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Properties of the New Volcanic Substrate of Mt. Usu with Regards to Natural Revegetation

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Abstract

The 1977-78 eruptions of Mt. Usu deposited a thick ash-pumice mantle on the summit caldera. This deposit was immediately re-worked by erosion. Air-fall tephra and re-worked materials provided new substrates for plants. Natural revegetation occurred but not in a uniform manner. To check if different revegetation patterns reflected noticeable variations in the substrate, investigations were made on the substrate in 1983-84.

Tephra depth generally controlled plant survival. Pebble-granule sized pumices overlaid on the alluvial fans were more quickly invaded than silty-sand ash, probably because they offered better protection for seedling growth. Potential moisture was lower in pumice than in ash but actual moisture was probably higher on pumiceous fans due to better irrigation and less evaporation of the white surface. Actual moisture was also high in gullies and this favored plant establishment. Content in nutrients was generally low but this did not impede seed-plant invasion. Moisture and 20-45°C surface temperatures around vapour fumaroles could explain the extensive invasion of algae and mosses. Substrate instability after the eruption had damaging aspects but also transformed an initially poor habitat: a thick tephra mantle overlaid with ash, into better habitats for plants such as thinner new tephra, gullies and pumice-overlaid alluvial fans.

Key Words: Substrate, Revegetation, Ash, Pumice, Moisture, Plant nutrients, Temperature, Stability instability.

1. Introduction

Mt. Usu, located in southwest Hokkaido, Japan, is topped with a summit caldera where the last eruptions of 1977-78 occurred. About 20 new craters opened and discharged ca. 0.009 km^3 of ash and pumice (Katsui & Yokoyama, 1979). Tephra thickness largely surpassed 3 m near the largest crater (Gin-Numa) but only 20-30 cm of tephra accumulated on the relatively spared northeastern caldera rim. The natural forest which stood before the eruptions in the caldera was lashed and buried by the ejecta (Ito & Haruki, 1980; Higashi, 1980; Takahata, 1980; Okamura, 1985). Very few trees survived the damage. The new tephra mantle was immediately re-worked by erosion processes (Kadomura *et al.*, 1983; Chinen & Kadomura, 1984). On steep slopes, rilling and gullying took place whereas secondary redeposition occurred in depressions. The initial fallout deposit and the re-worked material provided basically new substrates for plants to grow on. Natural revegetation did occur but not in uniform manner (Rivière, 1982, 1986).

The purpose in investigating this new mineral substrate was to gather some basic data, rarely found in the literature, to be used as references in the study of volcanic soil development in correlation with natural revegetation. And as a first step, it seemed interesting to check if some of the differences recognized in the initial revegetation patterns reflected noticeable variations in the substrate.

The substrate was investigated in 1983–1984, ca. 5–6 years after the last eruption. Pedons were dug through the new deposit and described. Samples were collected and laboratory analysis which included moisture potential tests, particle size distribution, pH, EC and content of plant nutrients were conducted. Substrate temperature and stability/instability (due to erosion processes) were also investigated.

2. Sites location and methods

Figure 1 shows the location of the study sites and plots in the summit caldera. Field surveys and laboratory analysis were conducted as follows :

—*Texture and depth of air-fall tephra and redeposited material* :

Ten pedons were dug through the new pyroclastics to the buried soil in May 1984. Descriptions were made in the fresh pits. The redeposition layer was recognized by its "mixed-up" appearance and because it generally covered a homogenous fine ash deposit, the last ejecta deposited in 1978.

—*Soil moisture and particle size* :

The moisture potential tests performed on 100 cm^3 cylinder samples collected on the pedons sides in 1984 were the permanent and primary wilting points, the available moisture and the field capacity. These were approximated in the labo ratory by allowing the 100 cm^3 saturated samples to reach equilibrium under different pressures. Pressure was measured in PF (PF=Log H_2O cm) Suction method was used for $0 \leqslant PF \leqslant 2$ and centrifuge method for $2 \leqslant PF \leqslant 4$. Permanent and primary wilting points, and field capacity can be deducted from moisture curves for the respective PF of 4.2, 3.8 and 1.8. Available moisture is represented by the difference between primary wilting point and field capacity.

Actual moisture content measurements were repeated on 6 occasions by weighing samples before and after oven-drying at 105°C. The samples collected in 1983 and 1984 were surface samples at 0–10 cm depth. The sampling was done by forcing a 1000 cm^3 cylinder into the soil. Actual moisture content was also measured in the 100 cm^3 samples used for the moisture potential tests.

Particle size and texture are major elements influencing moisture. The dominant particle size of the samples used for moisture potential tests was approximated by hand crumbling. To get a more exact particle size distribution of the surface tephra in each site, separate samples (0–5 cm depth) were collected on the same day and the grains separated by sieving up to the silt size (mesh : 0.063 mm). The organic content was recognized by its smell and blackish color and the clay by

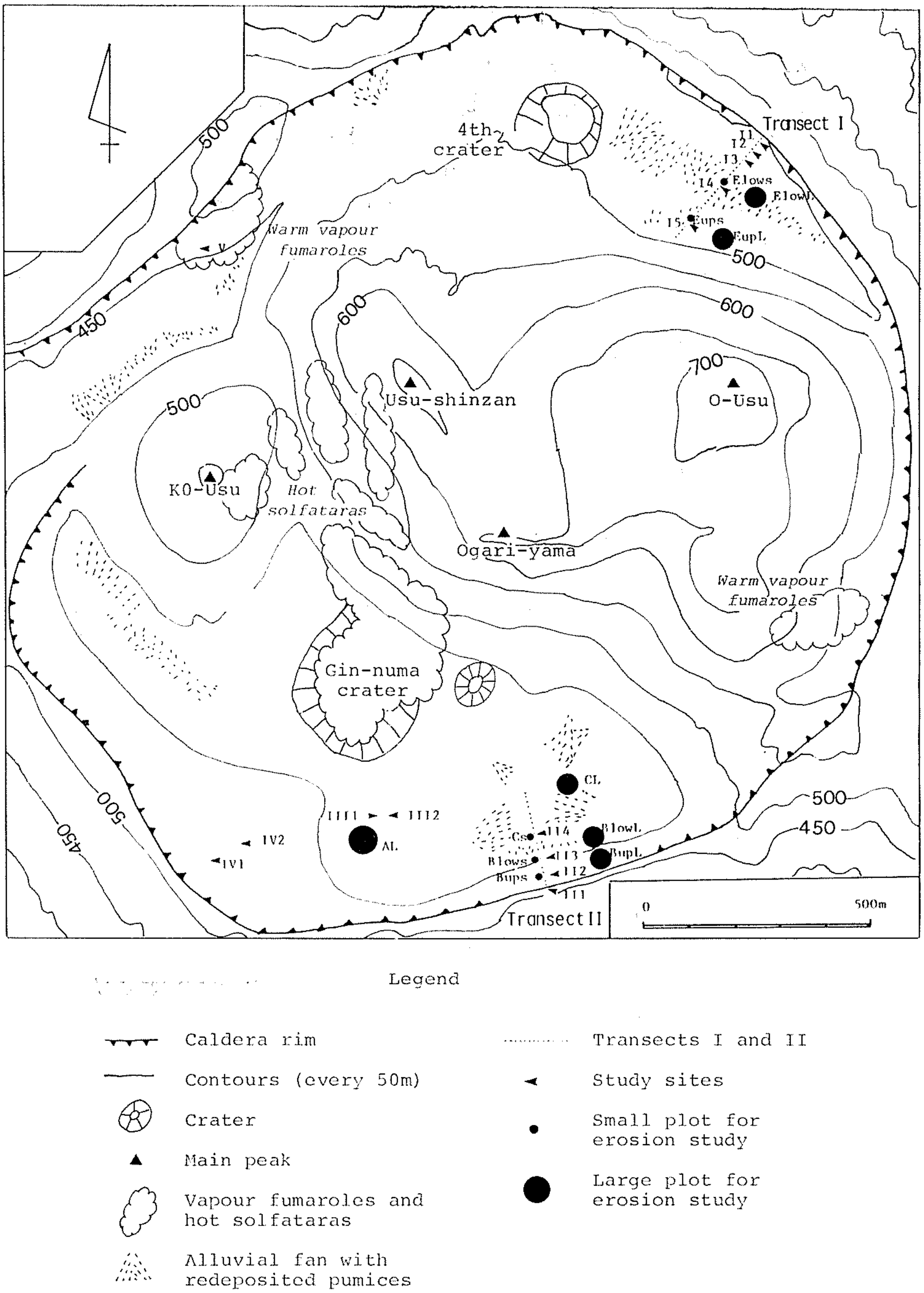

Figure 1. Location of study sites and plots in the summit caldera.

