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ANDISOL FORMATION IN A HOLOCENE BEACH RIDGE PLAIN UNDER THE HUMID TROPICAL CLIMATE OF THE ATLANTIC COAST OF COSTA RICA

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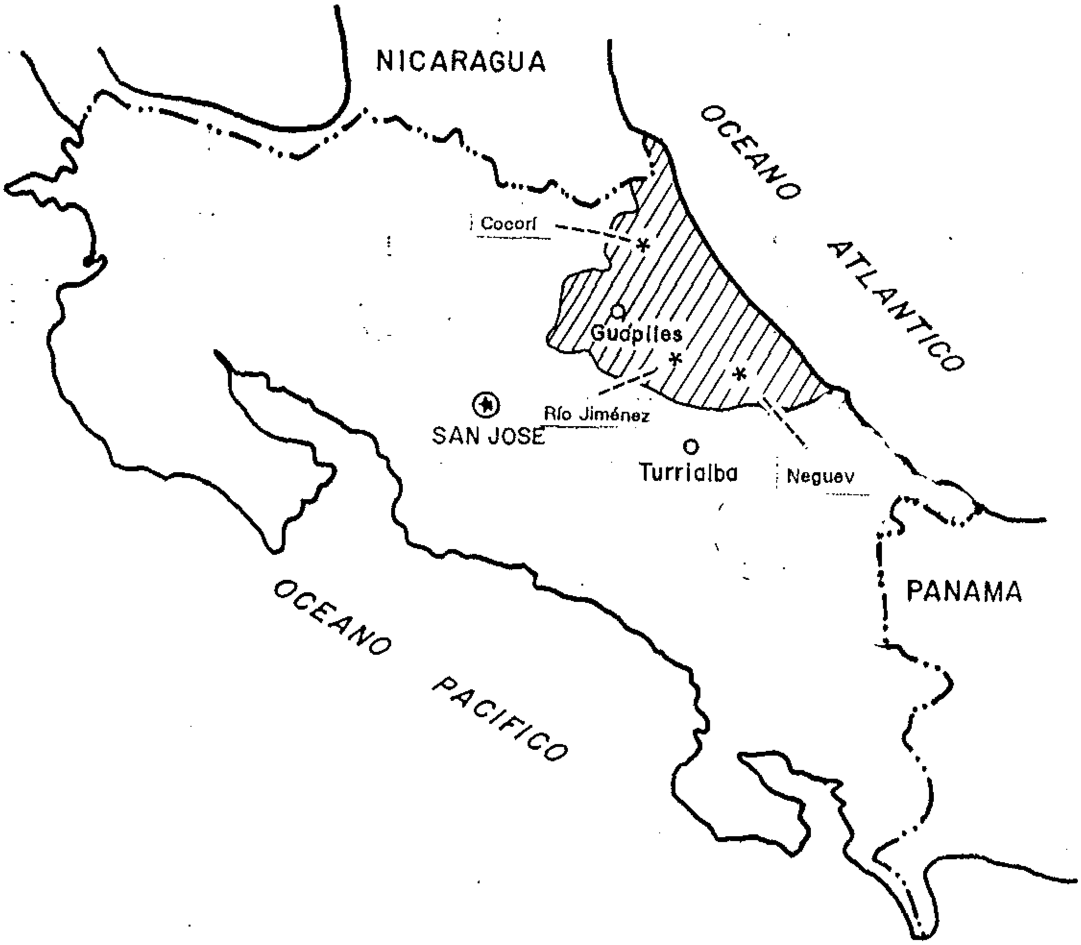

Figure 1. Location of the study area.

PREFACE

General description of the research programme on sustainable Landuse.

The research programme is based on the document "elaboration of the VF research programme in Costa Rica" prepared by the Working Group Costa Rica (WCR) in 1990. The document can be summarized as follows:
To develop a methodology to analyze ecologicaly sustainable and economically feasible land use, three hierarchical levels of analysis can be distinguished.
1. The Land Use System (LUS) analyses the relations between soil type and crops as well as technology and yield.
2. The Farm System (FS) analyses the decisions made at the farm household regarding the generation of income and on farm activities.
3. The Regional System (RS) analyses the agroecological and socio-economic boundary conditions and the incentives presented by development oriented activities.

Ecological aspects of the analysis comprise comparison of the effects of different crops and production techniques on the soil as ecological resource. For this comparision the chemical and physical qualities of the soil are examined as well as the polution by agrochemicals. Evaluation of the groundwater condition is included in the ecological approach. Criterions for sustainability have a relative character. The question of what is in time a more sustainable land use will be answered on the three different levels for three major soil groups and nine important land use types.

Combinations of crops and soils

	Maiz	Yuca	Platano	Piña	Palmito	Pasto	Forestal I II III
Soil I	x	x	x		x	x	x
Soil II						x	x
Soil III	x			x	x	x	x

As landuse is realized in the socio-economic context of the farm or region, feasibility criterions at corresponding levels are to be taken in consideration. MGP models on farm scale and regional scale are developed to evaluate the different ecological criterions in economical terms or visa-versa.

Different scenarios will be tested in close cooperation with the counter parts.

The Atlantic Zone Programme (CATIE-AUW-MAG) is the result of an agreement for technical cooperation between the Centro Agronómico Tropical de Investigación y Enseñanza (CATIE), the Agricultural University Wageningen (AUW). The Netherlands and the Ministerio de Agricultura y Ganadería (MAG) of Costa Rica. The Programme, that was started in April 1986, has a long-term objective multidisciplinary research aimed at rational use of the natural resources in the Atlantic Zone of Costa Rica with emphasis on the small landowner.

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Andisol formation in a Holocene beach ridge plain under the humid tropical climate of the Atlantic coast of Costa Rica

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ABSTRACT

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Soil formation has been studied in relation with time in a 5000-year old chronosequence on volcaniclastic beach ridges of the perhumid tropical Atlantic coast of Costa Rica. All soils are under tropical rainforest. Drainage conditions change by subsidence from excessively drained in the two youngest soils to imperfectly drained in the two oldest soils. Parent material is rather homogeneous andesitic sand with a volcanic glass component of less than 10%. It has been found that under these conditions Andisols form within 2000 years. Imperfect drainage caused mottling and accumulation of iron-coatings, as well as the formation of a thin O-horizon in the oldest profiles. Sand content of the soils decreases regularly with soil age, while the amount of fine material increases concurrently. The increase in fine material and the accumulation of organic matter cause an increase of CEC and andic properties, and a decrease in bulk density and pH with soil age. Depth of biological influence increases with soil age, but soil faunal activity is hampered in the oldest three profiles, probably by imperfect drainage. Due to the extreme leaching conditions, the sum of exchangeable cations is less than 2 cmol+ kg^{-1} in the B-horizons of the older soils, notwithstanding the presence of a considerable amount of weatherable primary minerals.

INTRODUCTION

Classification of volcanic-ash derived soils and soils with similar properties has recently been modified. In the Soil Taxonomy, they now form a new Order, the Andisols (Soil Survey Staff, 1990). In order to key out as Andisol, the soil material must have "andic soil properties", which are defined as follows:

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(1) Oxalate extractable Al (Al_o) + oxalate extractable Fe (Fe_o) $\geqslant 2.0\%$ *and*

(2) Bulk density of the <2 mm fraction, measured at 1/3 bar water retention, $\leqslant 0.90$ Mg m^{-3} *and*

(3) Phosphate retention >85%.

Special criteria have been defined for young soils which do not meet these requirements but do contain a certain amount of volcanic glass and some oxalate extractable Al and Fe. The minimum content of glass in this requirement can be expressed as: percentage glass $> 35 - 15(Al_o + 1/2\ Fe_o)$.

