up of the Alluvium and the Quaternary terrace deposits.

All the strata dip gently. The fault system also is relatively simple, and a number of faults have been active [5].

In general, the Yugashima Group is exposed in the lower altitudes of the central area; whereas, the Pleistocene volcanoes occupy the higher altitudes of the central to northern area. The Shirahama Group is widely distributed over the entire peninsula.

2.3. Rock Alteration

The rock alteration appearing in the Izu Peninsula can be classified genetically into weathering, diagenesis+contact metamorphism, and hydrothermal alteration.

A weathering zone often is present near the top of down hills composed mainly of volcanic debris, loam and terrace deposits. It is also found near the ridges of Pleistocene volcanoes. The alteration minerals, halloysite and smectite, are pervasive in the weathering zone. Gibbsite occasionally is associated with them in advanced weathered parts.

Diagenesis+contact metamorphism commonly appears in the volcaniclastic and reworked tuffaceous sediments of the Yugashima and Shirahama Groups. Clinoptilolite and mordenite occur regionally as replacing vitric materials. Analcime and laumontite are rather rare. The mode of occurrence of these zeolites is of typical diagenetic+contact metamorphism origin [6, 7]. The propylite and the smectite zones are distributed regionally in both volcaniclastic and volcanic rocks, parts of them probably having the same origin. Petrographically, it is difficult to discriminate between them and rocks having the same mineral assemblage of hydrothermal origin.

The most pervasive type of alteration is hydrothermal. A large numer of rocks in the Izu Peninsula have undergone various kinds of hydrothermal alteration, regardless of the original rock type. The Tertiary and Cretaceous rocks of Japan have been classified by Utada [8] into eighteen alteration zones based on the assemblage of authigenic silicate minerals presents. These zones can be arranged in three large groups (Table 1). In this study, each of the mineral zone formed by hydrothermal alteration has been definited according to mineral assemblage as shown in Table 2.

Each zone of the acidic zone group are defined by the presence of such "acidic minerals" as alunite, and pyrophyllite, or by kaolin minerals; that of the alkaline zone group by the presence of zeolites or authigenic albite; that of the intermediate zone group as lacking these minerals.

Table 1 Division of hydrothermal alteration zones after Utada (1980). Mineral constituents of each zone are listed in Table 2.

<table>
<tr><td rowspan="2">ACIDIC ZONE GROUP</td><td>SULPHATE SERIES</td><td colspan="3">ALUNITE-OPAL Z.</td><td colspan="5">ALUNITE-QUARTZ Z.</td></tr>
<tr><td>SILICATE SERIES</td><td>HALLOYSITE Z.</td><td colspan="4">KAOLINITE Z.</td><td>DICKITE Z.</td><td colspan="2">PYROPHYLLITE Z.</td></tr>
<tr><td rowspan="2">INTER-MEDIATE ZONE GROUP</td><td>POTASSIC SERIES</td><td colspan="3" rowspan="2">SMECTITE Z.</td><td rowspan="2">MIXED LAYER Z.</td><td colspan="2">SERICITE Z,</td><td colspan="2">K-FELDSPAR Z.</td></tr>
<tr><td>Ca-Mg SERIES</td><td colspan="4">PROPYLITE Z.</td></tr>
<tr><td rowspan="2">ALKALINE ZONE GROUP</td><td>Ca-SERIES</td><td>STILBITE Z.</td><td colspan="3">HEULANDITE Z.</td><td colspan="3">LAUMONTITE Z.</td><td>WAIRAKITE Z.</td></tr>
<tr><td>Na-SERIES</td><td colspan="2">MORDENITE Z.</td><td colspan="3">ANALCIME Z.</td><td colspan="3">ALBITE Z.</td></tr>
</table>

→ TEMPERATURE INCREASE

↓ ALKALI & ALKALI EARTH ION ACTIVITY
HYDROGEN ION ACTIVITY INCREASE

Table 2 Mineral constituents of the hydrothermal alteration zones.

Zone	Index Mineral	Associated Mineral
Alunite-quartz	Alunite & quartz	Pyrophyllite, kaolinite
Alunite-opal	Alunite & opal	Halloysite
Pyrophyllite	Pyrophyllite	Quartz, kaolinite, dickite, sericite
Dickite	Dickite or nacrite	Quartz, kaolinite
Kaolinite	Kaolinite	Quartz, (opal), halloysite
Halloysite	Halloysite	(quartz), opal, smectite
K-feldspar	K-feldspar	Quartz, chlorite, sericite, ser/smec
Sericite	Sericite	Quartz, ser/smec
Propylite	Chlorite & sericite	Quartz, ser/smec, chl/smec, (epidote) (prehnite)
Mixed layer	Ser/smec & chl/smec	Quartz, (opal), smectite
Smectite	Smectite	(quartz), opal
Wairakite	Wairakite	Quartz, chlorite, (sericite)
Laumontite	Laumontite	Quartz, chlorite, (sericite), ser/smec chl/smec, (yugawaralite), (scolecite)
Heulandite	Heulandite or chabazite	Quartz, chlorite, (sericite), ser/smec chl/smec, (smectite)
Stilbite	Stilbite	(quartz), opal, smectite
Albite	Albite	Quartz, Chlorite, (sericite)
Analcime	Analcime	Quartz, chlorite, (sericite), ser/smec
Mordenite	Mordenite	Quartz, opal, (chlorite), ser/smec, smectite, (ferrierite)

Parentheses denote rare occurrences.

Chlorite-smectite and sericite-smectite series are the main constituents of this group. K-feldspar is a characteristic mineral of the highest grade zone of a subgroup. Prehnite and/or epidote are characteristic of another subgroup.

