

As a result of this discussion, we postulate that pedogenesis in the lowlands can be divided into three phases: (1) a Tertiary phase in which warm climate induced the formation of hematitic twin, (2) Quaternary periglacial periods inducing temporary hydromorphic environments as occur actually in the humid temperate climate of the uplands and the formation of goethitic concretions, (3) the post-Wurmian phase in which eolian dusts embedded pedological features inherited from previous phases.

## REFERENCES

- Boero, V. and Schwertmann, U., 1987. Occurrence and transformations of iron and manganese in a colluvial terra rossa toposequence of Northern Italy. *Catena*, 14: 519–531.
- Brewer, R., 1964. *Fabric and mineral analysis of soils*. Wiley, New York, (4th edition), 498 pp.
- Bruckert, S. and Gaiffe, M., 1985. *Les sols de Franche-Comté*. Centre Univ. d'Etudes régionales, Besançon, 142 pp.
- Bullock, P. and Murphy, C.P., 1976. The microscopic examination of the structure of sub-surface horizons of soils. *Outlook Agric.*, 8: 348–354.
- Campy, M., 1982. *Le Quaternaire franc-comtois. Essai chronologique et paléoclimatique*. Thèse, Univ. Besançon, 575 pp.
- Ciric, M. and Skoric, A., 1972. Diagnostic characteristics of iron-manganese concretions in some pseudogleys in Yugoslavia. *Trans. Comm. V and VI Int. Soc. Soil Sci.*, Stuttgart, pp. 63–70.
- C.P.C.S., 1967. *Classification Française des Sols*. Doc. offset, INRA, 96 pp.
- Ferrari, G.A. and Pagliai, M., 1980. Micromorphometry and micromorphology of a clay soil sample treated with a ferric conditioner. *Z. Pflanzenenergie. Bodenkd.*, 143(3): 283–297.
- Fisher, W.R. and Schwertmann, U., 1975. The formation of hematite from amorphous iron (III) hydroxide. *Clays Clay Minerals*, 23: 33–37.
- Gaiffe, M., 1987. *Processus pédogénétiques dans le karst jurassien. Analyse de la complexation organo-minérale en ambiance calcique*. Thèse, Univ. Besançon, 160 pp.
- Gaiffe, M., 1990. Erosion of calcimagnesian soils as aggregates in jurassien pedological systems. *Catena*, 17: 141–149.
- Gaiffe, M. and Bruckert, S., 1985. Analyse des transports de matières et des processus pédogénétiques impliqués dans les chaînes de sols du karst jurassien. *Catena*, no. special "Soils and Geomorphology", 6: 159–174.
- Jouaffre, D., Bruckert, S., Williams, A., Herbillon, A. and Kubler, B., 1991. Rubéfaction post-würmienne en climat montagnard humide jurassien. Rôle du pédoclimat et actualité du processus. *Geoderma* (in press).
- Mehra, O.P. and Jackson, M.L., 1960. Iron oxide removal from soils and clay by a dithionite-citrate system buffered with sodium bicarbonate. *Clays Clay Miner.*, 7: 317–327.
- Pochon, M., 1978. *Origine et évolution des sols du Haut-Jura suisse. Phénomènes d'altération des roches calcaires sous climat tempéré humide*. Thèse Sci., Neuchâtel, 190 pp.
- Schwertmann, U. and Taylor, R., 1989. Iron oxides. In: J.B. Dixon and S.B. Weed (Editors), *Minerals in Soil Environments* (2nd ed.). Soil Sci. Soc. Am. Madison, WI, 948 pp.
- Soil Survey Staff, 1975. *Soil taxonomy: a basic system of soil classification for making and interpreting soil surveys*. USDA-SCS Agric. Handb., 436. U.S. Gov. Print Office, Washington, DC.

## Clay minerals of four soils formed in eolian and tephra materials in Iceland

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## ABSTRACT

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Clay minerals in a Vitricryand and three Haplocryands derived from eolian and tephra materials in different parts of Iceland and in glacial till samples representative of underlying strata were studied by a combination of methods. The soils are primarily used as rangelands and are highly susceptible to wind erosion. Allophanes, imogolite and poorly-crystalline ferrihydrite are abundant (> 700 g/kg of the clay) throughout the soils, including A horizons. This clay mineralogy would give rise to stable, low-density aggregates that influence the susceptibility of the soils to wind erosion. It also affects chemical properties such as high phosphate retention of the soils, even of the Cryands with relatively low clay contents (160–275 g/kg). Imogolite was found in some but not all horizons of all soils. No particular relationship of imogolite to measured Si/Al molar ratios of the oxalate-oxalic acid soluble fractions of the clays (0.51 to 1.13) was evident. Layer silicate minerals and laminar opaline silicas are either not present or occur in small quantities. Plagioclase, augite and/or their weathering residues were found in the clay and silt separates. Dark-colored glass is predominant in the fine sand throughout the soils and the tills. One till sample had a clay mineral composition similar to the eolian-andic soils, while the other contained smectite and possibly a spherical halloysite-smectite intermediate, but not allophane and imogolite, as major weathering products. The clay mineral composition of these soils and tills was compared with those derived from basic tephra in other regions.

## INTRODUCTION

The soils that are most susceptible to erosion in Iceland are those formed in eolian and tephra parent materials. They are primarily used as rangelands and cover 10,000–15,000 km<sup>2</sup>. Wind erosion is believed to be a major process degrading large areas of these soils. The eolian and tephra parent materials range from a few centimeters to several meters in thickness and commonly mantle glacial till or basalt. Pedons often include many distinct tephra layers with compositions ranging from basaltic to rhyolitic. Materials found between these tephra layers are of multiple origin; thin disrupted or indistinct

tephra layers, eolian and tephra materials redistributed by wind, and redistributed sediments of mainly glacial and glaciofluvial origin (Arnalds, 1990).