crumbling the finer grains in the hand.

—*pH, EC and content in plant nutrients*:

Sampling was done in spring 1984 by forcing a 1000 cm^3 cylinder into the soil then pouring its content into a plastic bag. In the laboratory, the samples were air-dried and chemical analysis was conducted on the fine earth. The particles of size <2 mm were separated by sieving and then ground with pestle. The following methods of routine analysis were used:

•pH (H_2O): Add 25 ml of distilled water to 10 g of soil. Shake for one hour. pH of suspension is measured with glass electrodes.

•pH (KCl): The same method as for pH (H_2O) but use 25 ml 1 M KCl.

•EC (Electric Conductivity): Add 50 ml of distilled water to 10 g of soil, shake for one hour. EC of suspension is measured with a glass electrode (ρS/cm, 25°C).

•NH_4N (Amonium nitrogen): Add 50 ml 10% KCl to 10 g soil, shake for 30 minutes, separate liquid portion by filtration. NH_4-N is determined by colorimetrical analysis using sodium phenolate (mg NH_4-N/100 g).

•NO_3-N (Nitrate nitrogen): Shake 10 g soil for 15 minutes with an extraction solution of 0.02 N $CuSO_4$ containing small amounts of $Ca(OH)_2$ and $MgCO_3$. NO_3-N is determined by colorimetrical analysis using phenol-di-sulfonic acid (mg NO_3-N/100 g).

•P_2O_5 (Available phosphorous): (Truog's method). Shake 1 g soil with 200 ml extraction solution (0.002 M H_2SO_4+0.2% $(NH_4)_2SO_4$) for 30 minutes. Phosphate in the solution is determined by colorimetrical analysis with Murphy and Riley method (mg P_2O_5/100 g).

•C (Total carbon): Thyurin's method (%).

•NH_4-N (Total nitrogen): Digest organic nitrogen by Kjeldahl's method. NH_4-N is determined by the distillation method (%).

•Ca, Mg, K, Na (Exchangeable bases): Replace the exchangeable bases by 1 M amonium acetate, pH=7. Ca and Mg in the solution are determined by atomic adsorption with 1000 ppm $SrCl_2$ as releasing agent. K and Na are determined by flame photometer. (meq exchangeable base/100 g).

—*Substrate temperature*:

Surface thermal mapping deduced from airborne infrared imagery was conducted by the bureau of Muroran Doboku Gengyosho in 1984. From that map, a simplified sketch of the caldera surface temperature was drawn.

Ground measurements were conducted in the sites investigated for moisture in three occasions and in a fumarollic area (site V) in one occasion using a common thermometer.

—*Substrate stability/instability*

The extent of past erosion (1977–1984), manifested by active gullying, was estimated by investigating the shape, the depth and the width of the gullies located on the southern caldera wall, along the transect II.

In eleven study plots established in August 1983, erosion and deposition rates

Table 1. Methodology for erosion and deposition measurements using pins

Sites	Slope angle	Pin number		Pin spacing (in m)	Time interval
		Set in 83	Undisturbed in 84		
Elows	10°	10	10	0.5	6.8.83— 6.7.84
ElowL	10°	22	22	2	6.8.83— 6.7.84
Eups	15°	10	10	0.5	6.8.83— 6.7.84
EupL	15°	22	22	2	6.8.83— 6.7.84
Bups	31°	10	10	0.5	6.8.83— 7.7.84
BusL	31°	22	22	2	6.8.83— 7.7.84
Blows	33°	10	7	0.5	6.8.83—30.6.84
BlowL	12°	22	21	2	6.8.83—30.6.84
Cs	3°	11	10	0.5	4.8.83—30.6.84
CL	3°	16	16	4	4.8.83—30.6.84
AL	4°	16	16	4	6.8.83—29.6.84

were measured until July 1984 by using erosion pins, 4 mm in diameter, driven vertically into the ground. Details on the average slope angle, number of erosion pins, spacing and time interval are given in Table 1.

3. Results and discussion

3. 1. *Texture and depth of airfall tephra and redeposited material*

3. 1 a. Pedon description :

A schematic representation of the pedons is given in Figure 2 and a detailed texture description of each profile is presented in appendix.

Ash was composed of silt and sand. Pumice and lithic fragments were made of granule and pebble. It was recorded that during the 7 years since the first eruption, water-erosion and redeposition of tephra had generally occurred at the lower slope portion and on the alluvial fans. The new substrate was generally made of ash on the hillslopes and of ash/pumice on the alluvial fans. When eruptions ceased, pumice beds were recovered with ash beds but when gullies cut through the deposits, pumice, lighter in density than ash, was more easily washed down to the alluvial fans.

Air fall tephra depth in transect I was superior to that in transect II. On the somma rims, tephra was three times thicker at II(1) : 60 cm than at I(1) : 20 cm. On slope bottoms, without considering the estimated water-eroded and redeposited material, 130 cm thick air fall tephra was deposited on II(3) but only 50 cm on I(3). Air fall tephra could not be calculated for the II(4) alluvial fan although the extent of tree burial allowed me to estimate a ca. 350 cm total deposit, that is an air fall tephra >200 cm. On I(4) air fall tephra was estimated to be 100-120 cm thick. At site III(1), 160 cm air fall tephra deposit was recorded.