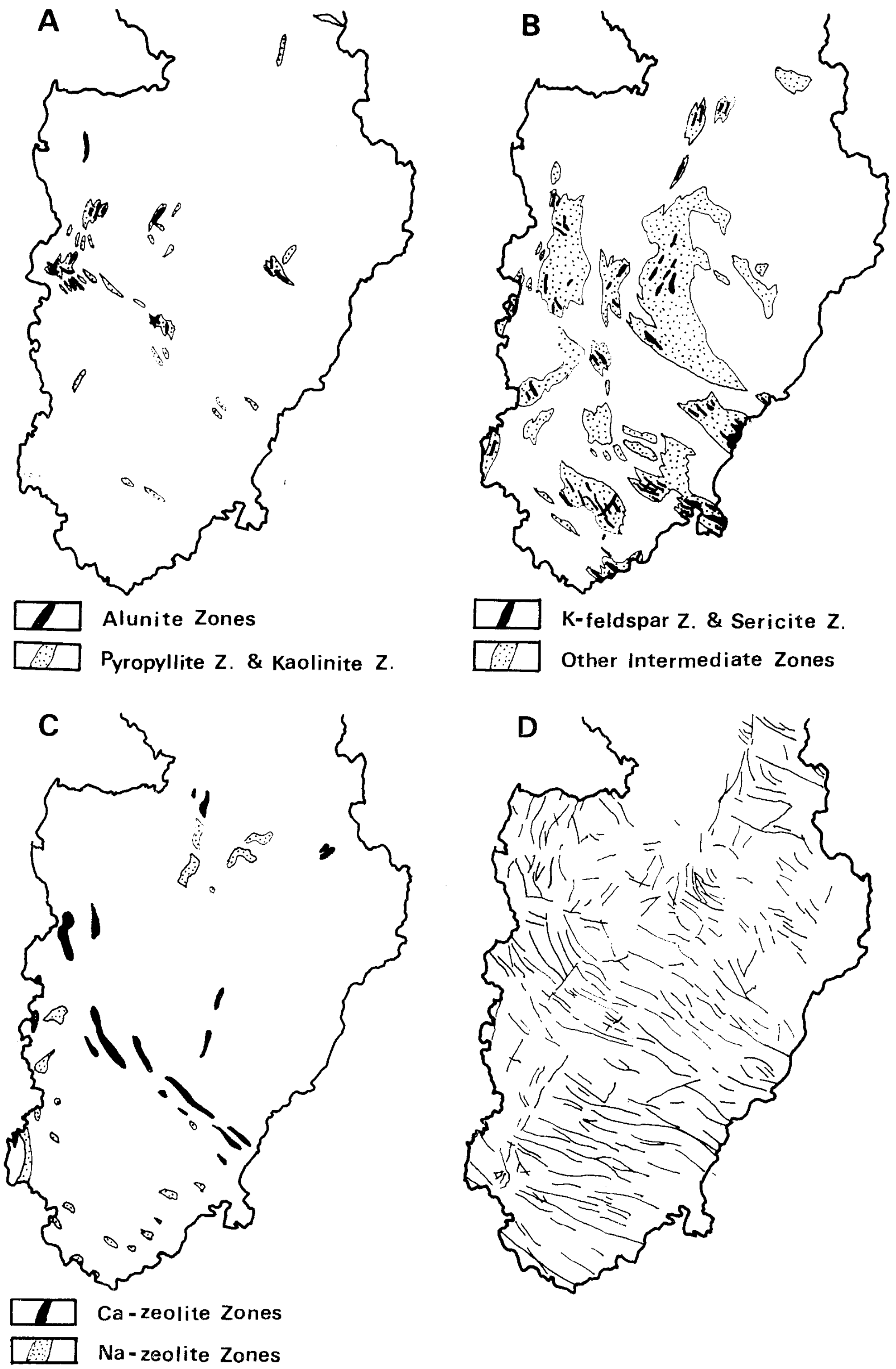


Fig. 2 Simplified maps of the Izu Peninsula showing the distributions of the acidic (A), intermediate (B), and alkaline (C) alteration zones, and the active faults (D) (after Murai and Kaneko, 1974).

Hydrothermally altered rocks commonly are distributed zonally around the probable paths of hydrothermal solutions. Therefore, this zoning is arranged from the highest grade* zone at the center to the lowest grade* zone at the periphery. Although various types can be shown by combining alteration zones, the predominant zonings are rather simple constituting zones of the same alteration zone group. An example of zoning made up of acidic zones only is, from the center to the periphery; silica→pyrophyllite→dickite→kaolinite→halloysite. Zoning that surrounds metalliferous veins, usually is composed only of such intermediate zones as, K-feldspar→(sericite) or propylite→mixed layer→smectite. Ca-zeolites occurring as veins, networks, or fracture-filling also are distributed in a zonal arrangement, wairakite→laumontite→heulandite and/or chabazite→stilbite. Commonly, various kinds of hydrothermal alteration have been superimposed on each other in specific areas.

It is notable that these hydrothermal alterations have been predominantly controlled by regional tectonics, as clearly seen when the simplified maps that show the distribution of these hydrothermal alterations (Figs. 2-A, -B and -C) are compared with the distribution of active faults (Fig. 2-D).

3. SLOPE FAILURES CAUSED BY HEAVY RAINFALL IN AUGUST 1982

3.1. *Outline of the Rainfall Disaster*

Central Japan twice was struck by severe typhoons in early August 1982. On the Izu Peninsula, rainfall was concentrated in the central mountain area where the estimated total amount of rainfall exceeded 400 mm for each typhoon. Fortunately, no fatalities occured. Serious damage mainly was confined to such constructions as buildings, bridges, and roads. A large number of slopes failures were concentrated along roadsides and intencely damaged to transportation networks.

3.2. *Distribution of Failed Slopes by Area*

This survey of the failed slopes began the week after the second heavy rainfall in August in 1982, and finished in December of 1985. Although the survey was restricted only to failed slopes of $1 m^2$ or more, a total of 1,986 was found.

The distribution of these failed slopes by area is shown in Fig. 3 which shows that slope failure occurred throughout the peninsula. The number of failed slopes were greater in the central mountainous area than on either coast. These distribution characteristics differ markedly from these for the Izu-Hanto-Oki Earthquake in which most failed slopes were concentrated around active faults [5].

3.3. *Volume of the Failed Slopes*

The volume of each failed slope was calculated as those of a rectangular prism whose area and depth were roughly measured in the field. The failed slopes were ranked from 1 to 6, based on their calculated volumes (Table 3). Although the total number of failed slopes was very large, about 85% had a volume of less than $n \times 10^3 m^3$.

3.4. *Locations of Failed Slopes*

The locations of the failed slopes are listed in Table 4. Conspicuously more than three-fourths of the slope failures are concentrated around roads. Whereas, they are very rare for mountain slopes and riverside cliffs. This is not due to a difference in the frequency of slopes in these locations, because the number of mountain slopes is far larger than for other slope types

* "High grade" is here used for "high temperature", and "low grade" for "low temperature".

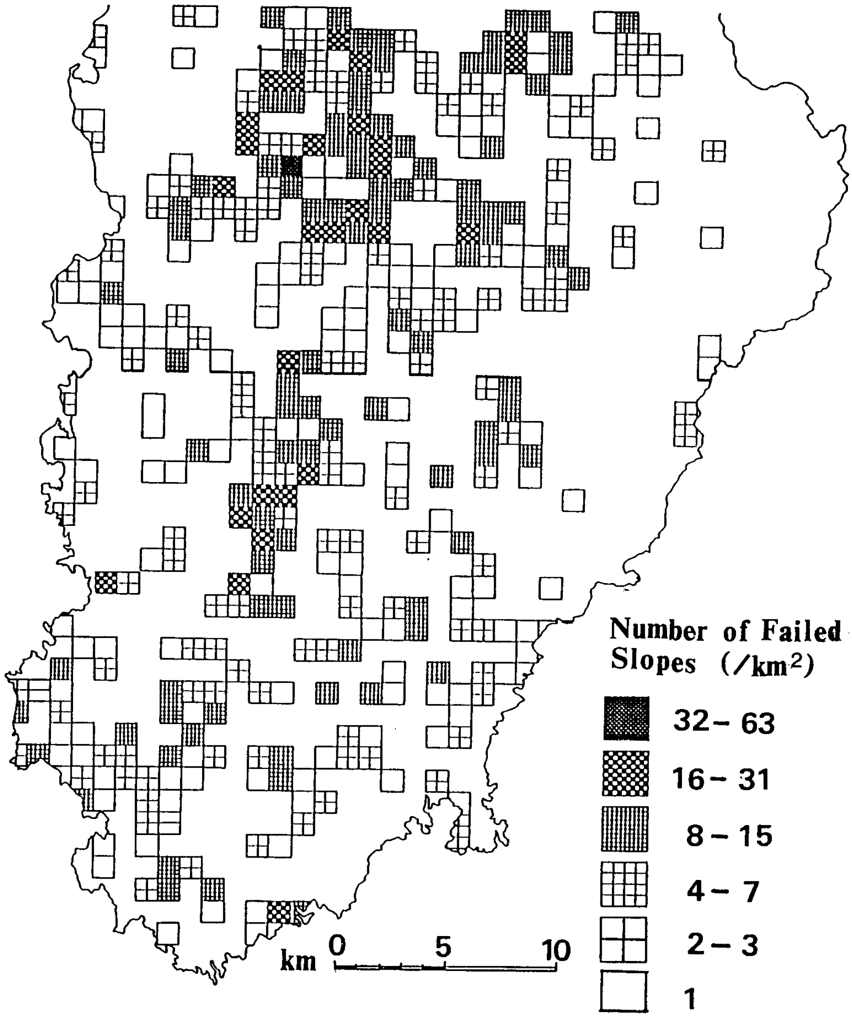


Fig. 3 Distribution of failed slopes by area.

Table 3 Number and frequency of failed slopes classified by Rank based on the volume of a failed slope.

Rank	Volume (m^3)	Number	Frequency (%)
1	$n \times 10^4$	5	0.5
2	$n \times 10^3$	18	1.8
3	$n \times 10^2$	120	12.2
4	$n \times 10^1$	352	35.9
5	$n \times 10^0$	333	34.0
6	$n \times 10^{-1}$	152	15.5
0	unknown	182	—

which include a large number of artificial slopes.

3.5. *Surface Features of Failed Slopes*

The surface features of the failed slopes are listed in Table 5. Most had been covered by grass, bushes, trees, or artificial fencing. Slope failure was frequent for outcrops, filled-in ground,

Table 4 Number and frequency of failed slopes classified by location.

Location \ Rank	1	2	3	4	5	6	0	Number	Frequency (%)
Artificial cutting by road	4	5	46	152	143	77	7	435	41.2
Natural slope along road	1	3	28	94	95	45	7	273	25.8
Slope below road	0	4	14	35	34	13	67	167	15.8
Slope between two roads	0	1	3	15	12	4	2	37	3.5
Slope between road and river	0	0	0	8	6	1	9	24	2.3
Artificial cutting	0	1	3	3	1	0	0	8	0.8
Mountain slope	0	2	11	12	9	0	2	36	3.4
Artificial slope along rice or corn field	0	0	2	6	15	7	3	33	3.1
Natural slope along river	0	3	14	19	4	1	1	42	4.0

Table 5 Number and frequency of failed slopes classified by surface feature.