Clay mineral data for soils derived from volcanic ash under cryic temperature regimes are scarce. Halloysite, allophane and gibbsite were found in illuvial horizons of soils that contain volcanic glass in eastern Siberia bordering the Okhotsk Sea, while soils without volcanic glass had minerals of the montmorillonite–chlorite series (Tedrow, 1977). Ping et al. (1988) reported the predominance of allophanes with Si/Al molar ratios of 0.43 to 1.0 together with laminar opaline silica and chloritized 2:1 minerals in three Cryands derived from Holocene-age, basic tephra on the Aleutian Islands and adjacent Alaska Peninsula. The amount of allophane was reported to be inversely related to the organic matter content in these and other soils derived from volcanic ash in other regions of southern Alaska (Ping et al., 1989). Murad and Schwertmann (1988) found that soils developed from recent basalts of Marion Island in the Sub-Antarctic contain oxalate extractable Fe (8–13%), Al (8–10%) and Si (2–4%). By Mössbauer spectroscopy they suggested that the Fe-bearing phase consists of a ferrihydrite–silica–alumina association.

The objective of the study presented here was to characterize clay minerals in selected horizons of four representative pedons derived from eolian and tephra materials from different regions of Iceland. Clay mineral analysis of these Icelandic Andisols provides information that is related to both chemical and physical behavior of the soils, including aggregation properties and susceptibilities to erosion. Icelandic Andisols also provide an opportunity to investigate pedogenesis in volcanic parent materials under a cold climate and low biomass production.

#### MATERIALS AND METHODS

All the pedons studied are located in rangeland under a cryic temperature regime (mean annual temperature 2 to 6°C). Pedon TH (medial, Typic Haplocryand; classifications by U.S. Soil Taxonomy, Soil Survey Staff, 1990) was sampled at Thingvallaveit in the Thingvallavatn area in southwest Iceland (Fig. 1), an area which receives about 1400 mm of mean annual precipitation (MAP). Pedon MY (medial over ashy, Typic Haplocryand) was from Myrdalur near the southern coast (2800 mm MAP while Pedon BI (ashy, Typic Vitricryand) was sampled at Biskupstungnaafrettur in south Iceland (1100 mm MAP). Pedon GO was from Godafoss in north Iceland in an area of about 700 mm MAP and is classified as an ashy over medial, Vitric Haplocryand. All pedons were developed in eolian and tephra parent materials overlying glacial till (< 10,000 years old). Pedon TH has very few, thin (< 1 mm) tephra layers while the other pedons have thick (up to 10 cm) distinct tephra layers. Glacial till samples from soils recently exposed due to massive erosion were also obtained in the immediate vicinity of the BI and GO sites.

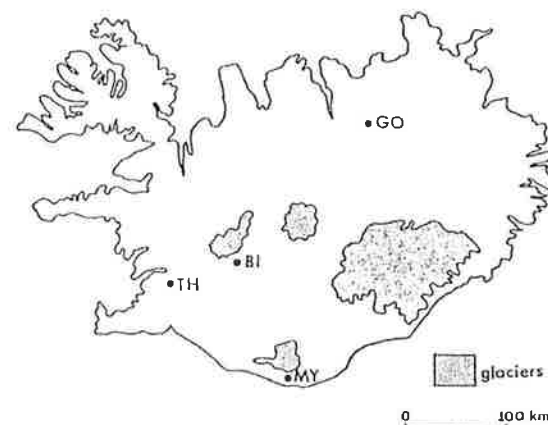


Fig. 1. Location of pedons sampled and studied in Iceland.

TABLE 1

Partial descriptions and analyses of selected soil horizons (Arnalds, 1990)

Site <sup>a</sup>	Horizon	Depth (cm)	Color (moist)	Field texture	Organic C (g/kg)	Base <sup>b</sup> saturation (%)	pH <sup>c</sup>			p <sup>d</sup> retention (%)
							H <sub>2</sub> O	KCl	NaF	
TH	A2	12–28	5 YR 3/3	SiL	76	29	6.1	5.7	10.7	99
	Bw2	61–68	10 YR 4/3	SiL	42	20	6.0	5.7	11.1	99
MY	A3	16–36	5 YR 3/3	L	26	28	5.9	5.3	10.2	98
	Cl	124–171	5 YR 3/4	SiL	20	43	6.4	5.7	9.8	98
BI	A3	23–43	5 YR 3/4	SL	22	43	6.2	5.5	10.3	96
	C3	195–205	5 YR 2/1	LFS	12	39	6.3	5.3	9.6	22
BI till	2Bw3	28–40	5 YR 3/2	SL	11	38	7.2	–	10.0	92
GO	Bw2	29–41	5 YR 3/2	SiL	71	83	6.7	5.9	9.9	99
	2Bw9	91–101	5 YR 3/4	L	13	59	6.6	5.8	10.1	94
GO till	C2	30–55	2.5Y 3/2	SL	1	99	6.8	5.4	9.9	44

<sup>a</sup>TH= Thingvallaveit, MY=Myrdalur, BI=Biskupstungnaafrettur, GO=Godafoss.

<sup>b</sup>Bases extractable in 1M NH<sub>4</sub>CH<sub>3</sub>COO (pH 7) and cation exchange capacity determined using 1M Na-CH<sub>3</sub>COO (pH 8.2).

<sup>c</sup>pH values in 1:2.5 soil–water, 1:2.5 soil – 1M KCl, and 1:50 soil – 1M NaF, respectively.

<sup>d</sup>From Blakemore et al. (1987).

On the basis of chemical analyses of the soils (Arnalds, 1990), two horizons were selected as representatives of the upper and lower parts of each pedon. The samples from selected horizons and two glacial till samples were analyzed for clay minerals. Partial descriptions and analyses of these samples are given in Table 1.