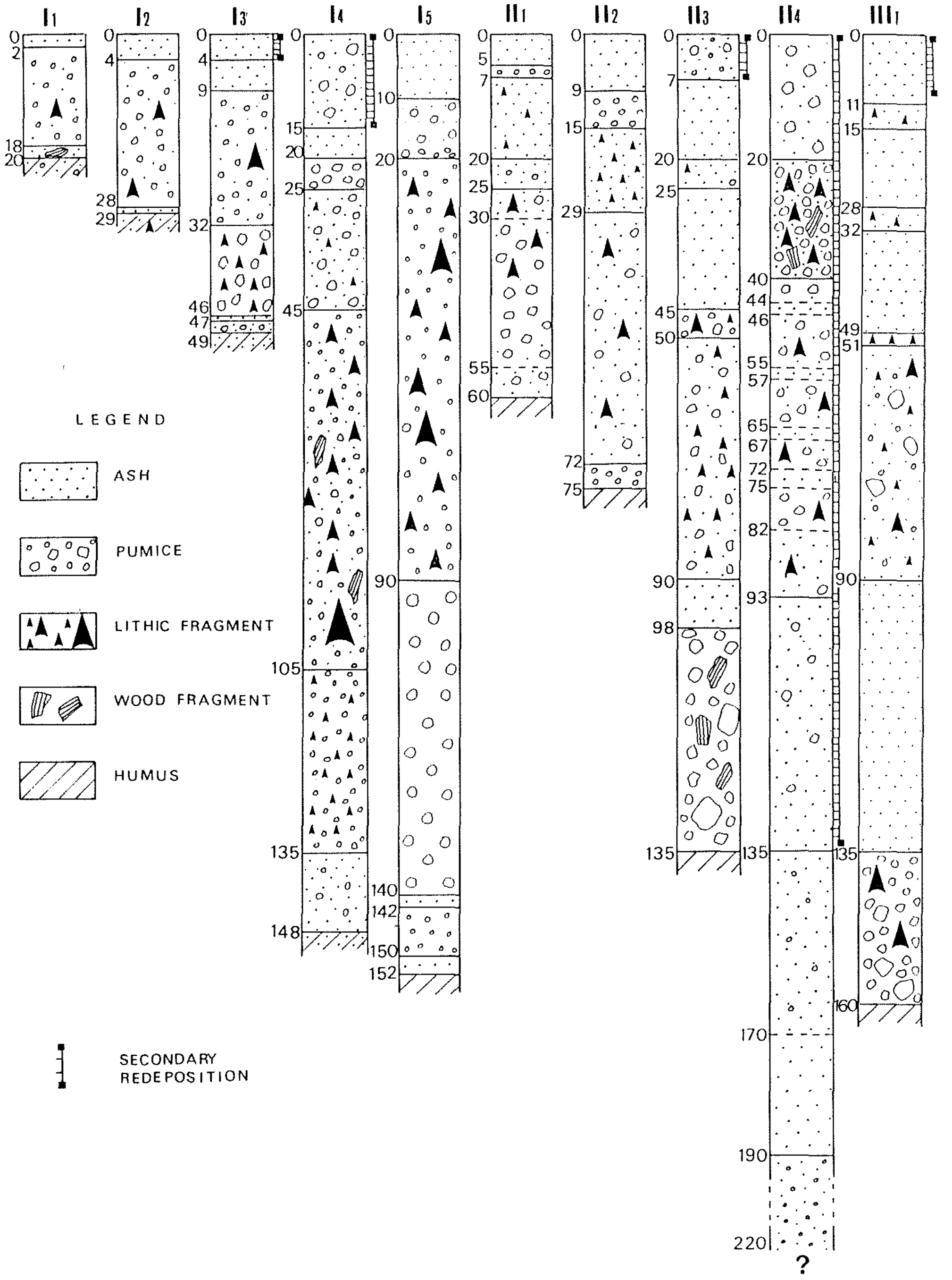

Figure 2. Air fall tephra and estimated secondary redeposition at ten sites of the summit caldera, as of May 1984. (The depth of the various layers is expressed in cm).

Differences in bedding also appeared between transects I and II. On I, the buried soil was generally covered with a thin bed of fine material (silty or sandy ash) then with thick beds of coarse materials (pumice and lithic fragments) and finally with fine material beds on the upper surface. On II, the buried soil was directly covered with thick deposists of coarse materials before ash layers deposited. Such differences can be explained by the different origin of tephra. The northeastern part of the caldera was more covered by the projections of a northeastern crater called "4th crater" and probably less covered by the products of central craters (which collapsed later on) than the southern area in 1977. In 1978, a characteristic fine ash upper bed was issued from a southwestern crater named "Gin-numa crater" and deposited all over the caldera.

At sites I(3) and II(3), located at the foot of the slopes, 4 cm and 7 cm of redeposition could be recognized. On site I(4) (northeastern alluvial fan), only 15 cm of redeposition was measured but 140–170 cm on site II(4) (southern alluvial fan). On III(1) (an ash covered gentle slope), wind-erosion and redeposition were evident.

3. 1 b. Plant response to air fall tephra deposit and secondary redeposition

— Forest survival only occurred in the area of shallow air fall tephra, i. e. on the eastern caldera wall where only 20 cm to 50 cm of new tephra deposited. The pedons I(1), I(2) and I(3) were located in this forest survival area. Tree basal remnants and buried branches of species such as *Acer mono*, *Populus maximowiczii*, *Salix bakko*, *S. integra* and *S. sachalinensis* sent new shoots. The strong rhizome of numerous herbaceous plants could also perforate the new deposit and the herbs reappeared at the surface.

— Herbs only could perforate thicker tephra i. e. those of sites II(1) and II(2). The strongest surviving herbs in thick tephra deposits were *Polygonum sachalinense*, *Petasites japonicus* var. *giganteus* and *Equisetum arvense*. The survival of these species was greatly facilitated on hillslopes where the ash mantle was locally lessened by erosion processes but totally impeded on areas such as the alluvial fans where secondary redeposition occurred. Plant survival after airfall tephra deposit is a phenomena commonly observed (Howard, 1962 ; Uhe, 1971 ; Aston, 1916 ; Hendrix, 1981 ; Franklin *et al.*, 1985, etc.), as well as tephra removal by erosion and its positive impact on revegetation (Griggs, 1933 ; Eggler, 1948 ; Segerstrom, 1950, 1966 ; Franklin *et al.*, 1985).

— The important tree and herb invasion observed in the northeastern alluvial fan (site I(4)) was possible because of the relatively stable surface condition which was confirmed by only 15 cm of redeposition. The very sparse or temporary nature of invasion on the southern alluvial fan (site II(4)) seemed to be due to a persistent surface instability confirmed by ca. 135 cm of redeposited material in successive layers.

— The absence of vegetation on slopes covered with thick ash (i. e. site III(1)) can be explained by the thickness of tephra which makes plant survival impossible and by the bare ash surface which is unfavourable to seed-plant invasion. Ash alone is highly susceptible to wind, and because of its dark color and its lack of cover probably experienced large fluctuations in surface temperature. Griggs (1919, 1933) also recognized that ash alone did not support vegetation.

3. 2. *Moisture and relation to particle size of tephra*:

3. 2 a. Result of laboratory analysis:

With sunlight and air, moisture is a primordial factor influencing plant survival and growth. Soil moisture is influenced by numerous factors and especially by texture and presence of organic matter.

The surficial tephra of the five sites examined (Fig. 3) was made of ash and pumice. For all the sites, ash was a silty sand composed of 1/4 silt and 3/4 sand. Redeposited pumices, abundant on the alluvial fans of I(4) and II(4) were ca. 2/3 pebbles and 1/3 granules.

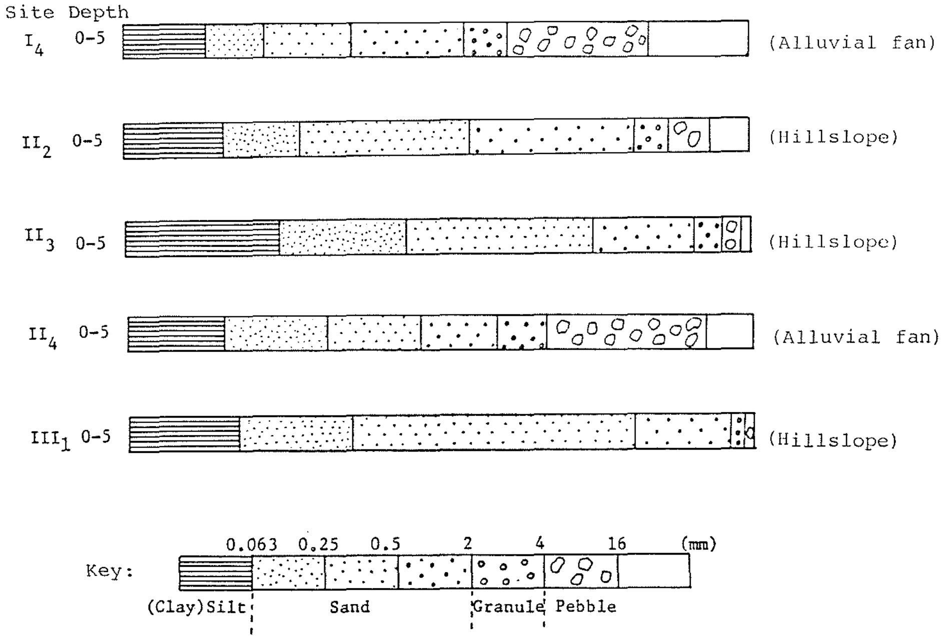

Figure 3. Grain size distribution of surficial material.