The rate of formation of Andisols has been studied by various authors under a variety of environmental conditions, but mostly in the humid temperate climates of Japan and New Zealand (Theng, 1980; Wada, 1985). Although some work was done on weathering and neoformation of minerals in Andisols in the humid tropics (summarized in, e.g., Wada, 1989), little is known about the relation of soil formation to time in the humid tropics.

Soils developed in volcaniclastic deposits often have recieved later ash additions, which hampers a straightforward interpretation of the effect of time on soil formation (e.g. Allbrook and Radcliffe, 1987; Bleeker and Parfitt, 1974).

The amount of clay-size materials in volcaniclastic deposits generally increases with soil age (Lowe, 1986). However, the amount of fine material is also influenced by other factors. Clay contents tend to be lower at higher altitudes, due to slower weathering at lower temperature (e.g. Chartres and Pain, 1984). Mineralogy, particle size and porosity of the parent material may play an important role, too.

Under a cool humid climate in Japan 100–500 years were needed for the formation of a clear AC horizon sequence, while an ABC horizon sequence was found only in soils older than 1000 years (Yamada, 1968 in: Wada, 1985). In andesitic–dacitic Quaternary volcaniclastic deposits above 600 m altitude in the dry western part of the USA (Neall and Paintin, 1986), Bw horizons were present in soils older than about 450 years, illustrating that horizon differentiation can be rapid in these parent materials in spite of unfavorable (dry) climatic conditions. In a humid tropical environment differentiation of soil horizons would be expected to occur more rapidly than in the western USA.

The aim of the present study is to investigate Andisol formation in sand of volcanic origin in the humid tropical Atlantic lowland of Costa Rica. A series of beach ridges of different age provided an excellent opportunity to study the effect of soil age on Andisol formation. A second paper (Nieuwenhuyse et al., 1992) focusses on the mineralogical aspects of weathering and neoformation of minerals in this chronosequence.

SITE CONDITIONS

The study area is located in the Limón basin, a sedimentation basin of tectonic origin (Weyl, 1980). In the northeastern part of this basin a sandy beach ridge plain is found. Beach ridges are exposed in a relatively narrow (< 3 km) coastal strip, while further inland they are overgrown by peat or covered by alluvial deposits. Based on a previous soil survey, eight sampling sites were selected (designated AT1 to AT8) in the Tortuguero National Park, along a 2.5 km transect of progressively older beach ridges perpendicular to the coast (Fig. 1).

Beach ridges close to the actual coastline are at < 3 m above sea level, while those further inland are slightly lower, due to the ongoing subsidence of the Limón basin and the Holocene sea-level rise.

Parent material of all soils is well sorted andesitic sand (SiO_2 contents vary from 52 to 60%) of uniform texture (median value M.50 between 150 and 250 μm). The sediments are derived from the Central Cordillera, where active volcanism provides an episodic supply of sandy sediments (Nieuwenhuyse and Kroonenberg, 1992).

The parent material is mineralogically homogeneous, it contains many an-

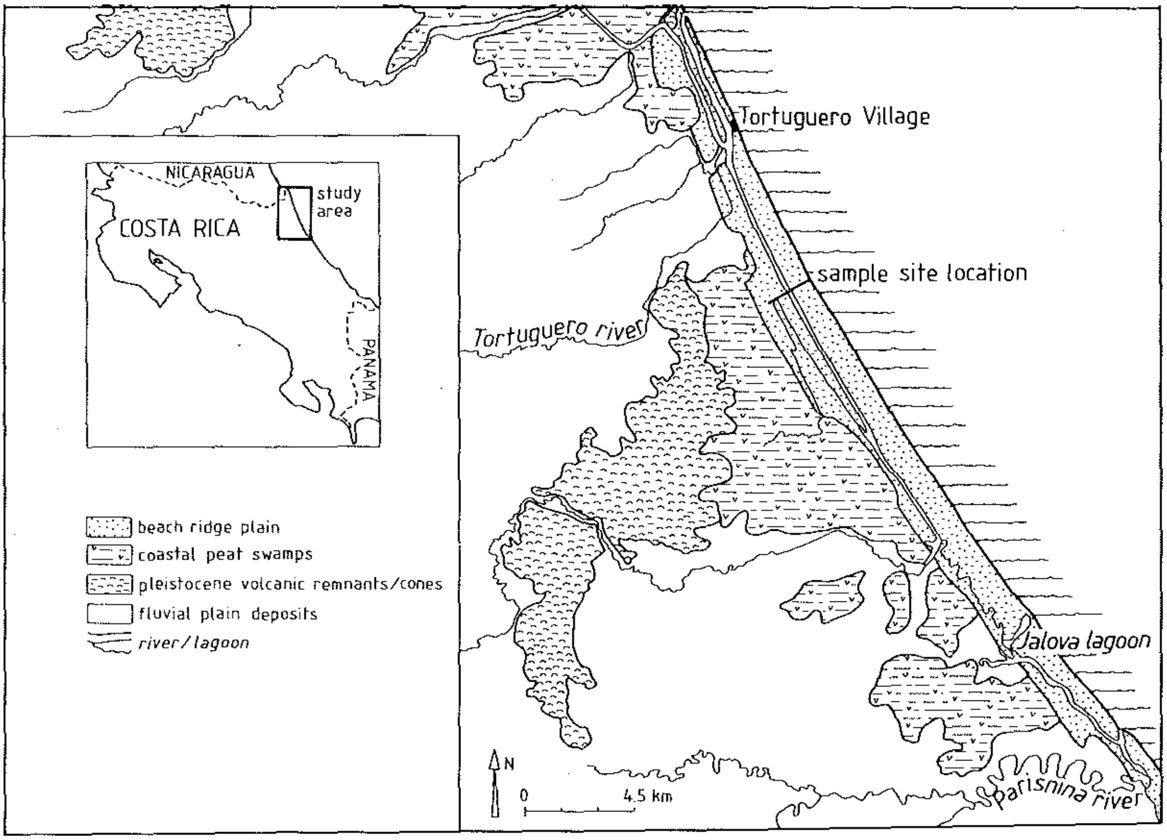


Fig. 1. Location of study area and sampling sites.

desitic rock fragments, composed of plagioclase, pyroxene and magnetite phenocrysts in a matrix in which volcanic glass regularly can be recognized. Few microcrystalline rock fragments occur, composed of quartzite, sandstone and hornstone. Further, many plagioclase and common to many pyroxene (both augite and hypersthene) and very few magnetite, hornblende, biotite and olivine mineral grains are found, sometimes containing volcanic glass inclusions. Finally, common spherical clay bodies are found. In a number of the andesitic rock fragments phenocrysts have been transformed into such clay bodies. Based on point counting in thin sections, the total volcanic glass content is estimated to be less than 10%, on a volume basis (Nieuwenhuyse et al., 1992). Shell fragments were not found, although they may be expected in beach sediments.

The ratios of andesitic rock fragments to pyroxenes vary in the different beach ridge sediments, and their chemical composition varies accordingly (Nieuwenhuyse and Kroonenberg, 1992). Higher concentrations of andesitic rock fragments are accompanied by lower contents of pyroxene and rather high (57–58%) SiO_2 content, while relatively high pyroxene and low andesitic rock fragment contents are reflected in lower (52–54%) SiO_2 contents.

No volcanic ash particles larger than 10 μm were observed in a 4450 year old peat deposit located between the Central Cordillera and the study location. However, very small additions of volcanic dust to the sites cannot be excluded (Nieuwenhuyse, unpubl. data).

At the actual beach, the parent material is homogenized to a depth of about 0.9 m by sea turtles which nest each year in large numbers in the Tortuguero park. Also crabs contribute to this homogenization.

All sites are under humid tropical forest and presumably always have been so. There is no evidence of agricultural use in historical or pre-columbian times, but some logging took place before 1970. At the AT1 and AT2 sites, vegetation composition is influenced by sea salt inputs.