The clay (< 2 μm) and other particle-size fractions were separated from H<sub>2</sub>O<sub>2</sub>-treated (10 g soil/50 ml 7% H<sub>2</sub>O<sub>2</sub>) samples by repeated dispersion (10

g soil/300 ml water) using 15 min sonic vibration (38 kHz; 200 W) and sedimentation. The pH of the soil suspension was adjusted to pH 10 by adding 0.1 M NaOH before sedimentation. The collected clay was suspended in a dilute NaCl solution of known volume. The clay content of the soil was measured by determining the amount of clay in this suspension. The contents of silt (2–20  $\mu\text{m}$ ) and sand (>20  $\mu\text{m}$ ) were determined by weighing the collected silt and sand.

Minerals fractionated as clays were characterized by dissolution analysis with 0.2M ammonium oxalate-oxalic acid (pH 3.0) (OX) and with dithionite-citrate (DC), infrared (IR) spectroscopy, X-ray diffraction (XRD) analyses and electron microscopy (EM) (Wada et al., 1986). The treatment with OX was conducted in the dark at 25 °C for 4 h using a clay/solution ratio of 20 mg/30 ml and that with DC was conducted twice at 80 °C for 15 min using a clay/solution ratio of 30 mg/4.5 ml (4 ml of 0.3M sodium citrate, 0.5 ml of 1M NaHCO<sub>3</sub>, and 0.1 g of Na<sub>2</sub>S<sub>2</sub>O<sub>4</sub>). Extracted Si, Al and Fe were determined by atomic absorption spectrophotometry.

The XRD analyses (Fe-filtered, Co-generated radiation; 30 kV, 10 mA) were made on the clay (<0.2 or 2  $\mu\text{m}$ ) subjected to the OX or DC treatment and oriented on a glass slide; untreated, air-dried clay (<2  $\mu\text{m}$ ), silt (2–20  $\mu\text{m}$ ) and fine-sand (20–200  $\mu\text{m}$ ) packed into a depression in an aluminum holder or glass slide holder prior to XRD analysis. IR spectra were obtained of the untreated and treated clays (2 mg untreated clay or equivalent weight of treated clay/600 mg KBr). IR spectra were also obtained for materials dissolved by OX or DC treatment via difference IR spectroscopy, whereby the untreated and treated clays were placed in the sample and reference positions of an IR spectrophotometer, respectively. For EM, suspensions of untreated and DC-treated clays were spotted onto a carbon-coated collodion film or microplastic grid and air-dried. An electron microscope (JEM 100B; JEOL, Tokyo) was used at 80 or 100 kV.

## RESULTS

### Particle-size distribution

Clay content was highest in the TH samples (461 and 366 g/kg) while it was considerably lower in the other samples (130–275 g/kg) (Table 2). This may reflect greater transportation distances of tephra and eolian materials at the TH site and differences in pedogenic weathering. Higher clay contents were found in horizons that also had higher organic carbon throughout the A, B and C horizons. Higher organic carbon and clay contents may be attributed to a more stable pedologic environment marked by a gradual admixture of eolian and tephra materials into an organic-rich substrate. Cool climates also favor preservation of organic matter against decomposition.

TABLE 2  
Particle-size distribution of total soils and dissolution analyses of clays

Sample	Content (g/kg oven-dry soil)			Content (g/kg oven-dry clay)			Molar ratio		
	Clay (<2)	Silt 2–20	Sand >20 $\mu\text{m}$	Si <sub>o</sub> (Si <sub>d</sub> )	Al <sub>o</sub> (Al <sub>d</sub> )	Fe <sub>o</sub> (Fe <sub>d</sub> )	Sum* (Sum)	Si <sub>o</sub> /Al <sub>o</sub>	Si <sub>o</sub> /(Al <sub>o</sub> +Fe <sub>o</sub> )
TH-A2	461	182	357	58	109	145	535	0.51	0.31
TH-Bw2	366	364	270	86 (32)	151 (69)	101 (132)	615 (385)	0.55	0.41
MY-A1	184	161	655	75	93	150	550	0.77	0.43
MY-C1	219	139	642	86	94	157	585	0.88	0.49
BI-A3	159	111	730	75	96	138	540	0.75	0.44
BI-C3	130	98	772	117	99	186	705	1.13	0.60
BI-till	158	115	727	(67)	(58)	(221)	(565)		
GO-Bw2	275	124	601	101	112	133	620	0.87	0.55
GO-2Bw9	184	140	676	83	87	139	540	0.92	0.52
GO-till	92	213	695	(42) 115	(50) 118	(172) 136	(430) 665	0.94	0.60
				35	48	48	230	0.70	0.47

\*Sum of Si, Al and Fe as oxides.

### Dissolution and mineralogical analyses of soil clays

The contents of Si, Al and Fe extracted from the clay by OX (Si<sub>o</sub>, Al<sub>o</sub> and Fe<sub>o</sub>) were high (Table 2), suggesting the predominance of allophane, imogolite, noncrystalline and poorly crystalline Fe oxides. The sum as oxides which ranged from 535 to 705 g/kg clay in non-till samples was comparable to or higher than that (350 to 590 g/kg clay) reported for three Andepts derived from basalt-andesitic to andesitic tephra on Maui, Hawaii (Wada et al., 1986). The content of the OX-soluble minerals was estimated assuming a H<sub>2</sub>O (+)/(SiO<sub>2</sub>+Al<sub>2</sub>O<sub>3</sub>+Fe<sub>2</sub>O<sub>3</sub>) weight ratio of 0.25, an intermediate value of the ratios for allophane and imogolite (0.23 to 0.33) and ferrihydrite (0.20). The OX-soluble minerals ranged from 670 to 880 g/kg clay and were higher in the B or C than in the A horizons (TH, MY and BI pedons). They were also higher in the deeper 2Bw9 horizon than in the Bw2 at the GO site. This suggests more weathering in the older subsurface horizons.