Table 2 shows for each sample the dominant particle size, the results of the laboratory tests and the actual water content.

—Dominant particle size: Coarse layers, with granule and pebble as dominant materials, were differentiated from fine layers, composed of sand and silt.

—Potential moisture: Available moiture (A. M.) was lowest for coarse layers and ranged from 9% to 13% whereas it ranged from 15% to 23% in fine textured layers. Field capacity (F. C.) also tended to be low for the coarse textured samples and ranged from 20% to 27% whereas it ranged from 28% to 37% for the fine textured ones. No major differences in texture were reflected at the wilting points although the lowest primary wilting point (8%) was found in a coarse layer and

Table 2. Water content/volume of variously textured tephra samples

SAMPLES 100 cm^3		DOMINANT GRAIN SIZE IN THE SAMPLE						WATER CONTENT/VOLUME (%)											
								LABORATORY TESTS				ACTUAL WATER CONTENT							
								Wilting point		Field capacity (F.C.)	Available moisture F.C.–P.W.P.	sampling date	SAMPLES	Sampling date					
site	depth	Organic mat.	Clay	Silt	Sand	Granule	Pebble	Permanent PF=4.2	primary (P.W.P) PF=3.8	PF=1.8		24.5.84	1000 cm^3 site date	20.6.83	3.7.83	16.10.83	27.10.83	27.4.84	22.5.84
I $_4$	0– 5			+	+		+	11	14	29	15	20	I $_4$ 0–10	26	15 t^*: *18°*, *15°*	18 t^*: *30°*, *11°*	21 t^*: *6°*, *7°*	45	15
	5–10				+	+	+	8	10	20	10	19							
	20–25					+	+	13	16	27	11	—	20–30						20
II $_2$	0– 5			+	+			8	11	28	17	35	II $_2$ 0–10						14
	5–10			+	+			9	12	32	20	49							
	10–15					+	+	6	8	21	13	18							
	45–50			+	+			12	14	34	20	25							
(B.s)	80–85	+		+	+			16	19	35	16	27	(B.s)80–90						24
II $_3$	0– 5			+	+			10	13	30	17	9	II $_3$– 0–10	35	25 t^*: *13°*, *13°*	34 t^*: *18°*, *13°*	34 t^*: *6°*, *8°*	23	14
	5–10			+	+			12	15	31	16	14							
	10–15			+	+			7	10	33	23	18							
	90–95					+	+	10	12	24	12	25							
(B.s)	140–145					+	+	12	14	23	9	25	90–100						16
II $_4$	0– 5		+	+	+		+	18	21	37	16	22	II $_4$ 0–10	30	39 t^*: *13°*, *13°*	30 t^*: *20°*, *13°*	31 t^*: *7°*, *7°*	44	17
	5–10				+		+	18	20	30	10	26							
	10–15				+	+	+	13	15	26	11	24							
III	0– 5			+	+			11	14	33	19	13	III 0–10 (bare	25	16 t^*: *16°*, *14°*	21 t^*: *20°*, *14°*	37	27	13
	5–10			+	+			10	13	29	16	18	surface)						
	20–25			+	+			13	16	34	18	23	0–10						18
	45–50			+	+			14	18	36	18	32	(tree foot)						

t^* Temperature of the soil surface and at 10 cm depth, in °C
(B.s) Buried soi (humus layer)

the highest (21%) in a layer rich in clay-silt-sand, but also containing pebbles. The layers having the highest F. C. (37% and 35%) were II(4)0-5 which contained clay and II(2)80-85 which contained organic matter of the buried soil. However, since the primary wilting points of these layers were also high (21% and 19%), the A. M. was only in the average range.

Yamamoto & Imagawa (1983) conducted similar laboratory tests on the freshly deposited tephra of Usu. Sampling was done at the northwestern foot of the volcano in October 1978, just after the last eruption. They obtained A. M.=6% and F. C.=14% for a coarse pumiceous layer and A. M.=9% and F. C.=25% for a fine ash layer. Four years later (in 1982), the A. M. of the same ash layer rose to 13%, thus showing an increase of available moisture through time. That value is inferior by 2%-7% to those we obtained in 1984 in corresponding ash beds. This can confirm the increase in available moisture through time.

—Actual water content: Measurements of actual water content were repeated on 6 occasions only and this is considered a too limited number of times for estimating variations in moisture over the year. We can nevertheless observe that actual moisture content was never found below the wilting point.

3. 2 b. Plant invasion response to moisture and particle size:

If we consider the 0-10 cm depth as the milieu where invading plants first extract water and nutrients, we can compare the potential available moisture of the five sites in relation to their location and the plant invasion state. The surface available moisture is higher for the ash-covered sites II(2), II(3) and III(1) than for the ash-pumice-covered alluvial fans II(4) and I(4). However, invading plants established sooner on the pumiceous sites II(4) and I(4). This indicated that plant invasion did not respond to surfaces with better moisture potentials.

It is probable that, although the surface of the two alluvial fans had relatively low moisture potentials due to the presence of coarse pumice materials, they were more frequently irrigated by runoff coming from the adjacent slopes. It is also possible that the white pumices on the surface helped to reduce the evaporation rate when comparing with the dark ash surface of the other sites. Considering these aspects, the pumiceous substrate of the fans is thought to constitute a moister substrate than the ash substrate for invading plants. Griggs (1933) remarked that water-laid deposits were preferential habitats for willow seedlings and explained the fact by a better drainage of these outwash deposits.

It was frequently observed on ash covered slopes that gully sides and the areas surrounding tree trunks were darker in color, therefore wetter. As it is shown in Table 2, the sample III(2), taken at a tree foot, was 5% more humid than the sample III(1) taken 1 m away from the tree. It is presumed that comparatively high moisture in gullies and at the foot of trees was partly responsible for a preferential plant invasion in such places.