Annual rainfall (1978–1990) ranged from 4100 to 6600 mm with an average of 5350 mm. Mean potential evapotranspiration, based on Penman (using climatic data from nearby stations) amounts to between 12 and 48% of the mean monthly rainfall, and to 22% of the mean annual precipitation (Ta-

TABLE 1

Rainfall and Penman potential evapotranspiration for Tortuguero in millimeters

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Pot. evapotransp.	85	86	113	107	111	96	95	103	106	102	83	81	1168
Precipitation	455	302	235	286	453	403	591	499	326	460	668	666	5345
Surplus	370	216	122	179	342	307	496	396	220	358	585	585	4177

Source: *Instituto Meteorológico Nacional*, Costa Rica.

ble 1). However, each year dry periods varying between one and three weeks occur, causing the younger soils and the topsoil of the older soils to dry out.

Hydraulic conductivity of all soils is very high providing for a rapid infiltration. During many visits to the sites surface runoff has never been observed.

Based on data from nearby stations at the same altitude, mean annual temperature is estimated to be 25–26°C. Difference between hottest (June) and coolest month (January) is 2–2.5°C.

METHODS

Study sites were chosen on a flat part of the top of each ridge. At each site a pit was dug to describe and sample the soils. The soils were described according to FAO (1977) and classified according to Soil Survey Staff (1990). In and around the profile pits evidence of faunal activity was annotated.

To reduce spatial variability, bulk samples of each horizon were collected over a width of about 50 cm along the pit wall. Samples below the ground water table were taken with an auger. After removal of roots and litter and passing the samples over a 2 mm sieve to obtain a well-mixed sample, part of each bulk sample was sealed into plastic bags to keep it at field moisture and was stored at 4°C. Another part of each sample was air-dried and stored at ambient temperature. Field moisture was determined for use as a correction factor to express analyses of field-moist and air-dried samples on the same basis.

Physical analysis

Texture was determined in the field-moist sample after destruction of organic matter with H_2O_2, and dispersion using a mixture of 20 ml sodium polyphosphate (5%) and 20 ml NH_4Cl (10%). Clay (<2 μm) contents were measured by the hydrometer method (Gee and Bauder, 1986). Many of the samples did not disperse well, either in the above mentioned dispersants, or in HCl (pH 4) or NaOH (pH 10). The clay contents reported in this study only refer to samples which did not show flocculation. Sand contents (>53 μm) were determined by sieving.

Bulk density was determined at two to four different depths by measuring the oven-dry weight of 100 ml core samples taken in triplicate.

Moisture retention at 1.5 MPa was estimated in duplicate by equilibrating for 72 h a slurry made from field moist soil on a pressure plate.

Chemical analysis

Soil pH was measured 30 min after intensive stirring for 2 min of a 1:5 (w/w) field moist soil–water mixture. Organic carbon was determined in air-dry samples, using the Walkley–Black wet digestion method. Incomplete recovery was compensated for with a correction factor of 1.3 (Walkley, 1947). Organic matter contents were estimated by multiplying measured C values by 1.72. pH-NaF was measured in field moist samples, after exactly 2 min stirring in 1N NaF (1 g soil to 50 ml NaF).

Exchangeable bases were measured in triplicate in the leachate of a 1M ammonium acetate (pH 7) solution. CEC was determined in triplicate by measuring the absorbed $NH4^+$ after washing with ethanol and replacing ammonium by potassium, using 1M KCl. Exchangeable acidity was determined by leaching the soil sample with 1M KCl and titrating the leachate with 0.1M NaOH. For both methods field moist samples were used.

Phosphate retention was determined according to Blakemore et al. (1987) in air-dry samples. Acid ammonium oxalate extractable iron (Fe_o) and aluminium (Al_o) were determined by shaking a suspension of 1 g of air-dry soil and 100 ml of oxalate solution for 4 h in the dark (Blakemore et al., 1987) and measuring Fe and Al by AAS.

All results have been recalculated on oven-dry (105 °C) basis.

Micromorphological analysis

Undisturbed samples of the major soil horizons were taken for preparation of thin sections (7 by 7 and 2 by 2 cm). In the deeper soil horizons of the older profiles disturbance of the soil during sampling could not be prevented. Samples were treated with a fungicide and sealed into plastic bags immediately to maintain field moisture. Field-moist samples were impregnated with acetone without prior drying according to Miedema et al. (1974). Thin sections were made following the method of FitzPatrick (1970), and described according to Bullock et al. (1985).

Age determinations

The ages of the different soils were estimated using ^{14}C datings of organic rich deposits in the coastal plain and between some of the beach ridges (Nieuwenhuyse and Kroonenberg, 1992).

RESULTS

The ages of the different soils (Table 2) range from less than 100 years in the recent beach ridge to maximally 5000 years in the oldest soil, AT8. With increasing age the soils show an increasing profile development as evinced by (i) a change in colour from dark gray in the unchanged parent material to dark yellowish brown B-horizon material, (ii) increasing thickness of the B-horizon from nil in the three youngest soils to more than 50 cm in the oldest

TABLE 2

Soil classification (Soil Survey Staff, 1990), estimated age (Nieuwenhuyse and Kroonenberg, 1992), average depth of groundwater level and drainage (FAO, 1977) of the investigated soils

Soil	Classification	Age (years B.P.)	Av. depth groundwater (cm)	Drainage
AT1	Typic Tropopsamment	< 100	+ 150	excessively drained
AT2	Typic Tropopsamment	< 200	+ 130	excessively drained
AT3	Typic Tropopsamment	< 500	70	somewhat exc. drained
AT4	Typic Hapludand	appr. 2000	70	mod. well drained
AT5	Acrudoxic Hapludand	2000–5000	95	well drained
AT6	Acrudoxic Hapludand	2000–5000	90	well drained
AT7	Aquic Hapludand	2000–5000	55	imperf. drained
AT8	Hydric Haplaquands*	2000–5000	30	imperf. drained

*Tentatively. 1.5 MPa water retention value has not been determined.

soils, and (iii) increasingly fine textures from fine sand in the recent beach ridges to loam in the oldest surface horizons (Table 3). The A-horizons tend to increase in thickness and in organic matter content from AT1 to AT7. The two oldest soils show an increasingly thick organic surface horizon, and display iron oxide mottling at depths of about 40 cm (AT7) and 20 cm (AT8) (Tables 3 and 4).

Field observations show that leaf-cutter ants and crabs are important burrowing animals in the three youngest profiles, while in the older profiles earthworms and rodents are active. In the AT7 and AT8 profiles very few worms were observed.

Micromorphological changes with age include (i) increasing degree of alteration of both andesitic rock fragments and pyroxene and plagioclase mineral grains from weakly weathered in the A horizons of the three youngest soils to strongly weathered in the topsoil of the two oldest soils, (ii) increasing content of fine materal over a greater depth, consisting of a mixture of organic matter and pale yellow isotropic material, displaying an undifferentiated b-fabric; (iii) changing of intermineral grain microstructures in the three youngest soils into granular and spongy microstructures in the older profiles. (Sub)angular blocky and locally massive structure dominate A horizons of AT7 and AT8; (iv) decreasing amount of mineral excremental infillings in the topsoils of the oldest profiles; (v) occurrence of (non) laminated isotropic orange-brown to yellowish brown (hypo)coatings in the B and BC horizons of AT7 and AT8. In the oldest soil these coatings cover mineral excremental infillings (Figs. 2 and 3).