Surface feature \ Rank	1	2	3	4	5	6	0	Number	Frequency (%)
Outcrop	1	0	14	66	41	34	3	159	15.1
Grass-covered surface	2	2	54	167	194	97	56	580	54.9
bush- or tree-covered surface	1	10	39	85	58	15	17	225	21.3
cement- or mortar-plastered surface	1	3	2	1	2	0	1	10	0.9
Net-fenced surface	0	0	1	2	1	0	0	4	0.4
Stone- or block-fenced surface	0	2	3	4	6	1	0	16	1.5
filled in ground	0	1	7	14	17	1	21	61	5.8

and for grass- and/or bush-covered slopes, but rare for net- and stone-fenced, and for cement- and mortar-plastered slopes.

4. LITHOLOGIES OF THE FAILED SLOPES

4.1. *The Original Rock Types of the Failed Slopes*

The original rock types of the failed slopes vary as shown in Table 6. Slope failures occurred in all the stratigraphic units found on the Izu Peninsula. About half of the failures took place in soft rocks of Quaternary age that made up soil, volcanic debris, talus and filled-in ground. The remainder mainly were found in volcanic, volcaniclastic and intrusive rocks of the other three units. But, about 20% of the original rocks could not be identified because of the extreme alterations that had taken place.

4.2. *Alteration Zone of Failed Slopes*

All the rock samples gathered from the failed slopes excluding soil, volcanic debris, talus and filled-in ground were analyzed by X-ray diffractometry. About four thousand samples that were gathered as evenly as possible from the surrounding areas also were analyzed by the same technique. Each of the analyzed samples were classified in one of eighteen alteration zones according to the mineral assemblage given in Table 2. The results of this classification are presented in Table 7.

On the assumption that the percentage of samples from the whole area (D) is roughly

Table 6 Number and Frequency of failed slopes classified by rock-type.

Rock-type \ Rank	1	2	3	4	5	6	0	Number	Frequency (%)
Soil	1	2	18	77	60	34	0	192	17.6
Talus	0	6	20	71	46	28	0	171	15.8
Loam and volcanic debris	0	2	9	37	25	6	1	80	7.3
Sedimentary rock	0	1	10	12	11	2	1	37	3.4
Volcaniclastic rock	0	4	9	27	20	3	3	63	5.8
Brecciated volcanic rock	0	1	9	58	33	20	1	122	11.2
Massive volcanic rock	0	3	10	37	54	22	1	127	11.6
Instrusive rock	0	1	2	2	5	1	0	11	1.0
Extremely altered rock	4	4	41	77	55	25	0	206	19.2
Filled in ground, etc.	0	2	9	24	35	11	0	81	7.4

Table 7 Number and frequency of failed slopes in the alteration zones.

Alteration Zone	Failed slope		All samples		Relative frequency
	Number (A)	Frequency (%) (B)	Number (C)	Frequency (%) (D)	(E)
Alunite zone	6	1.05	131	3.23	4.58
Pyrophyllite zone	7	1.49	97	2.39	7.21
Dickite zone	2	0.35	32	0.79	7.21
Kaolinite zone	30	5.26	141	3.48	21.28
Halloysite zone	80	14.04	252	6.22	31.75
K-feldspar zone	14	2.44	238	5.87	5.88
Sericite zone	9	1.57	128	3.16	7.03
Propylite zone	54	9.43	641	15.81	8.42
Mixed layer zone	68	11.93	519	12.80	13.10
Smectite zone	182	31.93	828	20.42	21.98
Wairakite zone	4	0.70	37	0.91	10.81
Laumontite zone	12	2.11	109	2.69	11.01
Heulandite zone	2	0.35	21	0.52	9.52
Stilbite zone	0	0.00	8	0.20	0.00
Analcime zone	4	0.70	45	1.11	8.89
Mordenite zone	10	1.75	55	1.36	18.18
Clinoptilolite-mordenite zone	8	1.40	67	1.65	11.94
Fresh glass zone	22	3.86	251	6.19	8.76
Silica rocks	58	10.16	477	11.77	12.15
Others	2	0.35	9	0.22	22.22

correlated to the percentage for the distribution area, the relative frequency index (E) in each zone can be shown by the ratio of the number of failed slopes to the number of slopes in the entire area; (A)/(C).

As shown in figure (D), the intermediate zone group appears to be distributed over about 60% of the entire area, and the number of failed slopes (B) is nearly the same. The value for the acidic zone group exceeds that for the estimated distribution area. These results are consistent with the writer's field observations that slope failure appears to have occurred selectively in

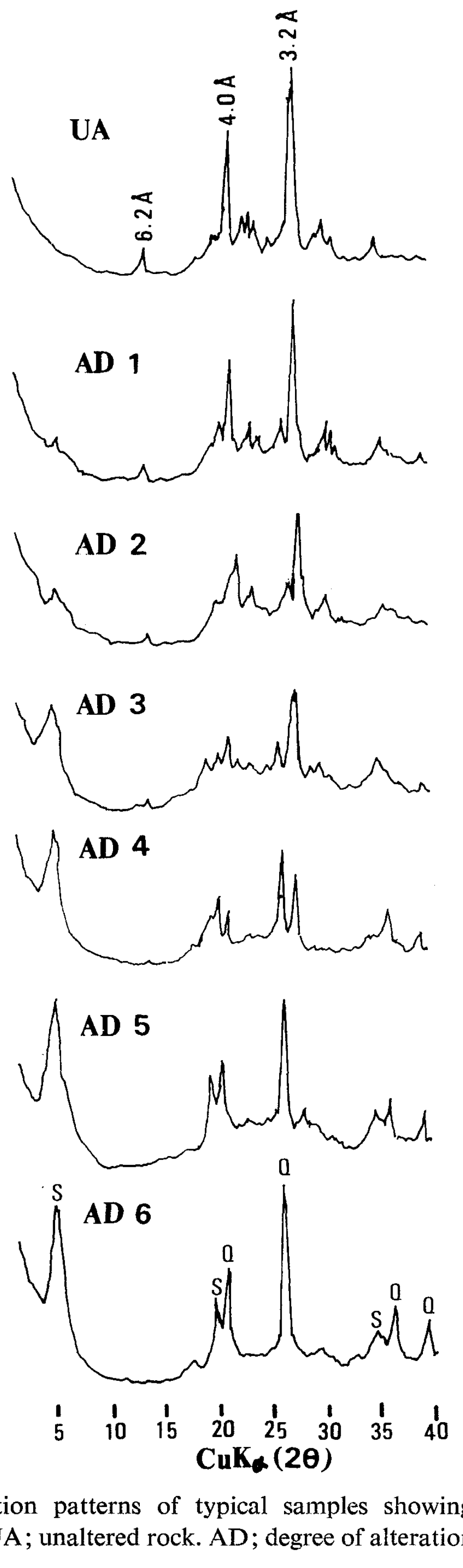


Fig. 4 X-ray diffraction patterns of typical samples showing various degrees of alteration. UA; unaltered rock. AD; degree of alteration (1 lowest, 6 highest).

"white alteration areas".

Of all the alteration zones, the relative frequency index of slope failure, (E), is largest in the halloysite, even though this zone probably was formed by both weathering and hydrothermal alteration. The index for the smectite zone also is very large, and this zone, of weathering and hydrothermal origin, may be the most widely distributed zone in the Izu Peninsula, as judged by index (D). Furthermore, slope failure most commonly occurred in this zone as indicated in indices (A) and (B). Index (E) for the kaolin zone is large, about five times that of the alunite zone belonging to the same acidic zone group. Within the alkaline zone group, the mordenite zone has the largest index (E), and the clinoptilolite-mordenite zone of diagenetic origin has a very small index.

In general, index (E) is smaller in the high grade than in low grade zones. For instance, this index regularly increases from the propylite to the smectite zone through the mixed layer zone. The exception is the laumontite zone which has the largest index (E) of the Ca-zeolite zones.