In support of the dissolution analysis, IR spectra, particularly the absorption bands in the region (800–1200 and 400–800 cm<sup>-1</sup>), show dissolution of allophane and possibly some imogolite (Fig. 2; Table 3). Usually allophane shows a strong and broad absorption band in the region (1200–800 cm<sup>-1</sup>)

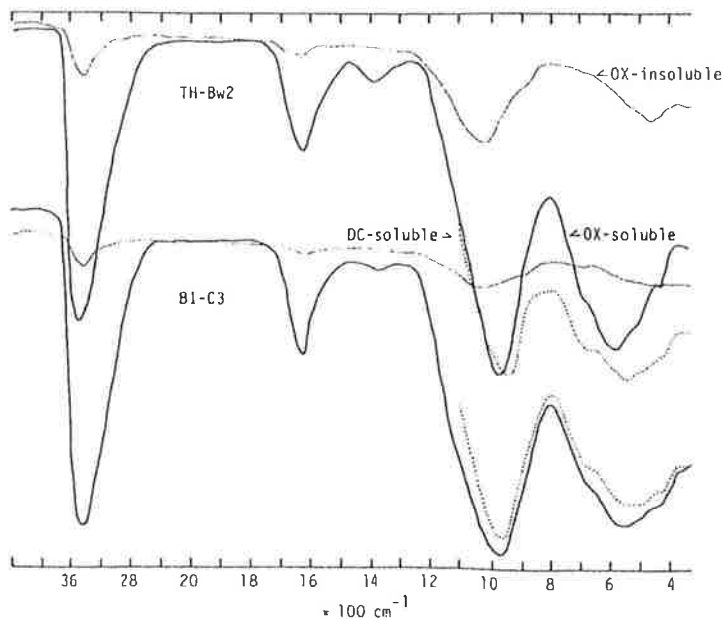


Fig. 2. Infrared spectra of the OX-soluble (thick line), OX-insoluble (thin line) and the DC-soluble (dotted line) fractions of TH-Bw2 and BI-C3 clays.

TABLE 3

Silicate minerals identified by IR spectroscopy, XRD analysis and EM in clays and silts\*

Sample	Clay		Silt	
	IR	XRD	EM	XRD
	OX-soluble/ OX-insoluble	OX-insoluble		
TH-A2	A, Im/Fd(8:2) <sup>b</sup>	Fd(+++) <sup>c</sup>	A, Im	Fd(+++), Aug(+++)
TH-Bw2	A, Im/Fdw(8.5:1.5)	Fd(+), 1.4 nm	A, Im	Fd(+++), Aug(+++)
MY-A1	A/Fdw(8:2)	Fd(+++), 1.4 nm	A, Im(?)	Fd(+), Aug(+)
MY-C1	A, Im/Fdw(8.5:1.5)	Fd(+)	A, Im	Fd(+), Aug(+)
BI-A3	A, Im(?) / Fd(7.5:2.5)	Fd(+++), 1.4 nm	A, Im(?)	Fd(+), Aug(+)
BI-C3	A/Fdw(?) (9.5:0.5)	Fg(+)	A	Fd(+), Aug(+)
BI-Ill	A, Im(?) / Fdw(8:2)	Fd(+), Aug(+)	A	Fd(+), Aug(+)
GO-Bw2	A, Im(?) / Fdw(7.5:2.5)	Fd(+++), 1.4 nm	A, Im	Fd(+++), Aug(+++)
GO-2Bw9	A, Im/Fdw(8.5:1.5)	Fd(+++), Aug(+)	A	Fd(+++), Aug(+++)
GO-till	LS(?) / Fd, LS(?) (4:6)	Fd(+++), Aug(+)	Sm, Ht(?)	Fd(+++), Aug(+++)

\*A = allophane; Fd = feldspar (plagioclase); Fdw = weathered feldspar; Ht = halloysite; Im = imogolite; LS = layer silicate; Aug = augite; 1.4 nm = the un-identified 1.4 nm mineral.

<sup>b</sup>The quantity ratio of the OX-soluble fraction: the OX-insoluble fraction; the ratios are estimated based on the absorbance ratio of the strongest Si-O absorption band in the region from 1100 to 900 cm<sup>-1</sup> on their IR spectra.

<sup>c</sup>The content (++++ = high to ++ = low) estimated based on the 0.347 and 0.299 nm XRD peak height of feldspar and augite, respectively.

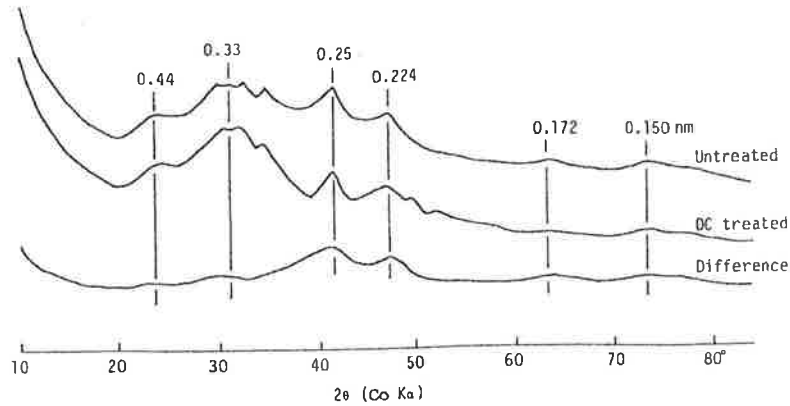


Fig. 3. X-ray diffraction patterns of the untreated and DC-treated GO-2 Bw9 clays and their differences. A scaling factor of 0.8 was used to obtain the difference in minimizing the 0.33 nm XRD band from allophane.

whose absorption maximum decreases from a frequency of  $1020$  to  $975\text{ cm}^{-1}$  with decreasing molar Si/Al ratio from about 1.0 to 0.5 (e.g., Wada, 1989). Thus, the observed frequency decrease has been attributed to the increase of SiO(Al) bond formation. However, the OX-soluble fraction in the Icelandic Andisols did not show this feature; the absorption maximum was found at  $980$  to  $960\text{ cm}^{-1}$  for all the OX-soluble fractions whose Si/Al molar ratio ranged from 1.13 to 0.51 (Table 2). The high  $\text{Fe}_o$  content suggests formation of SiO(Fe) bonds, which may bring about a similar effect on the SiO absorption frequency. The  $\text{Si}_o/(\text{Al}_o + \text{Fe}_o)$  molar ratios calculated for the samples are 0.31 to 0.60 and suggest the possibility of SiO(Fe) bond formation.