Physical changes with increasing age involve (i) decreasing sand and increasing clay contents, (ii) increasing water retention at 1.5 MPa and (iii) a decrease in bulk density from about 1.2 Mg m^{-3} in the parent material to

TABLE 3

Major macromorphological characteristics[1]

Profile	Horizon	Depth	Boundary	Color (moist)	Mottles[2]	Field texture	Structure		Consistence
							type	grade	
T1	A	0	c,s	10YR 2/2	–	fs	s.grain	–	l
	CA	4	c,s	10YR 2/3	–	fs	s.grain	–	l
	C	20–80		10YR 3/1	–	fs	s.grain	–	l
AT2	A	0	a,s	10YR 2/1	–	ls	crumb	mod.	l
	AC	3	c,s	10YR 2/2	–	fs	s.grain	–	l
	C1	12	c,s	10YR 2/3	–	fs	s.grain	–	l
	C2	45–80		10YR 3/1	–	fs	s.grain	–	l
AT3	A1	0	c,w	10YR 2/1	–	sl	crumb	mod.	vfr
	A2	3	c,w	10YR 2/2	–	sl	sub.bl	weak	vfr
	AC	9	c,s	10YR 2/3	–	ls	s.grain	–	l
	CA	16	g,s	10YR 3/3	–	fs	s.grain	–	l
	C	27–55		10YR 3/2	–	fs	s.grain	–	l
AT4	A	0	c,s	10YR 2/3	–	l	crumb	mod.	fr
	AB	12	c,s	10YR 2/3	–	l	crumb	str.	vfr
	Bw	19	c,s	10YR 4/3	–	sl	sub.bl.	weak	fr
	BCw	35	g,s	10YR 4/3	–	ls	massive	–	fi
	CB	50	g,s	10YR 4/1	–	fs	massive	–	fi
	C	85–120		10YR 4/1	–	fs	s.grain	–	l
AT5	A1	0	c,s	10YR 2/2	–	l	crumb	str.	vfr
	A2	5	c,s	10YR 2/3	–	l	sub.bl.	str.	vfr
	AB	11	c,s	10YR 2/3	–	sl	sub.bl.	mod.	vfr
	BAw	18	g,s	10YR 3/3	–	sl	sub.bl.	weak	fr
	Bw	30	g,s	10YR 4/3	–	ls	sub.bl.	weak	fi
	BCw	50	g,s	10YR 4/2	–	fs	massive	–	vfi
	C	80–150		10YR 4/1	–	fs	s.grain	–	l
AT6	A	0	c,s	10YR 2/3	–	l	crumb	str.	vfr
	Bw1	17	c,s	10YR 4/3	–	sl	sub.bl.	weak	fr
	Bw2	26	c,s	10YR 4/3	–	sl	sub.bl.	weak	fr
	Bw3	38	c,s	10YR 3/4	–	ls	massive	–	fi
	BCw	48	g,s	10YR 4/2	–	ls	massive	–	fi
	BCwr	80	g,s	10YR 4/1	c2d(o)	fs	massive	–	fi
	C	105–120		N 3/1	–	fs	s.grain	–	l
AT7	O	2	a,s	7.5YR 2/3	–	l	crumb	mod.	(nd)
	A1	0	c,s	10YR 3/4	–	l	sub.bl.	weak	(nd)
	A2	12	c,s	10YR 3/3	–	l	sub.bl.	weak	(nd)
	Bw	25	c,s	10YR 4/3	–	sl	sub.bl.	weak	(nd)
	Bwr	36	c,w	10YR 4/2	c1d(o)	sl	massive	–	fi
	BCwr	53	g,s	10YR 4/1	2d(o)	sl	massive	–	vfi
	CBr1	75	g,s	10YR 4/1	c2d(o)	ls	massive	–	fi
	CBr2	90	g,s	10YR 4/1	c2d(r)	fs	massive	–	fi
	CBr3	110	g,s	N 3/1	c2d(r)	fs	s.grain	–	l
	C	150–170		N 3/1	–	fs	s.grain	–	l
AT8	O	5	a,s	10YR 2/3	–	(nd)	crumb	mod.	(nd)
	A	0	c,s	10YR 3/4	–	l	sub.bl.	weak	(nd)
	Bwr	20–35+		10YR 4/2	c2d(o)	l	massive	–	(nd)

[1] Abbreviations according to Soil Survey Staff, 1951, p. 139.

[2] Color mottles: (o) = orange, (r) = red. (nd) = not determined.

TABLE 4

Selected chemical properties of the soils

Soil	Horizon	Sample depth (cm)	Clay (g kg^{-1})	pH-H$_2$O	Organic matter (g kg^{-1})	CEC	Sum cations (cmol+kg^{-1})	Exch. acidity
AT1	A	0–4	30	5.6	51	13.0	11.2	nd
	CA	4–10	20	5.7	23	13.5	6.8	nd
	C	20–25	–	6.4	3	12.0	5.3	nd
	C	50–55	0	6.7	2	11.6	4.3	nd
AT2	A	0–2	60	5.7	131	26.1	17.5	nd
	AC	4–8	–	5.8	53	14.2	8.1	nd
	C1	25–30	10	6.5	21	11.3	3.9	nd
	C2	55–60	–	6.6	2	10.2	4.0	nd
AT3	A1	0–3	60	5.7	103	22.6	7.8	nd
	A2	4–8	50	5.9	61	16.1	3.2	nd
	AC	10–15	–	5.8	46	11.8	2.5	nd
	CA	17–23	20	6.1	20	9.2	2.0	nd
	C	28–34	10	6.3	8	9.3	2.2	nd
	C	50–55	0	6.4	4	8.9	2.4	nd
AT4	A	0–3	180	6.0	128	33.9	8.9	0.6
	A	6–10	160	6.0	107	29.8	5.1	nd
	AB	13–17	150	5.9	88	25.7	4.2	nd
	Bw	25–30	110	6.2	42	23.7	1.5	0.3
	BCw	45–50	–	6.1	9	nd	nd	nd
	CB	50–70	–	6.4	6	18.4	2.7	nd
	C	100–110	–	6.5	2	18.7	4.5	nd
AT5	A1	0–3	240	5.4	148	38.7	5.2	0.6
	A2	5–8	170	5.5	121	35.2	2.1	0.5
	AB	12–16	–	5.6	105	30.7	1.6	0.3
	BAw	22–26	–	6.3	51	21.5	1.2	nd
	Bw	40–45	–	6.7	25	16.1	1.0	0.1
	BCw	70–80	–	7.4	7	13.5	2.2	0.1
	C	135–145	–	nd	3	18.1	4.1	nd
AT6	A	0–3	170	5.5	120	35.5	3.2	0.3
	A	6–12	240	5.3	117	34.2	1.6	0.3
	Bw1	18–24	–	5.9	50	26.1	2.0	nd
	Bw2	30–35	–	6.5	30	25.6	1.8	nd
	Bw3	41–46	–	6.5	17	20.0	1.5	nd
	BCw	60–65	–	6.7	10	20.8	1.5	nd
	BCwr	85–95	–	6.6	9	25.0	2.6	0.2
	C	110–120	–	6.4	1	16.4	2.8	nd
AT7	O	2–0	–	4.6	321	79.1	7.9	4.0
	A1	2–8	270	4.9	149	53.2	1.7	1.5
	A2	14–20	–	5.5	147	28.5	1.3	0.2
	Bw	28–33	–	6.1	46	24.0	1.3	nd
	Bwr	38–48	–	6.3	34	18.7	1.5	nd
	BCwr	60–70	–	6.0	25	19.2	2.5	nd
	CBr	90–100	–	6.7	9	24.2	2.9	0.2
	C	150–160	–	6.1	6	16.2	nd	nd
AT8	O	5–0	nd	4.5	413	79.6	7.9	5.9
	A	1–11	nd	5.1	110	56.1	3.3	1.0
	Bwr	15–25	nd	6.0	67	41.3	2.7	0.5
	BCr1	30–45	nd	6.3	35	36.3	5.3	0.3
	BCr2	60–75	nd	6.7	24	29.7	6.7	0.3
	CBr	90–100	nd	6.6	8	nd	8.3	0.1

nd = not determined; – = not determined because of flocculation.