4.3. *Degrees of Alteration of the Failed Slopes*

As described in the previous section, the relative frequency varies with the alteration zone. It also varies within a particular alteration zone, according to the degree of alteration. The degree of alteration is indicated by the amount of authigenic minerals present or the amount of primary minerals that remain. Fortunately, the original rocks seem to have contained a relatively constant amount of plagioclase; therefore, the relative intensity (I_a/I_0) of the plagioclase peaks in each X-ray diffraction pattern can be used as an indicator of the degree of alteration.

Eight hundred twenty eight samples from the smectite zone were classified in six degree of alteration groups according to the average relative intensity (I_a/I_0) of the 3.2Å, 4.0Å and 6.2Å peaks of their plagioclases. A typical X-ray diffraction pattern for each degree is shown in Fig. 4; the classification list is given in Table 8. As shown in this table, the relative frequency index, (E), of the highest degree of alteration ($I_a/I_0<0.9$) attains 75%; whereas the lowest value ($I_a/I_0<0.1$) is less than 5%. All the large scale failed slopes of Ranks 1 and 2 were found in the rock that registered the highest degree of alteration.

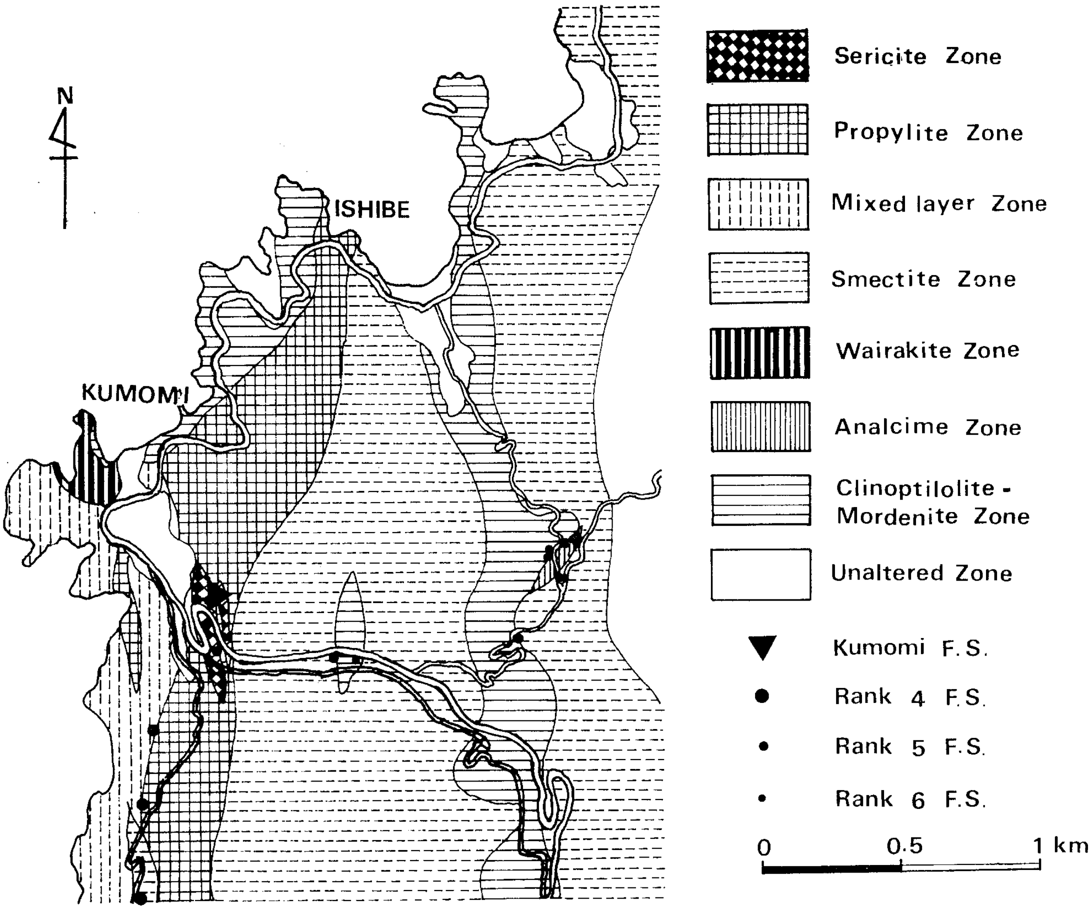
Table 8 Number and frequency of failed slopes in the smectite zone classified by the degree of alteration.

Degree of Alteration	I/Io	Failed slope		All samples		Relative frequency (%)
		Number	Frequency (%)	Number	Frequency (%)	
1	90	3	1.6	71	8.6	4.2
2	70 – 90	49	26.3	340	41.1	14.4
3	50 – 70	45	24.2	189	22.8	23.8
4	30 – 50	39	21.1	136	16.4	28.7
5	10 – 30	36	14.0	60	7.2	43.3
6	10	24	12.9	32	3.9	75.0

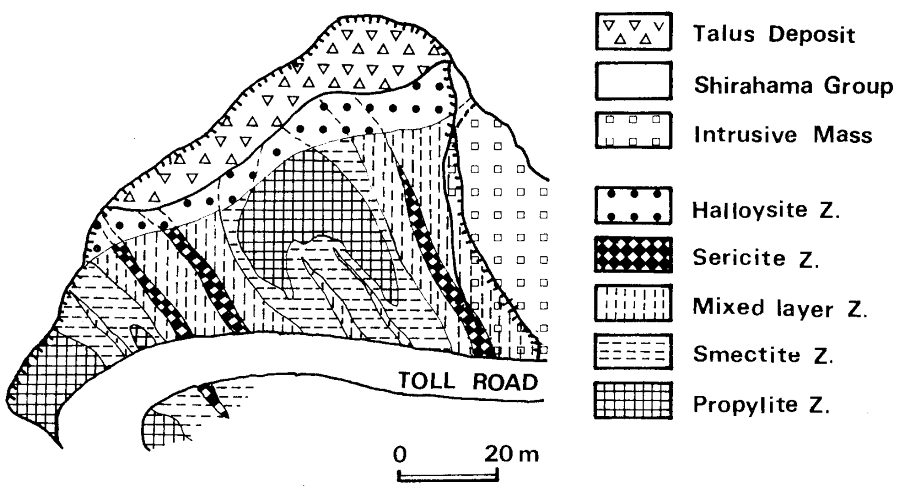
5. THE MODE OF OCCURRENCE OF SLOPE FAILURE IN RELATION TO ROCK ALTERATION

5.1. *Mode of Occurrence of Large Slope Failures*

The largest slope failure took place south of the fishing port of Kumomi where the amount of rainfall was relatively small. The mode of this failure was a block slide which occurred in extremly altered rocks. It started at a large cut at a U-shaped corner of a toll road and struck the fishing village. Several tens of buildings were destroyed and the toll road had to be closed for one year. The volume of the failed slope was estimated to be 10^4 to 10^5 m^3, as judged from the amount of dumped material. As shown in Fig. 5-A, the failed slope is situated at about the center of the propylite zone. This slope encompasses three visible hydrothermal veins near the boundary of volcaniclastic rocks of the Shirahama Group and an intrusive mass (Fig. 5-B). The center of



A



B

Fig. 5 (a) Distribution of the alteration zones around the failed slope at Kumomi.
(b) Geologic formations present in the failed slope at Kumomi.

each vein is composed of sericite and quartz associated with a small amount of pyrite. Sericite/smectites and smectite are present between the sericite vein and the propylite. The presence of these authigenic minerals suggests that the hydrothermal veins of the sericite-smectite series were superimposed on propylite which had been formed in an earlier stage. Propylitization probably was related to the intrusion of a dacite mass. A halloysite zone formed by weathering is located near the top of the slope which mainly is composed of talus deposits. The center of the slope failure probably was near the sericite veins which have been most deeply scooped out.

Another large scale slope failure occurred within the Ugusu Silica Mine. The Ugusu silica deposit is a huge network deposit which made up of many conjugated veins of various definite directions (Fig. 6). Each vein is arranged zonally from the center to the periphery as follows: silica→alunite zones or silica→pyrophyllite→kaolin zones. The silica zone at the center is subdivisible into leached and precipitated silica subzones.

This silica deposit is surrounded by a clay zone that contains among other minerals; smectite, sericite/smectites, rectorite, and chlorite/smectites. The slope failure took place in part of this clay zone. The volume of failed slope appears to be more than 10^4 m^3, but the slope failure damaged only the private road to the mine. Three other slope failures of Rank 1 occurred along the sides of the road from Funabara to Toi which passes through the western ridge. This road was greatly damaged by these slope failures and by other slope failures. For example, the toll road was closed for ten months, because a bridge near Hiraishi had been struck and destroyed by a slope failure. All the slope failures characteristically occurred in the peripheral smectite zone that surrounds the acidic alteration zones (Figs. 7-A and 7-B).