Particle size distribution of the new tephra may play an important role with regards to seed plant invasion. On a seed or seedling scale, the pebble-granule sized pumices which accumulated on the alluvial fans may offer a greater protection

Table 3. pH, EC and plant nutrients in samples collected in June 1984

Site	Sample depth (cm)	—: New tephra BS: Buried soil GB: Gully bottom	Water content/volume	pH		Electric conductivity $\mu S/cm$	Amonium nitrogen NH_4-N mg/100 g	Nitrate nitrogen NO_3-N mg/100 g	Available phosphorous P_2O_5 mg/100 g	Total carbon C %	Total nitrogen N %	Exchangeable bases (meq/100 g)				
				H_2O	KCl							Ca	Mg	K	Na	Σ
I (4)	0–10	—	15	5.7	4.2	28	0.14	0.10	3.12	0.14	0.18	1.55	0.26	0.16	0.18	2.15
	20–30	—	20	5.8	4.2	28	0.14	0.04	7.57	0.09	0.21	1.70	0.26	0.15	0.16	2.27
I (5)	0–10	—	9	5.6	4.1	25	0.20	0.09	4.51	0.13	0.10	1.60	0.30	0.13	0.13	2.16
	20–30	—	18	6.8	5.2	23	0.11	0.07	5.85	0.13	0.14	0.95	0.12	0.08	0.13	1.28
	150–160	BS	23	5.8	4.9	117	0.92	0.26	4.68	2.41	0.58	5.25	0.84	0.17	0.19	6.45
II (2)	0–10	—	14	4.6	3.9	78	0.04	0.11	3.28	0.17	0.17	1.35	0.20	0.51	0.14	2.20
	80–90	BS	24	5.4	5.1	640	0.92	0.60	4.23	2.07	0.44	6.50	1.48	0.13	0.52	8.63
II (3)	0–10	—	14	4.6	3.8	62	0.07	0.07	2.39	0.15	0.08	1.25	0.21	0.46	0.30	2.22
	90–100	—	16	4.5	3.8	46	0.10	0.17	3.40	0.26	0.08	0.90	0.18	0.18	0.17	1.43
II (4)	0–10	—	17	5.2	4	53	0.24	0.11	3.12	0.21	0.16	2.80	0.54	0.31	0.30	3.95
III (1)	0–10	—	13	4.6	3.8	54	0.08	0.23	4.79	0.15	0.04	1.45	0.18	0.35	0.26	2.24
III (2)	0–10	—	18	4.5	3.6	76	0.04	0.25	3.12	0.15	0.13	1.40	0.22	0.45	0.33	2.40
IV (1)	0–10	—	4.5	5.1	3.9	38	0.13	0.07	2.61	0.12	0.14	1.35	0.26	0.35	0.21	2.17
	50–60	GB	16.5	5.3	4.3	76	0.35	0.15	4.68	0.76	0.15	2.00	0.43	0.61	0.13	3.17
IV (2)	0–10	—	8	5	3.9	52	0.11	0.11	2.00	0.06	0.11	1.40	0.24	0.38	0.27	2.36
	130–140	—	12	4.9	3.9	47	0.12	0.04	2.56	0.13	0.15	1.20	0.21	0.23	0.24	1.88
	160–170	GB	?	5.2	4.1	46	0.37	0.07	3.28	0.27	0.11	1.35	0.33	0.33	0.17	2.18
V	0–10	—	27	6.6	5.1	85	0.20	0.28	8.41	0.35	0.21	2.85	0.74	0.24	0.26	4.09

against the wind and the sun rays than the silty-sand ash which cover the hillslopes. Another nefarious property of fine ash is crust formation. Like Griggs (1918), Eggler (1959) and Dilmy (1965), I did not observe any vegetation in places where surficial crust had formed.

3. 3. *pH, EC and content in plant nutrients*:

3. 3 a. Results of the chemical analysis (Table 3):

—pH:

pH(H_2O) varied between 4.5 and 6.8 and pH(KCl) between 3.6 and 5.2. Almost all our samples can be placed in the value range of Hokkaido-Honshu mineral soils with moderate to acidic values. pH(H_2O) normally favourable to plant growth was found in the buried soil and on the northeastern alluvial fan (samples I(4) and I(5)). All the other samples showed pH values inferior to those of the buried soil.

—EC (Electric conductivity):

EC expresses richness in minerals. Most of our soil samples fall in the Hokkaido range with EC values around 50. The buried soils and the vapour fumarole samples showed especially high EC values. Concerning the vapour fumarole (site V) sample, mineral enrichment from fumarole activity is probable.

—NH_4-N (Amonium nitrogen):

NH_4-N showed relatively high values for the buried soil samples and the samples collected in gully bottoms invaded by organic debris. However, even these values are considered very low if referring to agricultural purpose; at least 10 mg/100 g is necessary for poor crops such as maize.

—NO_3-N (Nitrate nitrogen):

Similar remarks as above.

—P_2O_5 (Available phosphorous):

Unlike the other nutrients, P_2O_5 did not show its highest values in buried soil but showed high values in new tephra. This can be explained by an originally high phosphorous content in the fresh tephra. Accumulation seems to have occurred at 20–30 cm depth after a leaching phase.

—C (Total carbon):

The highest values were found in the buried soil and at the gully bottom of IV(1) where organic debris accumulated. Elsewhere, the very low values clearly showed that soil formation has not yet taken place in the 1977–78 tephra.

—N (Total nitrogen):

Total nitrogen showed relatively high values for the buried soil. Low but not negligible nitrogen was found at the surface of the new tephra where plant survival (samples II(2)0–10, gully bottom IV(1)) or plant invasion (samples V, I(4), II(4)) had taken place. It was interesting that 3 times more nitrogen was found as the foot of a dead tree (III(2)) than 1 m away (III(1)).

—Ca, Mg, K, Na (Calcium, magnesium, potassium, sodium exchangeable bases):

The buried soil was the richest in bases. Another rich site was site V where bases may have been brought by fumarolic activity. All the other sites showed a low content in bases.

3. 3b. Plant response to nutrients:

A common characteristic of recent volcanic deposits is its lack of nutrients, especially nitrogen (Burke, 1964; Eggler, 1959, 1963; Cammerloher, 1935; Campbell, 1909; Griggs, 1933, 1934; Tezuka, 1961, etc.). However, plant invasion does occur, thus showing the very basic level of nutrient requirement of pioneer vegetation. Because of the multiple factors involved in the vegetation recovery processes, it may not be feasible to directly relate the observed vegetation progress and the measured nutrient content. Therefore, the remarks and hypothesis formulated below should not be accepted without question, but need further investigation.

—The buried soil of the caldera was not destroyed (burnt) because the air-fall tephra was not hot. Therefore, the root systems of the plants which survived by perforating the layers of pyroclastics could rely on a buried soil rich in nutrients with a pH favourable to plant growth.

—The surface showing the highest invasion rate was site V where large areas were 100% covered with mosses and algae. The high nutrient content of this site may be due to mineral enrichment from fumarolic activity and plant cover.

—Gully bottom (i. e. site IV(1)) also seemed to be a rich habitat with regards to nutrient content. Except for low values in Na and NO_3-N, all other nutrients were abundant. It is evident that the tall herbs which thrived in or near the gully in autumn brought abundant organic matter which enriched the soil's nutritive value for new plants. The lower nutrient content of the gully bottom IV(2) can be related to a lower input of organic matter from fewer surviving plants.

—Invasion of seed plants started on the alluvial fans. When investigating the nutrient value of the sites I(4) and I(5), it was noticed that this invasion happened on a surface of favourable pH, but of very low nutritive value. However, it was noticed that at sites II(4) and I(4) the total nitrogen content was not negligible (0.16%-0.18%). A probable cause of nitrogen enrichment at site I(4) was the presence of invading tree saplings belonging to the Betulaceae, especially alders, which may have nitrogen fixing bacterias in their nodules. We could also assume that some of the pre-existing soil (and its nitrogen) of close hillslopes was liberated through gully erosion and brought to the alluvial fans.