The values of DC-soluble Fe ( $\text{Fe}_d$ ) and  $\text{Fe}_o$  were high (Table 2) and comparable to those of soils derived from basic tephra in Hawaii (Wada et al., 1986, 1990). The high  $\text{Fe}_o$  contents and the large  $\text{Fe}_o/\text{Fe}_d$  ratios (0.80–0.86) suggest the abundance of noncrystalline to poorly crystalline Fe oxides. Differential XRD patterns, kindly obtained by Drs. C.W. Childs and N. Yoshinaga of Ehime University of untreated and DC-treated samples, indicated ferrihydrite with 0.25, 0.22, 0.17 and 0.15 nm reflections in the TH Bw2 and GO 2Bw9 samples (Fig. 3). The DC-treated sample was used instead of the OX-treated sample because of dissolution of allophane and imogolite by the OX treatment. The DC treatment also resulted in dissolution of Si and Al, but IR spectra showed some difference between the OX-soluble and DC-soluble fractions depending on the samples (Fig. 2). The DC-soluble fraction showed stronger relative absorption in the  $500$  to  $400\text{ cm}^{-1}$  region, which may indicate the concentration of ferrihydrite (Schwertmann and Thalmann, 1976; Henmi et al., 1980; Childs et al., 1986).

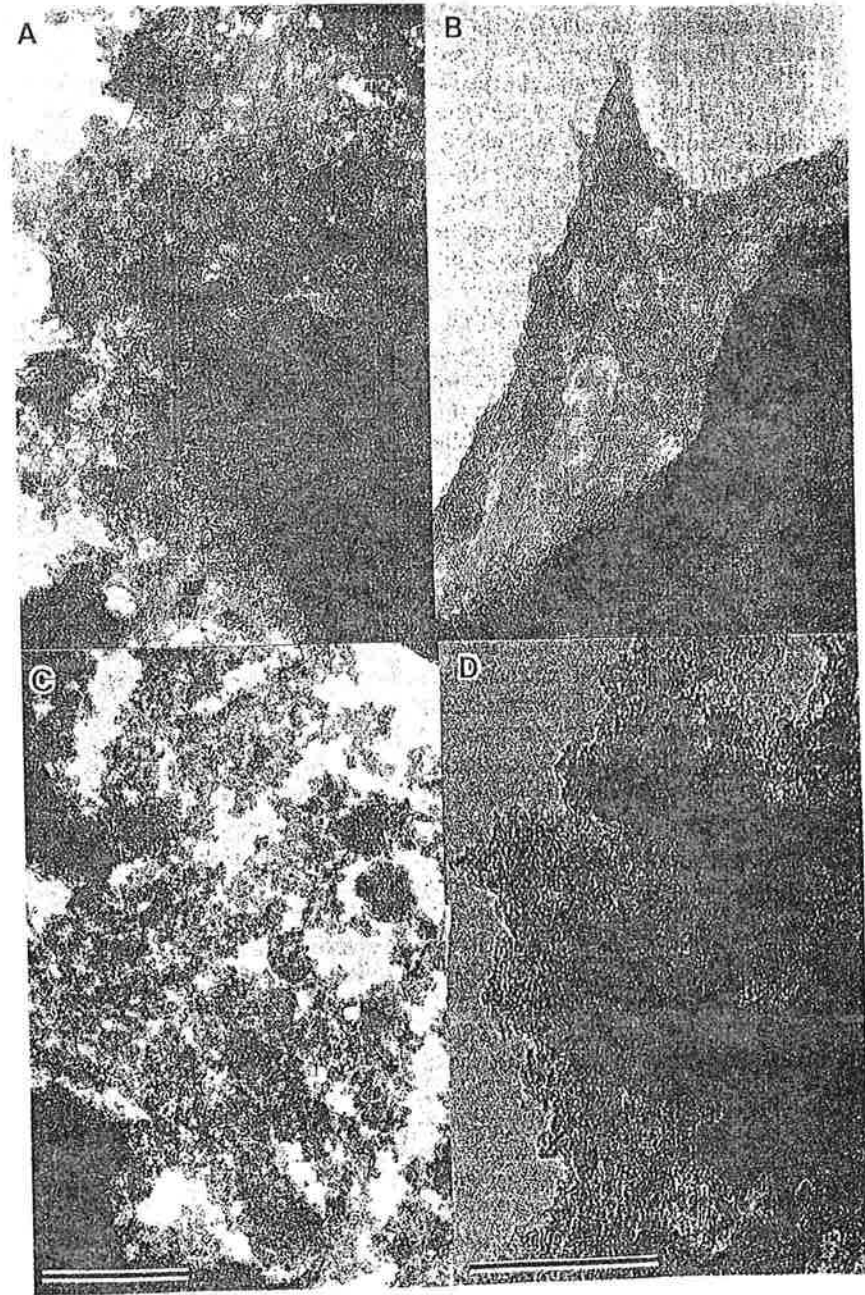


Fig. 4. Electron micrographs of the untreated MY-C1 (A), DC-treated MY-C1 (B), untreated BI-C3 (C) and untreated TH-Bw2 (D) clays. Scale =  $0.5\text{ }\mu\text{m}$  (A and C) and  $0.1\text{ }\mu\text{m}$  (B and D).