The mode of occurrence for slope failures of Rank 2 is much like that of Rank 1. Most occurred in acidic clay zones or the surrounding smectite zone; but, some took place in the halloysite zone of weathered origin. All the failures were in rocks in all the alteration zones that had undergone the highest degree of alteration.

5.2. *Mode of Occurrence of Moderate Sized Slope Failures*

Slope failures of Ranks 3 and 4 were found in various kinds of rocks that had been altered to various degrees. The largest number of them were concentrated in the halloysite zone of weathered origin. The mode of slope failure is somewhat similar to block slide and somewhat similar to rock slide. Among the hydrothermal alteration zones, failures were most concentrated in zones of the sericite-smectite series, and the mode of occurrence was similar to rock slide. In general, both the number and volume of failed slopes increase gradully from the sericite to the smectite zone through the mixed layer zone. Slope failures of the ranks also were common in the acidic alteration zones that constitute networks or parallel veins. Each vein is surrounded by acidic clay zones arranged zonally. Slope failure occurred in both the veins and the surrounding clay. A fairly large number of failed slopes were concentrated near the boundary between an acidic clay zone and the peripheral "propylite zone".

5.3. *Mode of Occurrence of Small Slope Failures*

Small slope failures of Ranks 5 and 6 in Table 3 took place in all kinds of altered rocks; the mode of occurrence mostly being rock slide. In general, small scale failed slopes were very common for outcrops and grass-planted artificial slopes; whereas, they were rare for fenced or plastered artificial slopes. Slope failure in the laumontite zone is notable. The relative frequency index (E) for this zone is higher than for the other Ca-zeolite zones (Table 7). When compared with propylites, laumontite rocks did not differ in the mode of slope failures; but laumontite rocks showed more frequent rock slide than did propylites. The reason will be discussed in the subsection 7.4.

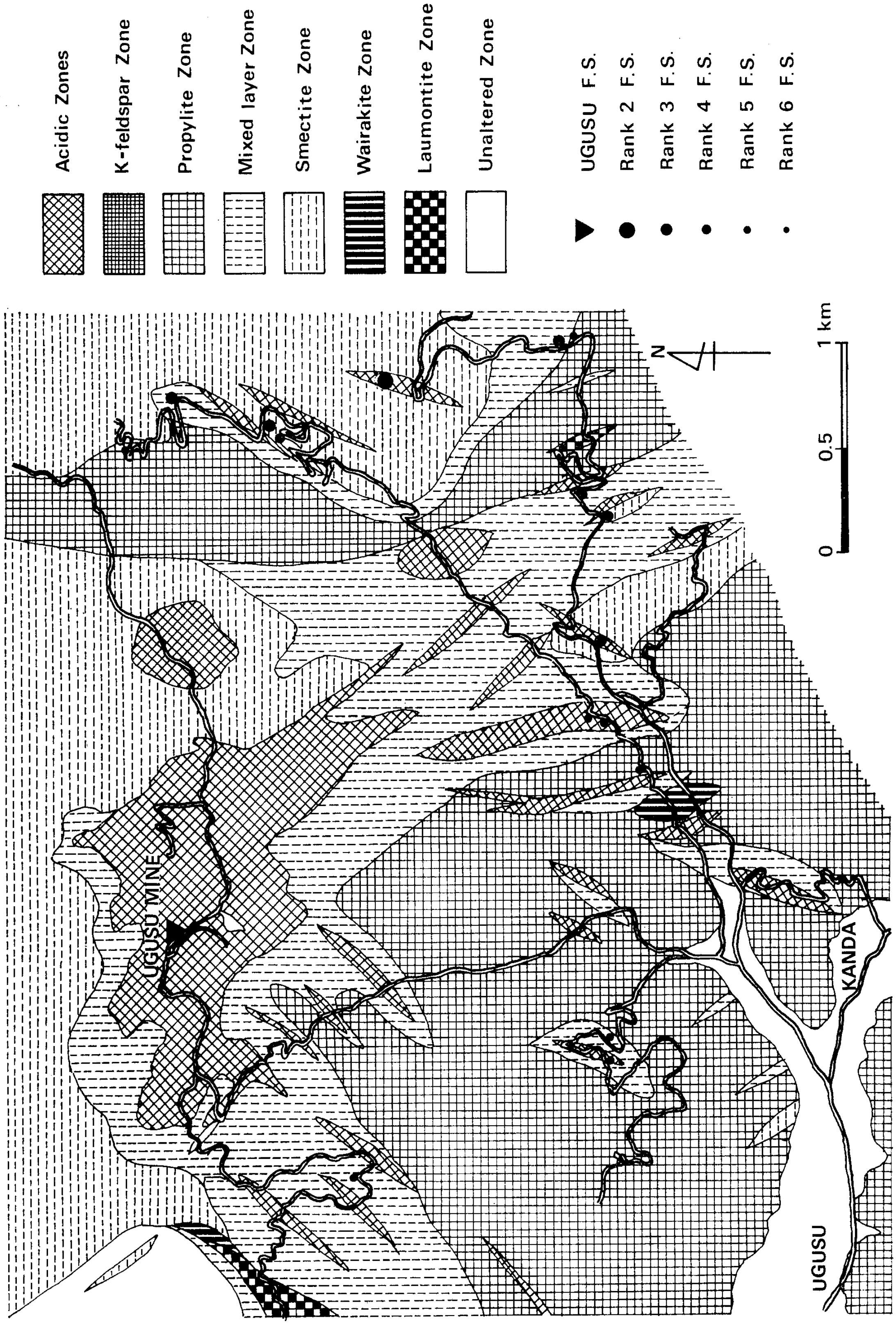


Fig. 6 Distribution of the alteration zones around the failed slope at the Ugusu Mine.