3. 4. *Substrate temperature*

Figure 4 presents a surface temperature map of the whole caldera. Hot spots coincide with solfataras and vapour fumaroles. The hottest area (solfataras) is located around Gin-numa crater and on the lava dome of Ko-Usu. The heat and

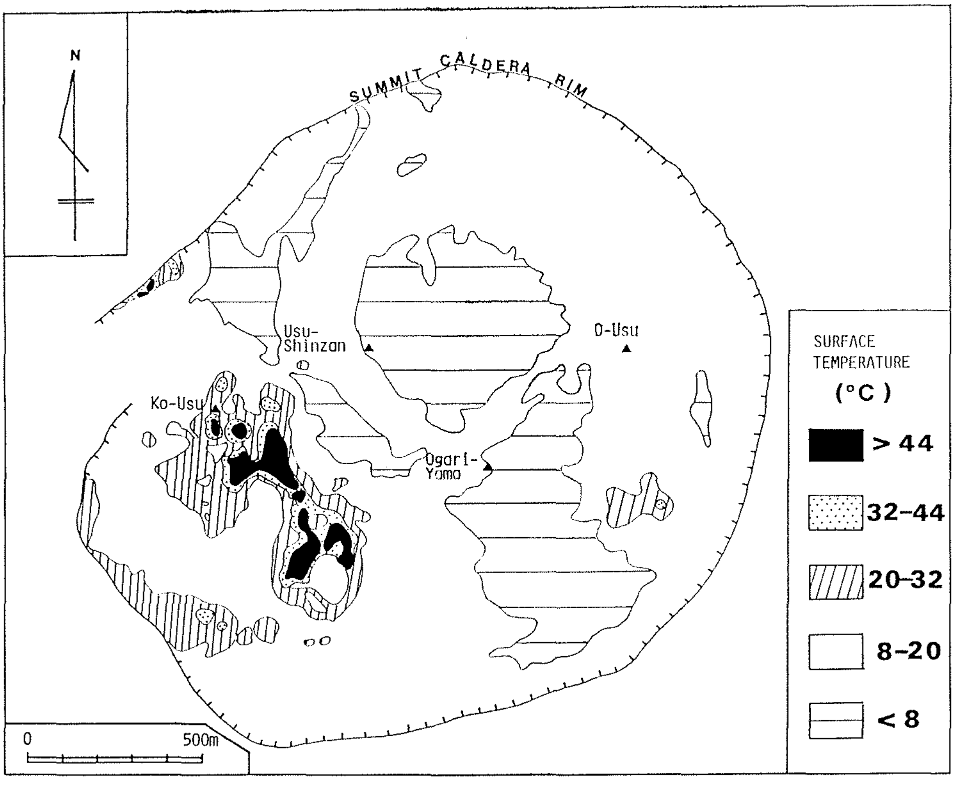

Figure 4. Surface temperatures of the caldera. As of 15. 9. 1983, 06 a.m.

Table 4. Surface and subsurface temperatures of substrates covered with algae and mosses in a warm vapour fumarole area. Site V, as of 5. 12. 1984, air temperature: 1°C.

Steam mouth 1	Algae on hardened white sublimates	Mosses on ash (1 m from the algae)
Surface	40°C	30°C
5 cm deep	94°C	36°C
10 cm deep	97°C	65°C
Steam mouth 2	**Algae on pumiceous substrate**	**Moss on ash (1 m from the algae)**
Surface	45°C	21°C
5 cm deep	45°C (rock)	35°C
10 cm deep	—	56°C
Steam mouth 3	**Algae on a hardened sublimates on a rill bottom**	**Moss on ash (10 m from the algae)**
Surface	43°C	21°C
5 cm deep	80°C	33°C
10 cm deep	93°C	50°C

the suffocating emission of sulfur are major inhibitors to plant invasion. However, vapour fumaroles with surface temperatures ranging from 20°C to 45°C i. e. on the north and south caldera walls and on the southern flank of O-Usu, are the prefeferential habitats for mosses and algae. No other direct relation was recognized between surface temperature and plant recovery. At the vapour fumarole of site V, surface and subsurface temperatures were measured. The results are presented in Table 4. Algae invaded surfaces of 40–45°C whereas mosses prefered a cooler substrate (20°C–30°C). In the winter season, vapour fumaroles were free of snow, and mosses and algae were prosperous. Invasion of mosses and algae around vapour fumaroles was also observed by Eggler (1959) on Paricutin and by Schwabe (1969) and Behre & Schwabe (1969) in Surtzey.

Surface and subsurface (10 cm depth) temperatures were recorded at a few sites (Table 2). These measurements are insufficient in number to estimate annual fluctuations but showed that surface temperature generally approached air temperature whereas subsurface was cooler than the surface in summer and warmer in the beginning of winter. From mid-December to mid-April, the soil freezes to a maximum ca. 40 cm depth (Kinoshita and Fukuda, 1982) under a deep (ca. 1 m) snow cover. Some steep slopes which are submitted to strong winds may remain snow-free in winter and surface temperatures can reach values approaching the air temperature, frequently below −10°C.

3. 5. *Substrate stability/instability*

3. 5 a. Past erosion (1977–1984)

Table 5 shows the profile area and the mean erosion depth of 22 rills and gullies which developed on the southern caldera wall. Although no relation was recognized between erosion and slope angle, the relationship between width and depth of the rills and gullies clearly appeared (Fig. 5).

On this southern hillslope, numerous linkages were recognized between the formation of rills and gullies and the vegetation. Although gullying destroyed surviving plants by cutting the roots, it mostly favoured survival of plants by lessening the new tephra cover or better, exposing the buried soil. This buried soil, made of a complex mat of roots, was more resistant than the new loose tephra and it often inhibited further gully incision. The development of surviving seeds and plant rhizomes from the buried soil greatly helped in inactivating gullying. Paradoxically, it was observed that dead standing trees and tall surviving herbs such as *Polygonum sachalinense* helped some gullies to develop. The rain water that ran from the trunks or the stems excavated ash at the tree or the herb foot and this initiated rill then gully formation. Gully courses controlled by dead standing trees and surviving herbs were frequently observed. Gullies also played a major role in transporting organic debris and seeds from areas of abundant plant survival such as the upper caldera walls to the lower walls of the caldera and to the alluvial fans. Inactivated gullies offered a favourable habitat to seedling growth by often being humid, protecting plants from wind and direct sun rays and accumulating

Table 5. Rill and gully measurements on the southern caldera wall, along the transect II

TRANSECT	SLOPE GRADIENT	SLOPE LENGHT (From somma rim) (m)	77–78 TEPHRA THICKNESS (cm)	RILL OR GULLY WIDTH W (cm)	RILL OR GULLY DEPTH D (cm)	PROFILE AREA P.R.A. (cm^2)	MEAN EROSION DEPTH M.E.D. P.R.A./W (cm)	RILL OR GULLY SHAPE (V/U)
II b	32° tg : 0.625	16	90	150	50	4100	27.33	V
				90	40	2200	24.44	V
				150	40	3300	22.00	V
				210	60	7800	37.14	V
II c	29° tg : 0.554	33	100	200	40	4800	24.00	V
				320	80	13100	40.93	V
				840	220	92000	109.52	V
II d	19° tg : 0.344	55	120	200	80	6800	34.00	V
				100	20	1400	14.00	U
				220	90	9300	42.27	V
II e	12° tg : 0.212	66	135	300	100	18800	62.66	U
				50	20	900	18.00	U
				60	40	1300	21.66	V
				150	80	6800	45.33	V
II f	10° tg : 0.176	77	160	100	50	4000	40.00	U
				110	60	4100	37.27	V
II g	7° tg : 0.123	85	190	90	20	1400	15.55	U
				70	20	1300	18.57	U
				60	30	1500	25.00	U
				40	20	700	17.50	U
II h	4° tg : 0.070	98	240	90	20	1700	18.88	U
				60	20	1100	18.33	U