Layer silicates in the clay fraction were absent or their content was very low based on IR spectroscopy of OX-insoluble fractions of all the samples (Fig. 2; Table 3). The layer silicate identified by the XRD analysis gave only a weak and poorly defined 1.4 nm reflection when saturated either with  $Mg^{2+}$  or with  $K^+$  and air-dried, suggesting that it is chloritized 2:1 layer silicate. The XRD analysis and IR spectroscopy showed that feldspar and its weathering residue were predominant in the OX-insoluble fractions.

Imogolite threads (Fig. 4A) and fine tubular units (Fig. 4B) were most abundant in the MY-C1 sample, followed by GO-Bw2, TH-A2 and TH-Bw2 samples. They were not found or were very few in abundance in the other samples (Fig. 4C). There was no evident relationship of imogolite to measured Si/Al molar ratios of the OX-soluble fractions of the clays (Tables 2 and 3). Hollow spherical particles were abundant in all samples (Fig. 4D) which were identified as allophane. The morphology of the Fe oxide particles was not evident. Laminar, opaline silica particles, which are circular and elliptical shaped and very thin, were found to be abundant in A1 horizons of Dystrandeps in Japan (Shoji and Masui, 1971). They were absent or few in number in these soils.

#### Dissolution and mineralogical analyses of till clays

As shown by the dissolution and other analyses (Tables 2 and 3), the BI till sample had a clay mineral composition similar to those of the BI soil (BI-A3 and -C3) samples. This indicates accumulation of eolian and tephra materials admixed at the surface of the till, which is supported by morphological evidence (Arnalds, 1990). In contrast, the clay separated from the GO till sample (GO-C2) was lower in  $Si_0$ ,  $Al_0$ , and  $Fe_0$  than those separated from the soil samples in immediate vicinity and at other sites. The XRD analyses and IR spectroscopy showed that it contained feldspar and some layer silicates (Table 3). Further XRD analysis showed that smectite was predominant in the GO-till fine clay (Fig. 5). Thinly spread films (arrow 1, Fig. 6A) and short curved or twisted threads (arrow 2) with lattice images having spacings of 1.2 nm (Fig. 6B) were observed by EM and they were identified as smectite. There were also a few concentric spherules with diameters of 30 to 100 nm (arrow 3, Fig. 6A). Their morphology suggested that they are halloysite, but their lattice images had largely spacings of 1.0 nm rather than 0.7 nm of dehydrated halloysite (Fig. 6B). The latter is usually found when halloysite is exposed to high vacuum in the electron microscope.

The 1.0 nm or 1.1 nm reflections of halloysite were barely visible on the XRD patterns of Mg-saturated, air-dried or glycerol solvated samples in parallel orientation, or even of Na-saturated, air-dried samples in random orientation (Fig. 5). The 0.7 nm reflection of dehydrated halloysite was also not visible for the K-saturated and 300°C-heated samples. These observations

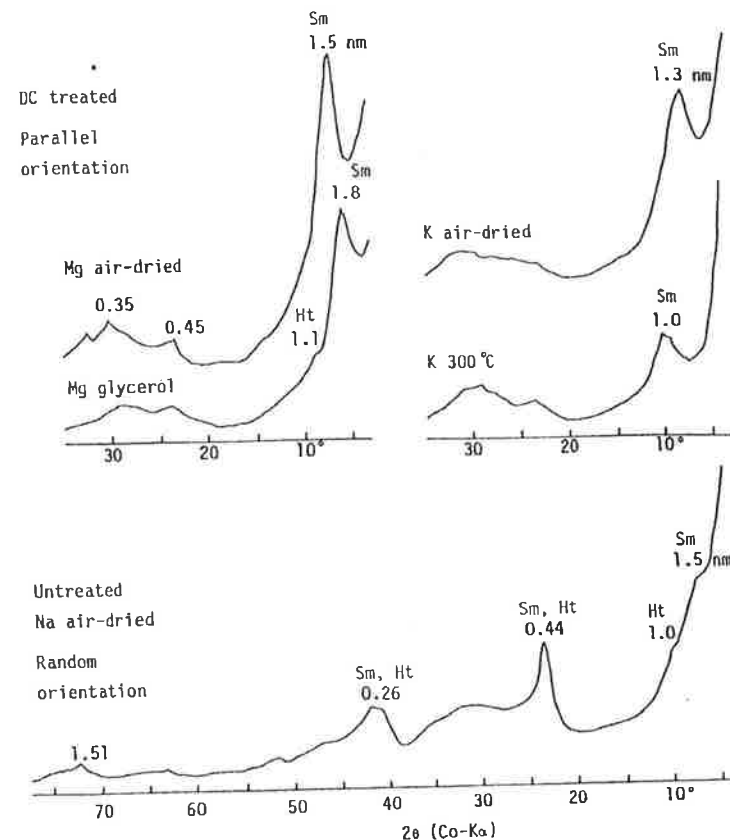


Fig. 5. X-ray diffraction patterns of the GO-till fine clay.

suggest that the Si tetrahedra in the halloysite, which may comprise the spherules, attach to both the top and bottom of an Al octahedral sheet and thereby prevent the interlayer collapse upon dehydration. This model has been suggested previously for "embryonic halloysite" in Ecuadorian volcanic ash soils (Wada and Kakuto, 1985).