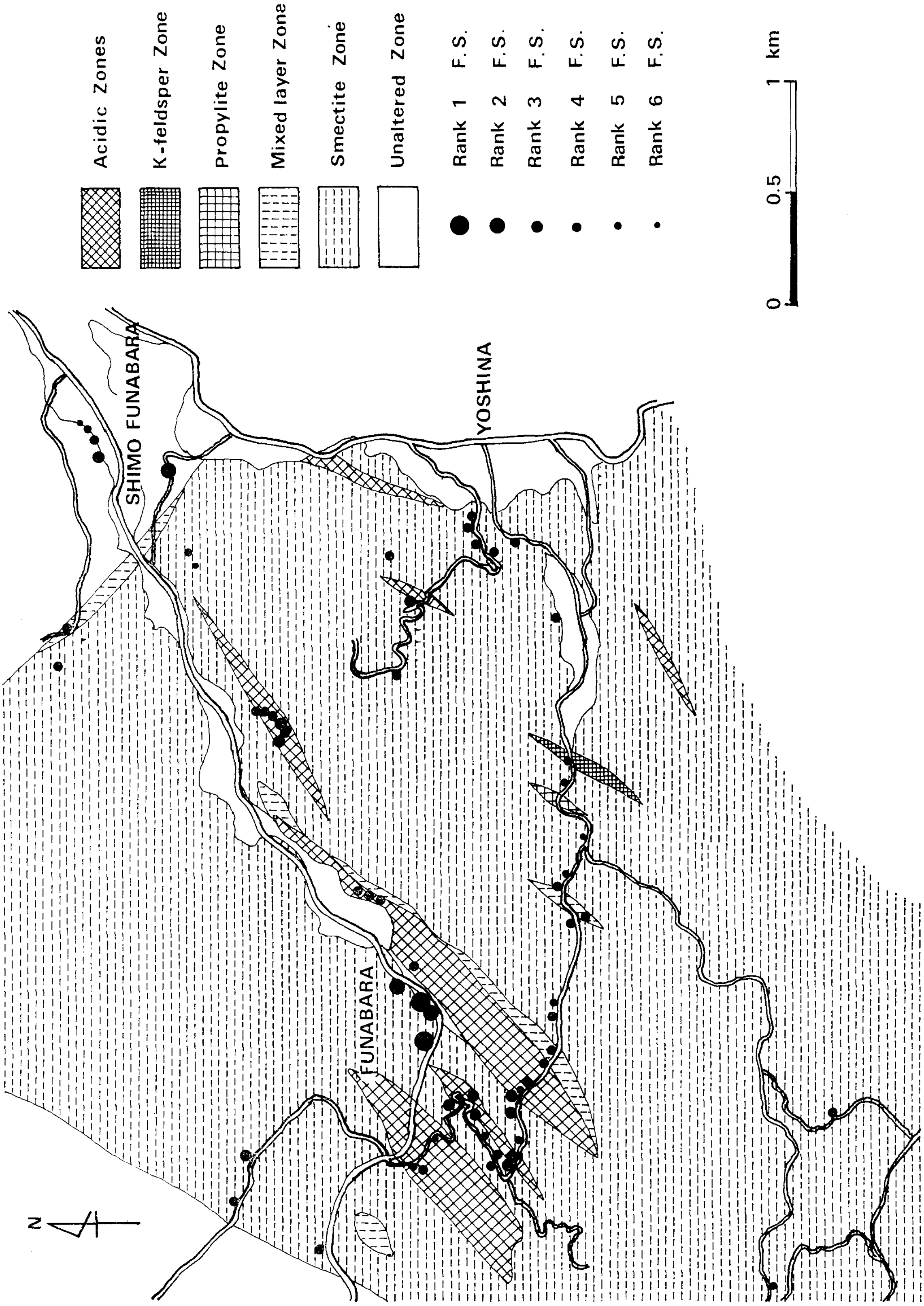


Fig. 7 (a) Distribution of the alteration zones and failed slopes in the Funabara area.

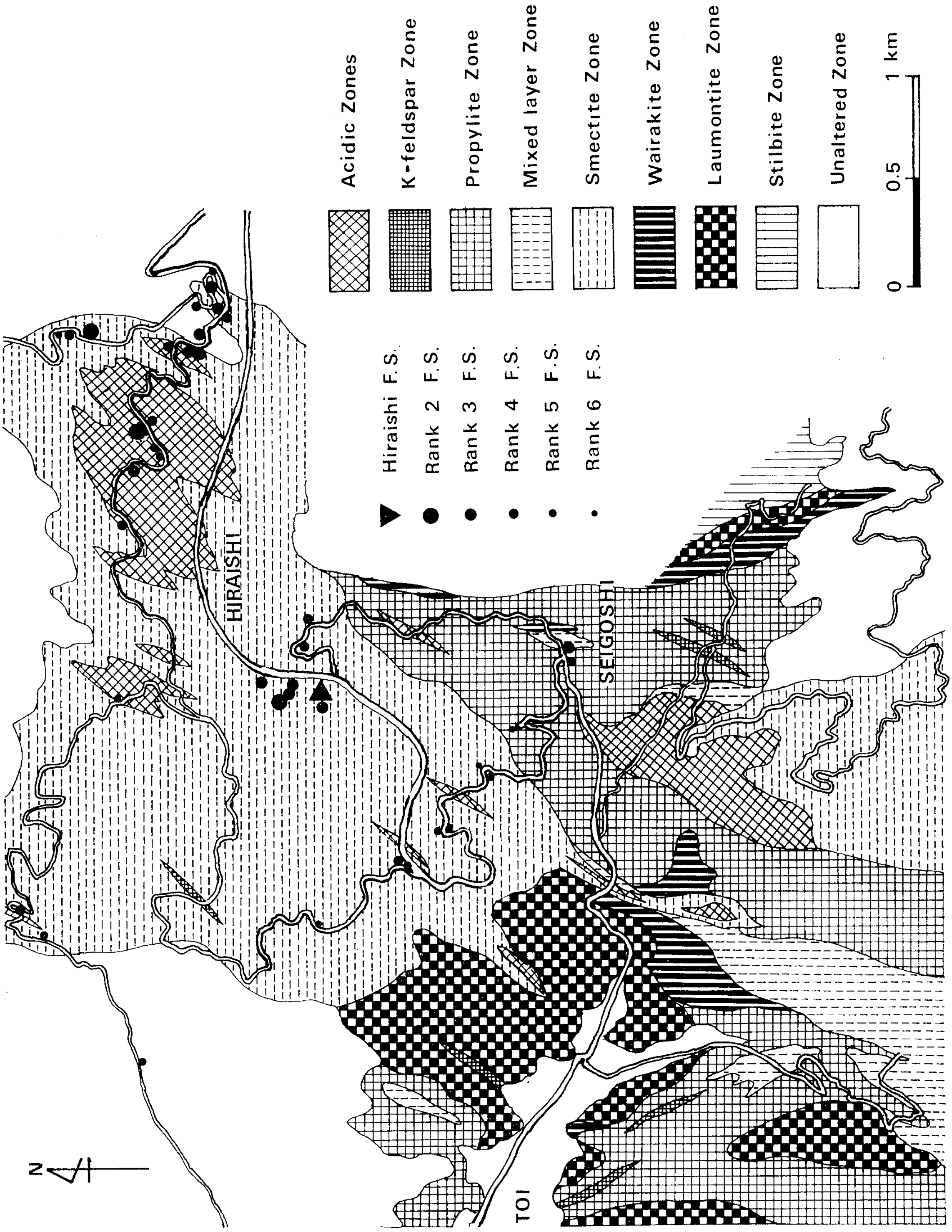


Fig. 7 (b) Distribution of the alteration zones and failed slopes in the Hiraishi area.

6. THE STRENGTH OF ALTERED ROCKS

6.1. *Method*

Rock strength was measured with a unconfined tensile test equipment developed by Hiramatsu et al. [10]. Kimiya's method [15] was used for the measurements and corrections. The rock strength index, (τ), was calculated from $\tau = \log_{10} S_t$, in which S_t is the corrected unconfined tensile strength (kg/cm^2). A total of 715 untreated samples were tested. Of these, 437 were probable andesitic or dacitic and the remainder volcaniclastic rocks.

6.2. *Strength of the Altered Rocks in Each Alteration Zone*

There is a clear difference in the distribution pattern for the rock strength index (τ) for unaltered volcanic rocks and unaltered volcaniclastic rocks (Fig. 8), which may indicate the difference in rock strength between the originals of both rocks. Here, "unaltered" means that no altered mineral could be identified by X-ray diffractometry. The fairly wide range of rock strength as seen in Fig. 8 suggests that they may be rocks that mechanically have been slightly altered or those that originally have been various in texture and fabric.

The distribution pattern for the strength of the volcanic rocks in each alteration zone in given in Fig. 9. The white bars show the distribution patterns of all the samples, and black ones those of samples from failed slopes. The distribution pattern for the alunite-quartz zone is almost the same as that of the unaltered volcanic rocks; whereas, the pattern for the alunite-opal zone differs markedly. The difference in the distribution patterns for these zones may be due to the difference in the species of silica minerals (opal and quartz) that are present.

The distribution pattern of the halloysite zone is unimodal and similar to that of the alunite-opal zone. The pattern for the pyrophyllite, dickite, and kaolinite zones, however, is bimodal, as seen from their contents; massive clay-quartz rocks of high strength and mono-clay veins of low strength. The same pattern is present for the sericite, mixed-layer, and smectite zones. The distribution patterns for the K-feldspar and prophylite zones are almost same as the pattern for the alunite-quartz zone, and the patterns for the Ca-zeolite zones are nearly bimodal. The distribution patterns for the alteration zones thus can be classified into one of three groups:

1) Unimodal (high rock strength)—High grade zones
2) Bimodal (high and low rock strength)—Intermediate grade zones
3) Unimodal (low rock strength)—Low grade zones

On the whole, the strength of volcanic rocks appears to have decreased in the course of hydrothermal alteration.

In contrast, the strength of the volcaniclastic rocks appears to have increased during hydrothermal alteration or diagenesis+contact metamorphism. Although based on a similar total of

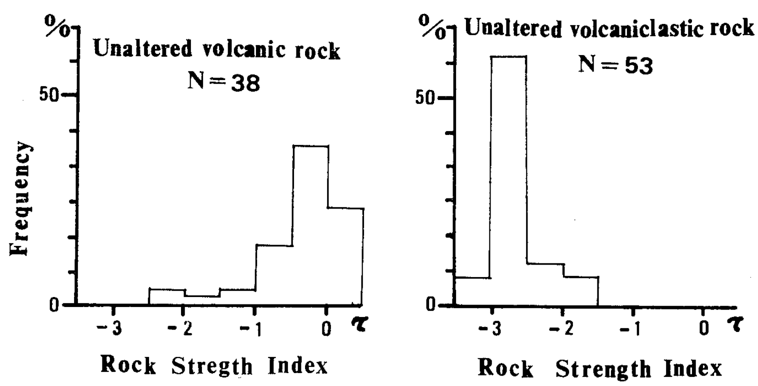


Fig. 8 Distribution of the frequency of the rock strength index (τ); (a) Unaltered volcanic rocks, (b) unaltered volcaniclastic rocks.