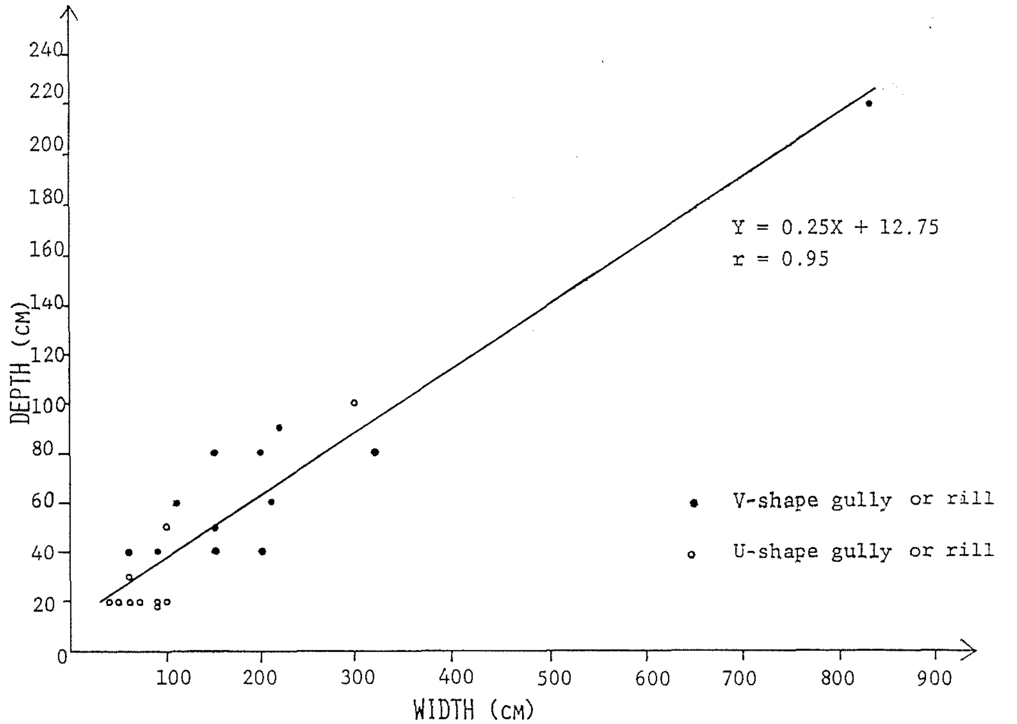

Figure 5. Relationship Width-Depth of rills and gullies located on the southern caldera wall, along the transect II.

organic debris.

3. 5 b. State of erosion and redeposition during 1983-1984 :

The results of the 11 months study period were converted into an annual estimate of erosion and redeposition (Fig. 6). It was recognized that although erosion acted as a major disturbance in dissecting hillslopes and controlling plant recovery just after the eruption, its rate 6-7 years after the main eruption was almost insignificant. Chinen (1986) recognized that erosion occurred mostly in rills and gullies. A marked redeposition only occurred on the southern alluvial fan (plots CL and Cs) and could explain the still very sparse or temporary invasion pattern of plants on that fan.

4. Conclusion

The immediate purpose of the research was to check if different revegetation patterns directly reflected substrate differences. However, by considering the complexity of factors involved, to directly relate an observed plant recovery pattern with a specific substrate property appeared to be a difficult and hazardous task. Table 6 summarizes briefly the results of this research and points out some substrate properties which may have positively influenced the natural revegetation. Further investigations seem necessary to better understand the complex linkages which exist

Table 6. Substrate properties which may have positively influenced (+++) the natural revegetation

GENERAL SUBSTRATE	SITES INVESTIGATED	NATURAL REVEGETATION PATTERN OBSERVED	AIR-FALL TEPHRA DEPTH	SURFICIAL GRAIN SIZE	AVAILABLE MOISTURE (0–10 cm DEPTH)	ACTUAL MOISTURE	CONTENT IN NUTRIENTS	TEMPERATURE	SURFACE STABILITY/INSTABILITY (DUE TO EROSION AND REDEPOSITION)
Dark ash covering caldera walls (initial airfall tephra)	I (1) I (2) I (3)	Abundant survival (trees and herbs)	+ + + 20–50 cm	Sand: 3/4 Silt: 1/4	—	—	—	—	—
	II (2) II (3) VI (2) IV (3)	Herb survival and invasion in gullies	75–135 cm	(same as above)	16–20%	+ + + Gully sides and bottom generally moist	+ + + Generally high-due to collection of organic debris and exposure of buried soil	Variable	+ + + Unstable just after the eruption: Formation of gullies (Stable in 1984)
	III (1) III (2)	Bare surface generally	150 cm	(same as above)	16–19%	Probably large fluctuations	Low	Variable	Apparently unstable in 1984 (Wind action)
	V	Extensive algae and mosses invasion	—	(same as above)	—	+ + + High (vapour fumarole)	Relatively high	+ + + Constantly high (20–45°C)	—
White pumice covering alluvial fans (eroded and redeposited)	I (4) I (5)	Extensive invasion (trees and herbs)	130–150 cm	+ + + Pebble: 2/3 Granule: 1/3	10–15%	+ + + Probably higher than on ash alone due to better irrigation and less evaporation	Low	Variable	+ + + Stable in 1984 (only 15 cm of past redeposition)
	II (4)	Temporary herb invasion	200 cm	+ + + (same as above)	10–16%	+ + + (Same as above)	Low	Variable	Unstable in 1984 (ca. 135 cm of past redeposition)

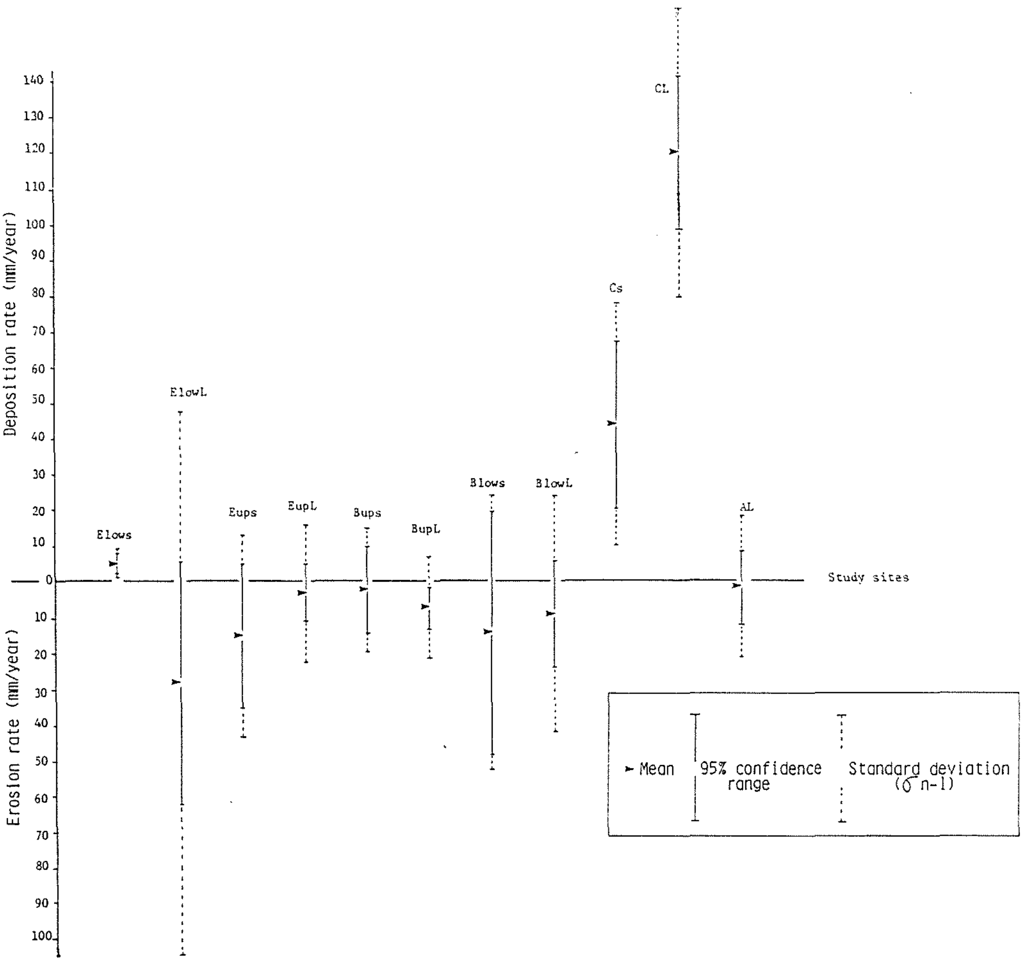

Figure 6. Ground erosion and redeposition measured by the erosion pin method at 11 sites of the caldera.

between the substrate and its vegetation cover.