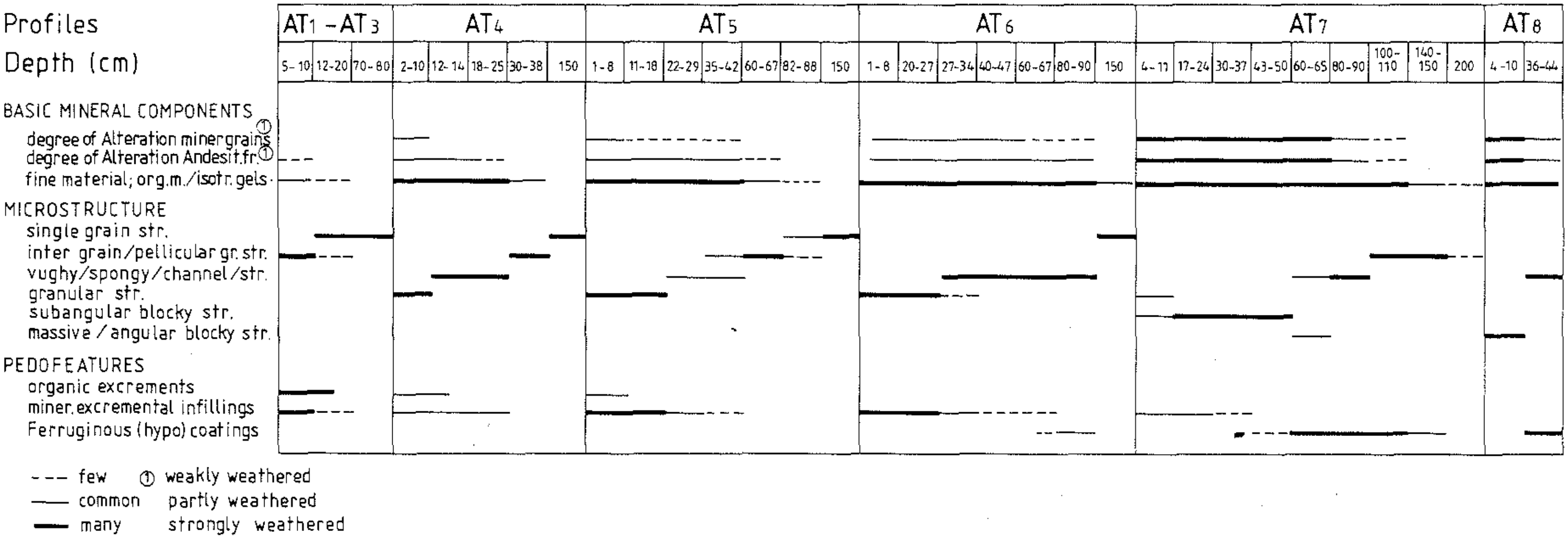


Fig. 2. Selected micromorphological characteristics.

values between 0.9 and 0.3 Mg m^{-3} in the solum of increasingly older soils (Fig. 4, Tables 4 and 5). Chemical development with increasing age is characterized by (i) a decrease in pH-H_2O from 6.5 to 7 in the unchanged parent material to around 5 in the oldest surface soils, (ii) increasing CEC and decreasing exchangeable base cations, (iii) a gradual increase in pH-NaF from just over 8 in recent beach ridge material to between 10 (C-horizon) and 11.5 (surface horizon) in the oldest soils (Tables 4 and 5). Furthermore, P-retention increases from about 25% in the parent material to values over 95% in the A- and B-horizons of AT4 to AT8, and Al_o increases from less than 5 g kg^{-1} in the two youngest soils to over 30 g kg^{-1} in B horizon of the two oldest profiles.

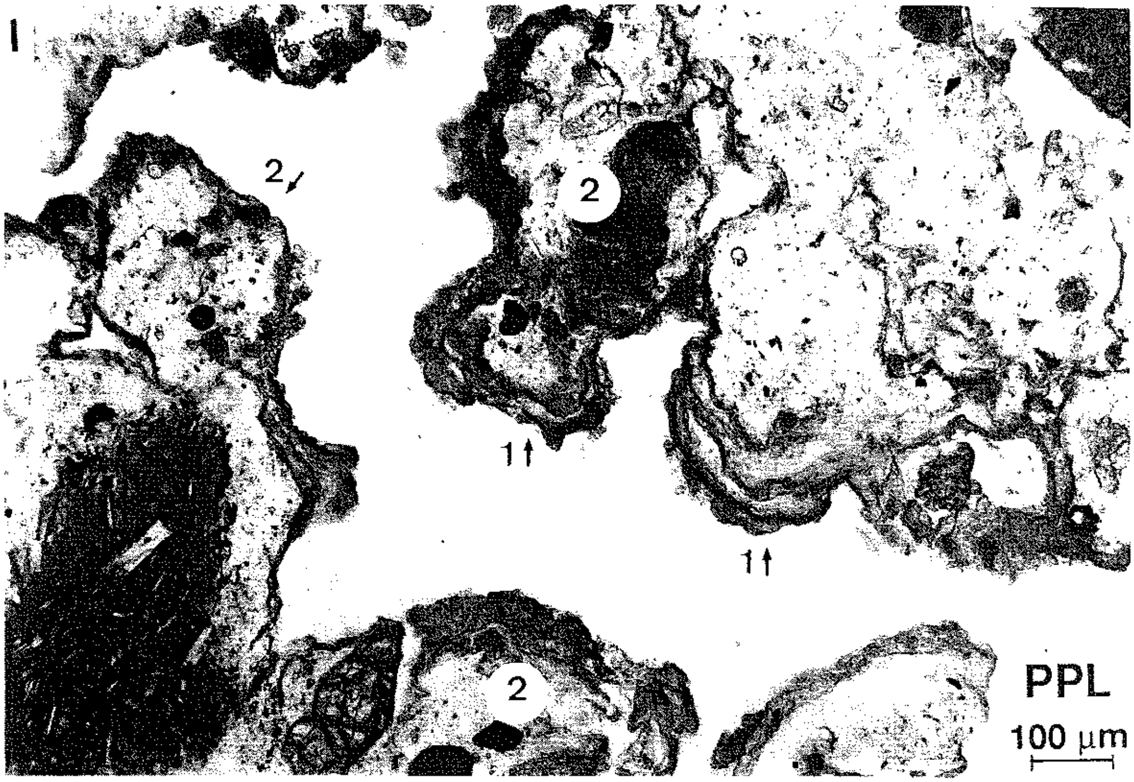
Classification (Soil Survey Staff, 1990) yields Tropopsamments for the three youngest soils and Hapludands for the older soils (Table 2).

DISCUSSION

All soils have developed from essentially the same kind of parent material. No significant differences in the soil forming factors climate, vegetation and human influence occur and rejuvenation by volcanic ash addition is absent or negligible. All soils presumably started their development under conditions of excessive drainage. Due to lowering of elevation, drainage decreased with soil age to imperfectly drained (Table 2). As a result, the differences in soil development can be ascribed to two soil forming factors: age and gradually changing of drainage conditions. The following soil forming processes will be discussed in some detail: organic matter accumulation, biological influence and weathering of primary minerals and neoformation of secondary minerals.