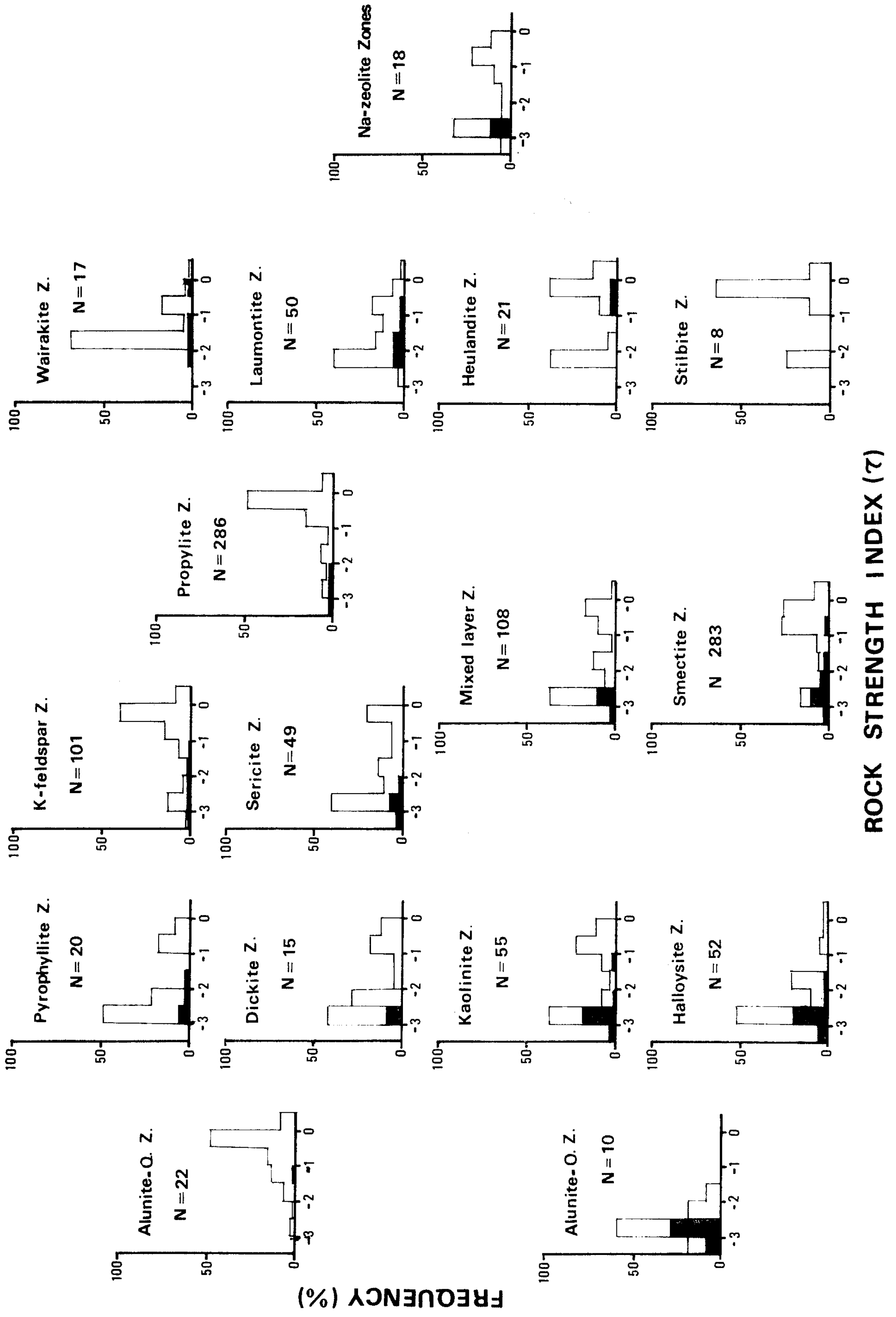


Fig. 9 Distribution of the frequency of the rock strength index (τ) for altered volcanic rocks.

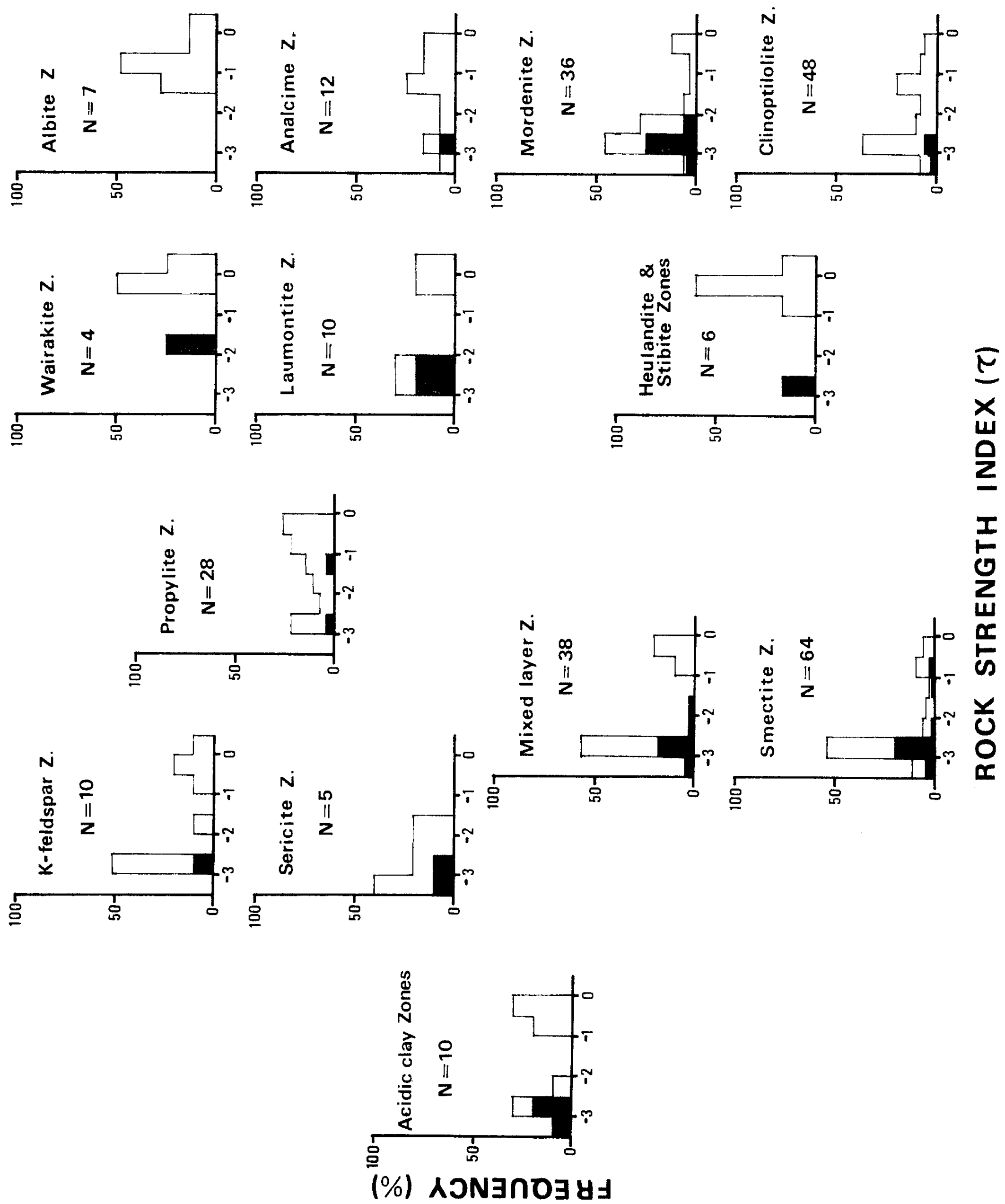


Fig. 10 Distribution of the frequency of the rock strength index (τ) for altered volcaniclastic rocks.