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(J): in Japanese, (JE): in Japanese with English summary.

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APPENDIX

a) Along the transect I

-I(1) Northeastern somma rim:

- 0–2 cm: Silty ash.
- 2–18 cm: Fine pumice, 4 mm in average diameter; sandy ash; few lithic fragments, 10–30 mm in diameter.
- 18–20 cm: Sility ash, frequent root fragments.
- +20 cm: Buried soil; sandy ash; pumice; fine to medium roots.

-I(2) About 60 m from the northeastern somma rim:

- 0–4 cm: Silty ash

4-28 cm : Fine pumice, 4 mm in average diameter ; sandy ash ; few lithic fragments, 10-30 mm in diameter.

28-29 cm : Silty ash.

+29 cm : Buried soil ; sandy ash ; lithic fragments, 10 mm in average diameter ; frequent fine to medium roots.

-I(3) About 80 m from the northeastern somma rim :

0-4 cm : Silty sand ash appearing as water-eroded and redeposited material.

4-9 cm : Silty ash of thickness varying from 2 to 10 cm.

9-32 cm : Fine pumice, 2-4 mm in diameter ; sandy ash ; few lithic fragments, 50 mm in average diameter.

32-46 cm : Coarse pumice, 5-10 mm in diameter ; lithic fragments, 5-10 mm in diameter.

46-47 cm : Silty sand ash.

47-49 cm : Silty sand ash ; fine pumice, 2-5 mm in diameter.

+49 cm : Buried soil, silt ; medium roots.

-I(4) About 160 m from the northeastern somma rim :

0-15 cm : Silty sand ash ; pumice, 5-10 mm in diameter ; fine roots. Layer appearing as water-eroded then redeposited.

15-20 cm : Silty sand ash.

20-25 cm : Pumice, 5-10 mm in diameter.

25-45 cm : Sandy ash ; pumice, 5-10 mm in diameter ; few lithic fragments, 2-7 mm in diameter ; fine roots.

45-105 cm : Fine white pumice, 2 mm in average diameter ; sandy ash ; abundant lithic fragments, 20 mm in average diameter, with some elements reaching 150 mm in diameter ; wood fragments, abundant fine to medium roots.

135-148 cm : Silty sand ash, pumice, 3-5 mm in diameter ; no roots ; high water content.

+148 cm : Buried soil (colour : 10Y R2/3) ; silty sand ash.
(Roots do not reach the buried soil).

-I(5) About 260 m from the northeastern somma rim :

0-10 cm : Silty sand ash.

10-20 cm : Sandy ash ; pumice, 5-10 mm in average diameter. Layer finer at the lower part.

20-90 cm : Pumice, lithic fragments.

90-140 cm : Pumice, 10-20 mm in diameter.

140-142 cm : Silty ash.

142-150 cm : Fine pumice, 2-3 mm in diameter.

150-152 cm : Silty sand ash.

+152 cm : Buried soil. (Roots do not reach the buried soil).

b) Along transect II

-II(1) Southern somma rim :

0–5 cm : Silty ash.
5–7 cm : Pumice, 2 mm in diameter.
7–20 cm : Sandy ash ; lithic fragments, 1–3 mm in diameter.
20–25 cm : Sandy ash ; few pumice, 2–4 mm in diameter.
25–60 cm : Sandy ash (at the upper and lower part : no clear boundary) ; pumice, 5–10 mm in diameter, lithic fragments, 10–30 mm in diameter.
+60 cm : Buried soil ; medium to coarse roots of *Equisetum arvense* and *Polygonum sachalinense*

-II(2) About 5 m from the southern somma rim :

0–9 cm : Silty sand ash (Colour : 7.5Y 3/2).
9–15 cm : Pumice, 2 mm in diameter.
15–29 cm : Sandy ash (Colour : 7.5Y 3/2) ; abundant lithic fragments, 10–30 mm in diameter.
29–72 cm : Silty ash (Colour : 5Y 3/2) ; pumice, 4–10 mm in diameter ; few lithic fragments, 10–30 mm in diameter.
72–75 cm : White pumice, 1–3 mm in diameter.
+75 cm : Buried soil (Colour : 10YR 3/3).

-II(3) About 70 m from the southern somma rim :

0–7 cm : Silty sand ash ; few pumice. Layer appearing as water-eroded and redeposited.
7–20 cm : Silty ash.
20–25 cm : Sandy ash ; few pumice and lithic fragments, 2–4 mm in diameter.
25–45 cm : Silty ash.
45–50 cm : Pumice and lithic fragments, 5 mm in average diameter, coarse elements up to 20 mm in diameter.
50–90 cm : Sandy ash ; pumice and lithic fragments, 5–10 mm in diameter.
90–98 cm : Silty sand ash.
98–135 cm : White pumice, 10 mm in average diameter, coarse elements up to 40 mm in diameter. Wood fragments.
+135 cm : Buried soil (Colour : 7.5YR 3/2).

-II(4) About 125 m from the southern somma rim :

0–20 cm : Silty sand ash ; white porous pumice, 10 mm in diameter ; good sorting ; loose layer appearing as water-eroded and redeposited.
20–40 cm : Sandy ash ; white and grey pumice, 10 mm in diameter ; lithic fragments, 20–30 mm in diameter ; wood fragments ; very compressed, dense layer appearing as water-eroded and redeposited.
40–93 cm : Silty ash and pumice-lithic fragments beds alternating. Pumice, 10 mm in diameter ; lithic fragments, 20–30 mm in diameter. Water

eroded and redeposited layer.

93–135 cm : Sandy ash, brownish colour (5Y 3/2); few pumice, 5–10 mm in diameter. Layer appearing as the inferior limit of water-erosion and redeposition.

135–170 cm : Black slity sand ash (colour : N 2/0); few pumice, 2–3 mm in diameter.

170–190 cm : Silty ash, high water content.

190–220 cm : Sandy ash; pumice, 1 mm in diameter.

220 cm : Buried soil is not reached.

c) Site III

-III(1) Southern crater basin, gently sloping ash field:

0–11 cm : Silty sand ash. Appears as partially composed of wind-eroded and redeposited materials.

11–15 cm : Sandy ash; lithic fragments, 5 mm in maximum diameter.

15–28 cm : Silty sand ash.

28–32 cm : Sandy ash; lithic fragments, 5 mm in maximum diameter.

32–49 cm : Sailty sand ash, finer in the middle part.

49–51 cm : Lithic fragments, 2–3 mm in diameter.

51–90 cm : Sandy ash; pumice and lithic fragments, 3–5 mm in diameter, coarse elements reaching 20 mm in diameter.

90–135 cm : Silty sand ash.

135–160 cm : White pumice, 5 mm in average diameter, coarse elements reaching 50 mm; lithic fragments, 7 mm in diameter.

+160 cm : Buried soil.