Organic matter accumulation

The organic matter contents of the dark surface soils formed in beach ridge sand (Tables 3 and 4), are high and typical for volcanic ash soils in humid tropical environments (e.g. Wada, 1985; Mizota and Van Reeuwijk, 1989). The relatively high organic matter contents of Andisols is due to the formation of stable complexes of organic material with Al and Fe (Mizota and Van Reeuwijk, 1989; Wada, 1989). Pyrophosphate extractable aluminium and iron increase with soil age from 0% in the AT1 profile to 1.7 and 1.8%, respectively, in the A horizon of the AT7 soil (Nieuwenhuyse et al., 1992). This indicates that the formation of such complexes indeed takes place. The wet climate and the relatively shallow water tables of AT3–AT8 may hamper soil aeration and could also contribute to decreased decomposition of organic matter.



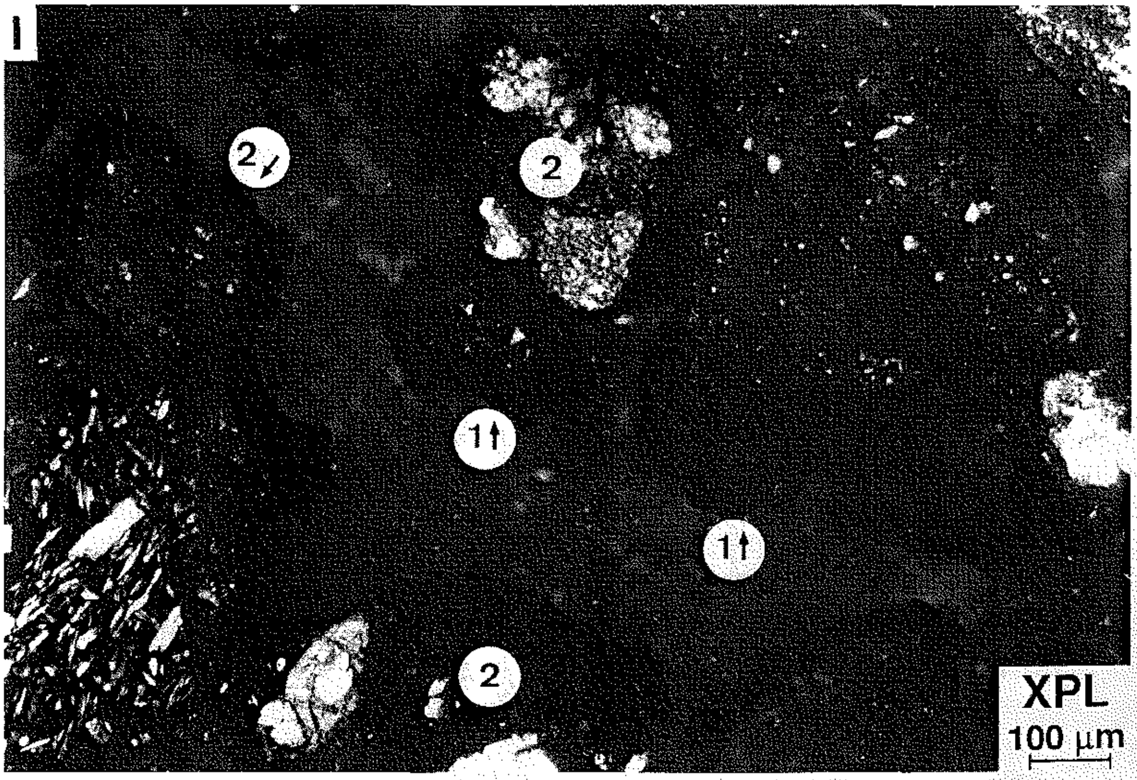


Fig. 3. For caption see p. 437.

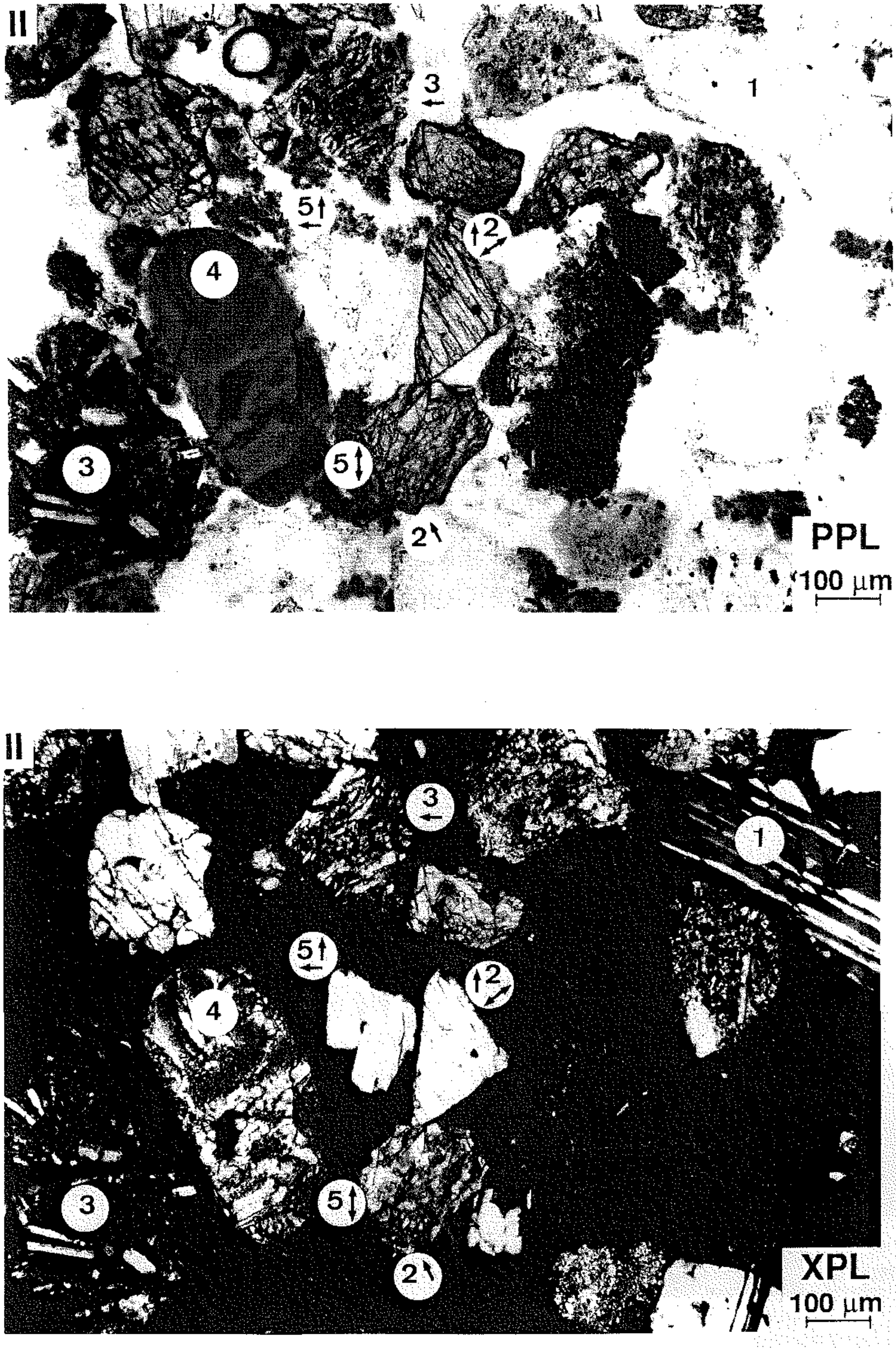


Fig. 3. For caption see p. 437.