#### Mineralogical analyses of silts and fine sands

Feldspar (plagioclase) and augite were identified in the silt of all soils and till (Table 3). These minerals were also identified in the fine sand, in which dark-colored volcanic glass was predominant. These results indicate that the

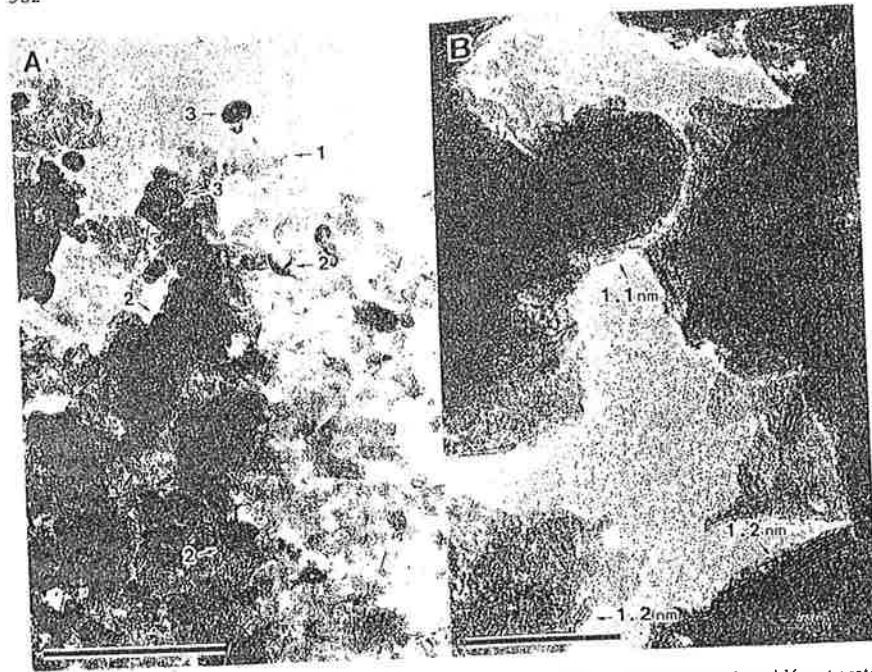


Fig. 6. Electron micrographs of the untreated GO-till clay (A) and DC-treated and K-saturated GO-till fine clay (B). Scale = 0.5  $\mu\text{m}$  (A) and 0.05  $\mu\text{m}$  (B). Structural features indicated by arrows are: thinly spread films (1) and short curved or twisted threads (2) of smectite and concentric spherules (3) of halloysite or possibly halloysite-smectite intermediate.

soils and tills are similar in the primary mineral assemblage of parent material and are derived from andesitic/basaltic tephra and rocks.

## DISCUSSION

The present study shows that imogolite and/or allophane and poorly crystalline ferrihydrite are predominant in the clay fraction of Icelandic Andisols. Although it was not possible to distinguish ferrihydrite from allophane by EM, its presence was indicated by difference XRD and IR spectroscopic analyses (Figs. 2 and 3). Thus, the low frequency of the SiO absorption maximum at 980 to 960  $\text{cm}^{-1}$  of the OX-soluble fraction (see before) may be accounted for by incorporation of Si into ferrihydrite forming SiO(Fe) bonds, as reported by Henmi et al. (1980), Carlson and Schwertmann (1981), and Childs et al. (1986), rather than the incorporation of Fe into allophanes. A Mössbauer spectroscopic study on Fe in Japanese allophane clays by MacKenzie and Cardile (1988) showed that the Fe occurs in poorly crystalline ferrihy-

drite, which is strongly bound to allophane particles, rather than substituting for Al in the aluminosilicate unit.

Arnalds et al. (1990) concluded from their study that the coarse texture and low bulk density of tephra and soil aggregates are principal factors influencing wind erosion susceptibility of Icelandic Andisols. The clay mineralogy of these soils elucidated in the present study would contribute to formation of the low bulk density, coarser-size aggregates, as found for many Andisols (e.g. see Wada, 1985, 1989), that are easily susceptible to saltation movement under wind velocities commonly experienced in Iceland. It also is responsible for observed chemical properties such as high phosphate retention and high pH NaF values (Table 1).

The study by Ping et al. (1988) and the present study show that the predominant process in weathering of basic tephra and eolian materials under cool moist climates of Alaska and Iceland is the formation of allophane with Si/Al molar ratios of about 0.5 to 1.0 or higher. The Si/Al ratio of allophane tends to be higher in soils with higher base saturations. Unlike the soils on the Aleutian Islands and the Alaska Peninsula, there is no apparent inhibition of allophane formation in the surface horizons of the Icelandic Andisols. However, some of the allophanes are possibly deposited on the surfaces as eolian materials. Because the two groups of soils are comparable in their organic matter contents and soil moisture and temperature regimes, this disparity may result from differences in pH in addition to the eolian activity of Iceland.

The pH values were lower in the Aleutian and Alaskan soils (5.2–6.1 in  $\text{H}_2\text{O}$  and 4.4–5.1 in 1M KCl) compared to the Icelandic Andisols (5.9–7.2 in  $\text{H}_2\text{O}$  and 5.3–5.9 in 1M KCl) (Table 1). The two groups of soils are also different in the amount of imogolite, opaline silica and chloritized 2:1 layer silicates, which may reflect differences in vegetation, parent material and other elements of the weathering environment.

As reviewed by Wada (1990), weathering of basic tephra in the tropics results in formation of different clay mineral suites as governed by climatic conditions, particularly the moisture regime. Under perhumid conditions, basic tephra weather mainly to ferrihydrite and noncrystalline hydrous alumina that probably changes to gibbsite. Under humid conditions, they weather to allophane, imogolite and noncrystalline to poorly crystalline iron oxides. Incorporation of eolian dusts that contain fine-grained quartz, mica and other minerals which originate from continental desert areas is believed to inhibit the formation of allophane and imogolite. Under subhumid conditions, basic tephra weather either to allophane and imogolite or to interstratified halloysite/smectite and smectite with iron oxides. These studies and the present study show that if the moisture regime is udic, basic tephra weather to imogolite and/or allophane and iron oxides including ferrihydrite in isothermic, isomesic, and cryic temperature regimes. The soil pH ( $\text{H}_2\text{O}$ ) of 5.9 to 6.7 and the organic carbon content of 13 to 76 g/kg in the Icelandic Andisols (Table

1) are within the ranges of those values that do not inhibit the formation of allophane, as found in Alaska (Ping et al., 1988, 1989) and in other climatic regions (Wada, 1980; Shoji et al., 1982; Parfitt and Kimble, 1989).