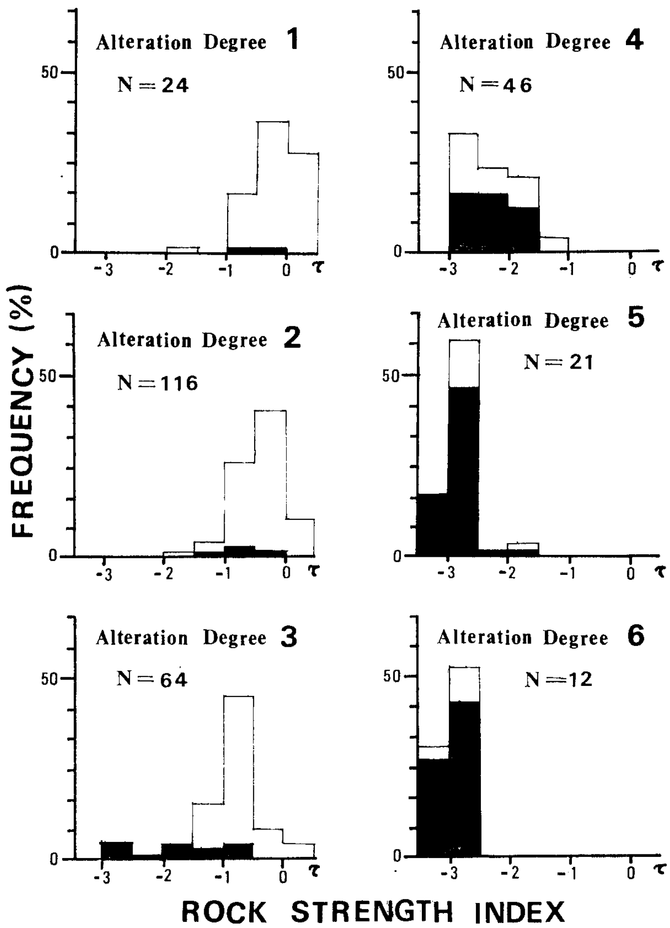


Fig. 11 Distribution of the frequency of the rock strength index (τ) for rocks in various degrees of alteration.

tested samples, Fig. 10 indicates that rock strength increases from the smectite to the propylite zone through the mixed layer zone. This same tendancy is present in the series of Na-zeolites and albite zones that are probably of diagenetic+contact metamorphism origin.

The finding that the slope failures took place mostly in the rocks of low strength in every alteration zone (as seen in Figs. 9 and 10) is very important.

6.3. *Relation between Rock Strength and the Degree of Alteration*

The distribution of the strength of smectitzed volcanic rocks for the various degrees of alteration is shown in Fig. 11. This figure also indicates that most slope failures took place in rocks of low strength. The genetic relation of slope failure to rock strength is discussed next.

7. GENETIC RELATION OF SLOPE FAILURE TO ROCK ALTERATION

7.1. *Summary of Field Survey and Laboratory Studies*

The results of the writer's field surveys of failed slopes and the results of mineralogical, and rock strength analyses of failed material done in the laboratory can be summarized as follows:
(1) For the heavy rainfalls of 1982, about half of the slope failures took place in hydrothermally altered rocks. This accounts for all the large scale failed slopes.
(2) In general, slope failures was more frequent in low grade than in high grade rock zones.
(3) All the large slope failures took place in the acidic clay or smectite zones, and the mode of

failure was block slide. In contrast, small scale failures occurred in all the alteration zones, the mode of failure being rock slide.

(4) Slope failure was more frequent in rocks that showed high degrees of alteration.

(5) Rock strength had a roughly inverse relation to the degree of alteration; slope failure taking place mainly in rocks of low strength.

(6) The strength of the volcanic rocks appears to have decreased owing to the formation of clay minerals and the decomposition of plagioclase; whereas, it appears to have been increased by silicification, especially quartz. The strength of volcaniclastic rocks, however, appears to have been increased by the formation of zeolites and silica minerals.

These results are evidence that slope failure and rock alteration, especially hydrothermal alteration, are closely related. Several factors related to slope failure are discussed in the subsection that follow.

7.2. *Relation of the Amount of Authigenic Minerals* Relating to Slope Failure*

As shown, slope failure took place mainly in the rocks of low strength. Decrease in rock strength may be caused mainly by the formation of authigenic minerals and the decomposition of primary ones during alteration as well as by fracturing produced by tectonic movements. As all authigenic minerals are formed by interactions between the original rocks and reacting solutions, an approximation of the amount of authigenic minerals present can be obtained from the ratio of these factors for the whole process.

As hydrothermal solutions may have dispersed from their original paths into surrounding areas, the amount of authigenic minerals should decrease, while that of primary minerals increase from the center of alteration to the periphery. Frequent slope failure did not always occur at the center of alteration (see section 5). In the case of diagenesis+contact metamorphism, the amount of authigenic minerals showed a general increase in the higher grade zones. Slope failure, however, was rarely in the volcaniclastic rocks of these zones (Fig. 10). Thus an increase in the amount of authigenic minerals is not always correlated with the frequency of slope failure.

Generally speaking, slope failure are more frequent where there has been an increase in the amount of clay minerals present, probably because of concomitant decrease in rock strength. Slope failure, however, is rare where quartz, K-feldspar, albite and sometimes zeolites have formed, because of increased rock strength.

7.3. *The Occurrence of Authigenic Minerals and Its Relation to Slope Failure*

As described in the previous section, the decrease or increase in rock strength appears to vary with the species of authigenic mineral. In particular, the rock strength of quartz-bearing and opal-bearing rocks markedly differ. This may, in part, be due to the difference in the mode of occurrence as well as to the hardnesses of these minerals. Microscopy showed that in high grade zones quartz is replaces the phenocrysts and fills the voids left by the dissolved precursors. The groundmass also is nearly completely replaced with other authigenic minerals and, on the whole, the rock seems very dense and hard. But when it's opal that replaces and partly fills voids and veins, the opal rocks retain many minute voids and appear very soft.

The mode of occurrence for K-feldspar and albite is almost the same as that for quartz, and they usually are associated with that mineral. Ca-zeolites commonly occur as vein- or fracture-filling minerals in volcanic rocks; whereas, Na-zeolites replace vitric materials or fill the interstitial spaces in volcaniclastic rocks. The former mineral probably decrease rock strength, and the latter increase it. Thus, the mode of occurrence of authigenic minerals is related to the increase or decrease of rock strength and the frequency of slope failure.

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* The term authigenic mineral here includes the secondary minerals in igneous rocks as well as the authigenic minerals found in sedimentary rocks.

The modes of occurrence for clay minerals vary. Their formation, however, should decrease rock strength, because they all have very low hardness.

7.4. *Relation of the Mineralogical Properties of Authigenic Minerals to Slope Failure*

Various kinds of authigenic minerals were found in the materials from the failed slopes. Of these, smectite and halloysite are notable because of their close relation to the frequency and mode of slope failures. The roles of these minerals, especially in the swelling phenomena related to the mechanism of slope sliding have been well discussed.

Sericite/smectites and other mixed-layered clay minerals probably have played the same role as smectite in the large scale failed slopes that took place at Kunimi and Ugusu.

Pyrite commonly is associated with hydrothermally altered rocks, especially in acidic alteration zones. It is easily dissolved under oxidizing conditions and produce strong SO_4^{2-} solutions. In the Izu Peninsula, both artificial and natural slopes often have been chemically attacked by such sulphate solutions, and failures have been frequent on these slopes.

Zeolites usually function to increase rock strength in volcaniclastic rocks as stated previously. Zeolitized rocks are used for building stone in many countries because mechanically they are strong while being porous and light. But, when Ca-zeolites and carbonate minerals are present in veins or fractures, they cause a decrease in rock strength because of decomposition. Laumontite, in particular, will easily discharge half its zeolitic water under dry conditions and is apt to be come a powder. The fact that laumontite-bearing rocks decrease rock strength by this mechanism, is the basic reason why the relative frequency of slope failure is higher in the laumontite zone than in the other Ca-zeolite zones (see Section 3).

8. CONCLUSION

Slope failures have been shown to be apt to occur in hydrothermally altered areas, as well as in weathered zones, based on the results of the writer's survey the 1982 slope failures on the Izu Peninsula. The frequency, volume and mode of slope failure differ with the type of the alteration zone, probably because of the differences in rock strength produced by the amounts, mode of occurrence and mineralogical properties of the authigenic minerals present.

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