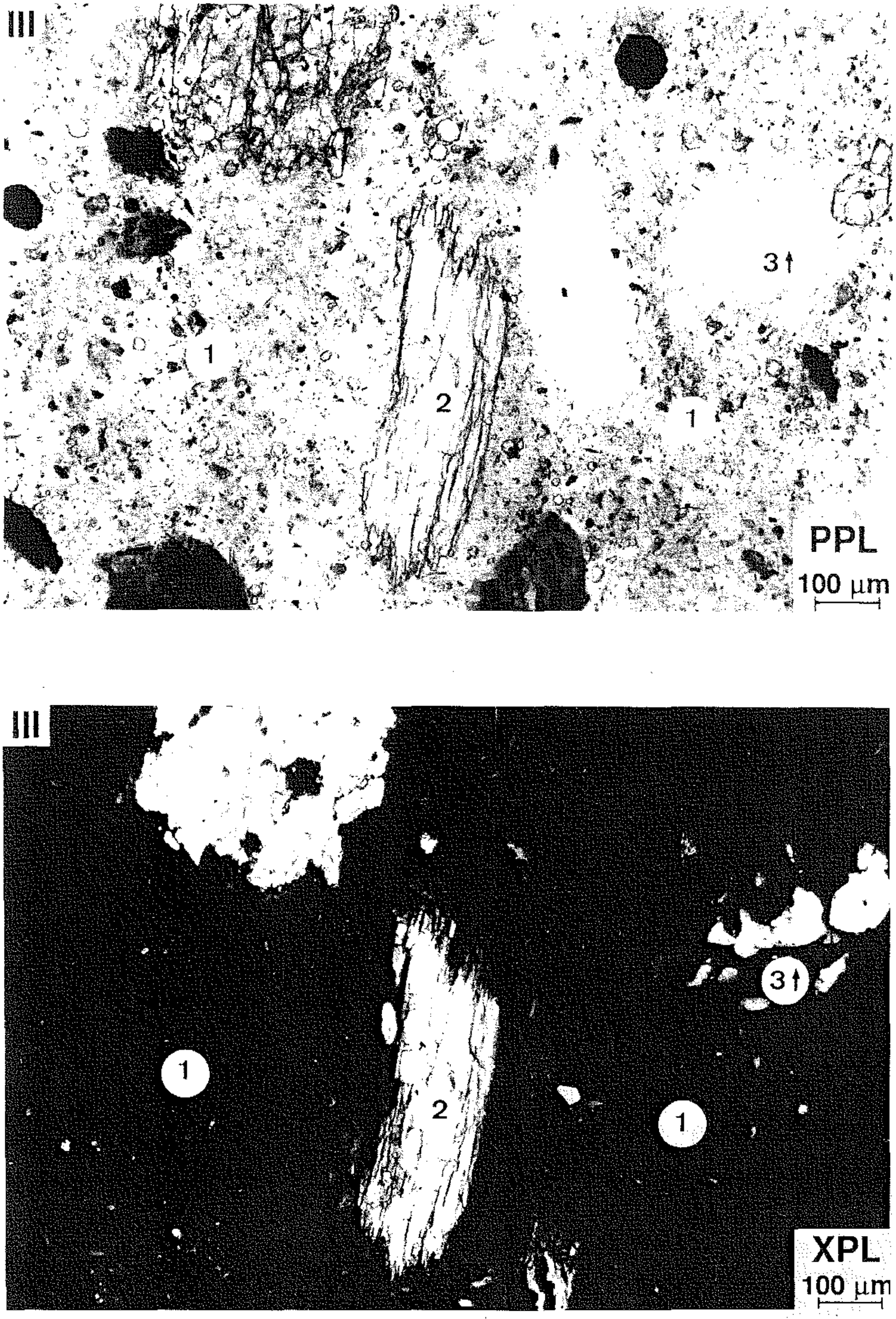


Fig. 3. For caption see facing page.

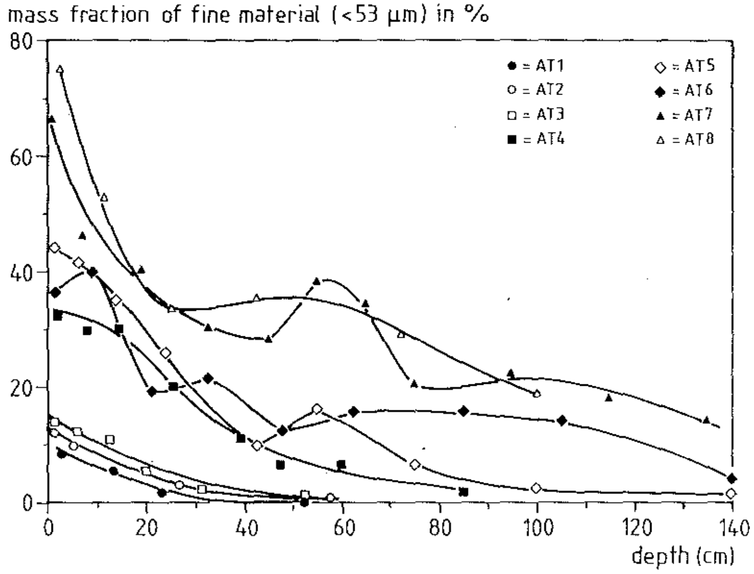


Fig. 4. Content of fine material (< 53 μm).

The organic surface horizons of the two oldest profiles reflects the imperfect drainage of those soils. The lighter color of the A-horizons of these soils suggests a different form of organic matter, perhaps also on account of a different decomposition pathway caused by poor aeration. The low bulk density of the AT7 profile as compared to the younger soils, points to a different form of organic matter accumulation. Possibly more hydrous complexes of organic matter and Al are formed under these wetter conditions.

The organic matter accumulation in the upper meter of the profiles has been estimated, using data about horizon sequence, organic matter content and bulk density (Tables 3–5). Values for the AT1 to AT7 soils are 7, 16, 13, 25, 26, 23 and 25 kg organic matter per m^3 soil, respectively. Due to the simultaneous decrease in bulk density, organic matter pools do not increase from AT4 onward, although organic matter mass fractions do increase.

Biological influence

The observed faunal activity and the granular and spongy structures observed by macro- and micromorphology (Table 3, Fig. 2) indicate a strong biological influence over a greater depth with increasing soil age. Apart from

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Fig. 3. Selected micromorphological features. (I) Microlaminated ferruginous coatings (*1*) covering coalescent mineral excrements (*2*) in the B-horizon of AT8. (II) Basic mineral components in the A-horizon of AT1, mainly consisting of unweathered grains: plagioclase (*1*), pyroxene (*2*), andesitic rock fragment (*3*), limpid anisotropic clay bodies (*4*) and some organic fine material (organic excrements) (*5*). (III) Basic ineral components in Ah horizon of AT8, mainly consisting of isotropic fine material (*1*), pellicular altered pyroxene (*2*), and minute residues of plagioclase (*3*). *XPL*=crossed polarized light; *PPL*=plain polarized light.