Allophane was not found in the glacial till sample at the GO site. This sample was collected below the zone of admixture of eolian-andic materials and has not been subjected to appreciable pedogenic weathering compared to the eolian-tephra soils. Smectite and spherical particles with diameters ranging from 30 to 100 nm, possibly halloysite-smectite intermediate, were found as major weathering products in the till. Till components are comprised of fine basalt fragments and showed 99% base saturation (Table 1). Clay mineral composition for the till is very similar to that found in a non-andic, base-rich soil formed from olivine-basaltic tephra in Hawaii under ustic moisture and isohyperthermic temperature regimes (Wada et al., 1990).

#### REFERENCES

- Arnalds, O., 1990. Characterization and erosion of Andisols in Iceland. Ph.D. Dissertation, Texas A&M University, College Station, TX.
- Arnalds, O., Wilding, L.P. and Hallmark, C.T., 1990. Characterization and wind erosion of Andisols in Iceland. Presented at 14th Int. Congr. Soil Science, Kyoto, 1990.
- Blakemore, L.C., Searle, P.L. and Day, B.K., 1987. Methods of chemical analysis of soils. New Zealand Soil Bureau Science Rep. 80, DSIRO, New Zealand.
- Carlson, L. and Schwertmann, U., 1981. Natural ferrihydrite in surface deposits from Finland and their association with silica. *Geochim. Cosmochim. Acta*, 45: 421-429.
- Childs, C.W., Wells, N. and Downes, C.J., 1986. Kokowai Springs, Mount Egmont, New Zealand: chemistry and mineralogy of the ochre (ferrihydrite) deposit and analysis of the waters. *J. R. Soc. N.Z.*, 16: 85-99.
- Henmi, T., Wells, N., Childs, C.W. and Parfitt, R.L., 1980. Poorly-ordered iron-rich precipitates from springs and streams on andesitic volcanoes. *Geochim. Cosmochim. Acta*, 44: 365-372.
- MacKenzie, K.J.D. and Cardile, C.M., 1988. The structure and thermal reactions of natural iron-containing allophanes studied by  $^{57}\text{Fe}$  Mössbauer spectroscopy. *Thermochim. Acta*, 130: 259-267.
- Murad, E. and Schwertmann, V., 1988. The characterization of poorly crystalline Si-containing natural iron oxides by Mössbauer spectroscopy. *Hyperfine Interaction*, 41: 835-838.
- Parfitt, R.L. and Kimble, J.M., 1989. Conditions for formation of allophane in soils. *Soil Sci. Soc. Am. J.*, 53: 971-977.
- Ping, C.L., Shoji, S. and Ito, T., 1988. Properties and classification of three volcanic ash-derived pedons from Aleutian Islands and Alaska Peninsula, Alaska. *Soil Sci. Soc. Am. J.*, 52: 455-462.
- Ping, C.L., Shoji, S., Ito, T., Takahashi, T. and Moore, J.P., 1989. Characteristics and classification of volcanic-ash-derived soils in Alaska. *Soil Sci.*, 148: 8-28.
- Shoji, S. and Masui, J., 1971. Opaline silica of recent volcanic ash soils in Japan. *J. Soil Sci.*, 22: 101-108.
- Shoji, S., Fujiwara, Y., Yamada, I. and Saigusa, M., 1982. Chemistry and clay mineralogy of Ando soils, Brown forest soils and Podzolic soils formed from recent Towada ashes, North-eastern Japan. *Soil Sci.*, 133: 69-86.

- Schwertmann, U. and Thalmann, H., 1976. The influence of  $(\text{Fe(II)})$ ,  $(\text{Si})$ , and pH on the formation of lepidocrocite and ferrihydrite during oxidation of aqueous  $\text{FeCl}_2$  solutions. *Clay Miner.*, 11: 189-200.
- Soil Survey Staff, 1990. Keys to Soil Taxonomy, 4th ed. SMSS Tech. Monogr., 19. Blacksburg, VA.
- Tedrow, J.C.F., 1977. Soils of the Polar Landscapes. Rutgers University Press, New Brunswick, NJ, pp. 512-514.
- Wada, K., 1980. Mineralogical characteristics of Andisols. In: B.K.G. Theng (Editor). Soils with Variable Charge. New Zealand Society of Soil Science. Lower Hutt, pp. 87-107.
- Wada, K., 1985. The distinctive properties of Andosols. In: B.A. Stewart (Editor). *Advances in Soil Science*, 2. Springer, New York, pp. 173-229.
- Wada, K., 1989. Allophane and imogolite. In: J.B. Dixon and S.B. Weed (Editors). *Minerals in Soil Environments* (2nd ed.). *Soil Sci. Soc. Am.*, pp. 1051-1087.
- Wada, K., 1990. Minerals and mineral formation in soils derived from volcanic ash in the tropics. *Proc. 9th Int. Clay Conf.*, Strasbourg, 1989, 1: 69-78.
- Wada, K. and Kakuto, Y., 1985. Embryonic halloysites in Ecuadorian soils derived from volcanic ash. *Soil Sci. Soc. Am. J.*, 49: 1309-1318.
- Wada, K., Kakuto, Y. and Ikawa, H., 1986. Clay minerals, humus complexes, and classification of four "Andepts" of Maui, Hawaii. *Soil Sci. Soc. Am. J.*, 50: 1007-1013.
- Wada, K., Kakuto, Y. and Ikawa, H., 1990. Clay minerals of two Eutrandedeps of Hawaii, having isohyperthermic temperature and ustic moisture regimes. *Soil Sci. Soc. Am. J.*, 54: 1173-1178.