TABLE 5

Selected andic properties of the soils

	Horizon	Sample depth (cm)	H-NaF	Bulk density (Mg m^{-3})	P ret. (%)	1.5 MPa wat. ret.	Al$_o$ (g kg^{-1})	Fe$_o$
AT1	A	0–4	8.4	nd	27	130	1	5
	CA	4–10	8.3	1.0	27	70	2	5
	C	20–25	8.3	1.3	22	30	1	6
	C	50–55	8.0	nd	24	30	1	8
AT2	A	0–2	8.2	nd	40	330	3	3
	AC	4–8	9.2	0.8	41	160	3	3
	C1	25–30	8.9	1.2	27	30	2	3
	C2	55–60	8.3	nd	22	30	1	5
AT3	A1	0–3	9.3	nd	62	320	6	4
	A2	4–8	9.9	0.8	70	240	7	4
	AC	10–15	10.5	nd	68	220	7	5
	CA	17–23	10.2	nd	54	100	5	5
	C	28–34	9.0	1.2	40	70	4	6
	C	50–55	8.6	nd	33	30	2	4
AT4	A	0–3	10.5	nd	91	560	14	4
	A	6–10	10.6	0.7	93	560	16	5
	AB	13–17	10.5	nd	94	520	17	5
	Bw	25–30	10.9	0.8	97	400	21	6
	BCw	45–50	10.5	1.1	81	200	15	2
	CB	50–70	9.8	nd	68	130	13	2
	C	100–110	9.2	nd	44	70	5	3
AT5	A1	0–3	10.6	nd	95	640	24	6
	A2	5–8	10.7	0.6	97	580	23	6
	AB	12–16	10.7	nd	97	500	23	6
	BAw	22–26	10.7	0.7	97	470	24	5
	Bw	40–45	10.6	0.9	88	230	18	2
	BCw	70–80	9.2	0.9	57	130	9	1
	C	135–145	9.5	nd	42	90	4	4
AT6	A	0–3	10.5	nd	96	510	21	6
	A	6–12	10.9	0.7	96	640	24	8
	Bw1	18–24	10.8	0.6	97	490	28	7
	Bw2	30–35	10.5	nd	97	500	24	6
	Bw3	41–46	10.5	0.7	92	400	20	4
	BCw	60–65	10.3	0.8	87	250	20	4
	BCwr	85–95	10.0	nd	80	350	16	3
	C	110–120	9.6	nd	46	90	8	4
AT7	O	2–0	8.7	nd	71	1540	6	10
	A1	2–8	10.3	0.3	93	1340	21	20
	A2	14–20	11.0	nd	98	1070	30	12
	Bw	28–33	11.2	0.4	98	740	31	9
	Bwr	38–48	11.2	0.6	97	600	27	7
	BCwr	60–70	10.3	0.6	93	520	26	7
	CBr	90–100	10.2	nd	88	440	22	6
	C	150–160	10.0	nd	75	220	14	5
AT8	O	5–0		nd	62	nd	5	8
	A	1–11	11.7	nd	96	nd	21	21
	Bwr	15–25		nd	97	nd	33	12
	BCr1	30–45	11.6	nd	97	nd	27	7
	BCr2	60–75	11.3	nd	94	nd	24	8
	CBr	90–100	11.1	nd	87	nd	18	5

nd = not determined.

structure development in a shallow (but increasing) surface soil, the three youngest profiles show hardly any horizon differentiation. The A-horizon gradually deepens from AT1 to AT4; in the AT4 to AT6 profiles depth of the A horizons is more or less constant. In the AT7 and AT8 profiles, differences in color between the A and B horizons become less clear. While homogenization of the parent material by nesting sea turtles facilitates study of soil genesis, later biologic activity may obscure some pedogenetic processes. In AT6, the horizon sequence in the topsoil was found to be affected by burrowing activity of a rodent (*Orthogeomys cherriei*), which has brought part of the B-horizon to the surface, as indicated by values for texture (Table 4, Fig. 4). The decreasing structural grade with age from AT5 onwards (Table 3), as well as the development of organic surface horizons point to reduced faunal bioturbation. Both effects can be caused by poor aeration as a result of imperfect drainage. The few earthworms observed and the absence of a granular microstructure and a low amounts of excremental infillings in the AT7 and AT8 profiles also indicate restricted biological activity. Faunal activity might also be hampered by the acidity of their surface horizons, where pH values lower than 5 and high amounts of exchangeable aluminium are found (Table 4). The spongy microstructure in the B-horizons of these profiles which may result from root activity, faunal biological activity or may be due to the buoyant force of water, contribute to the extremely low bulk densities and high moisture retention values at 1500 kPa (Table 5).

Weathering and neoformation

Weathering of volcanic parent material under well-drained conditions and high rainfall generally leads to the formation of short-range order materials such as allophane and Al-humus complexes (Mizota and Van Reeuwijk, 1989; Wada, 1989). Precipitation of Si–Al gels, liberated by weathering of the mineral grains, and accumulation and incorporation of soil organic matter are thought to be the main source of the increasing amount of fine material in the A and B horizons with soil age (Figs. 2–4). Complexes of Al and Fe with organic matter were found to be the main components of the clay fraction of the A horizons, while allophane was the most important clay component in deeper horizons (Nieuwenhuyse et al., 1992). The rate of weathering of andesitic sand, as can be deduced from the decrease of sand content (Fig. 4) is about 30–40% in the topsoil of AT4 and AT5. This is in the same order of magnitude as that of dacito-andesitic pumice under 2000–2500 mm rainfall in Martinique: Quantin et al. (1991) found an increase in material smaller than 0.05 mm from 12% to about 33% in a soil 1670 years old.

The decrease in bulk density with soil age and the concomitant, gradual increase of CEC, moisture retention at 1.5 MPa values and andic properties

(Tables 4 and 5), must be attributed largely to the formation of amorphous secondary material and the accumulation of organic matter.

The CEC of most samples can be accounted for by contents of clay and organic matter, assuming a CEC of 200 cmol+ kg^{-1} for organic matter and 100 cmol+ kg^{-1} for amorphous clay (allophane). However, in many of the subsurface horizons CEC values are higher than can be explained by their clay and organic matter contents. Possibly, the sand-sized clay bodies derived from the parent material contribute to these high CEC values. On the other hand, CEC values in Andisols obtained by conventional methods are often difficult to interpret (Wada, 1989) and a yet unknown phenomena or analytical errors might be the reason for the high CEC values.

The low sum of exchangeable cations in the B horizons of the AT4–AT7 profiles is remarkable. In all horizons still considerable amounts of weatherable primary minerals are present, and except for the topsoils of AT7 and AT8, soil pH values are relatively high. Therefore, a good supply of bases by weathering is likely, and the low amount of exchangeable cations must be attributed to the extremely high continuous leaching. The somewhat higher amount of exchangeable bases in AT8 may be due to imperfect drainage, which may somewhat hamper leaching.

P-retention increases with Al_o content to values of about 20 g kg^{-1} Al_o (Table 5). At higher contents of Al_o, P-retention remains more or less constant. These results suggest that above the limits defined by Soil Survey Staff (1990) for Al_o and Fe_o to classify a soil as Andisol, values for P-retention are rather insignicant, since they do not distinguish any further between the soils. At least for the studied soils, P-retention determinations have little value for classification purposes.

Fe_o contents are rather low and constant throughout the chronosequence, except in the surface horizons of the two oldest soils. Fe_o contents in the young soils and the less weathered subsoils exceed the content of Al_o. Apparantly, oxalate extracts Fe not only from poorly ordered Fe oxides, but also from the parent material components. Whether this iron is extracted from secondary Fe-oxides present in the parent material, or from primary minerals is not known. Oxalate is know to attack magnetite, which may be the source of some of the Fe_o (Borggaard, 1988). The distinctly higher Fe_o values in the surface horizons of AT7 and AT8 are associated with gley mottling and organic complexes. As a consequence, Fe_o is unsuitable for classification purposes in these soils.

The orange brown to yellowish brown (hypo) coatings and the accumulation of iron oxides in and around voids in the BC- (and B-) horizons of the AT6–AT8 may contribute to the firmness of some of the BC horizons of the AT4–AT8 soils (Table 3).

CONCLUSIONS

Mineralogical and textural data on the parent material indicate that the soils of this chronosequence spanning 100–5000 years of age have developed in essentially the same parent material.

Under the perhumid tropical circumstances of the study area, well developed Andisols may form in sandy andesitic parent material with a low volcanic glass content in less than 2000 years. The dominant soil forming factor in the studied chronosequence is soil age, but except for the youngest two profiles drainage plays an (important) role, too.

Increased weathering to greater depth with increasing soil age, results in decreasing sand contents and increasing contents of fine material over a greater depth with soil age. Biological homogenisation increases with soil age, but biological acivity is restricted in the oldest two soils as a result of gleying.

This study suggests that P-retention and Fe_o are of limited use for classifying these Andisols.

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