THREE SOIL PROFILES FROM ELEPHANT ISLAND, SOUTH SHETLAND ISLANDS

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Abstract. Three soil profiles from ice-free areas around the periphery of Elephant Island are described and discussed. All three sites are underlain by continuous permafrost and the time interval since exposure to subaerial weathering and leaching is believed to range from several hundred years to about 10,000 yr. Incipient profile-horizon differentiation is just detectable on the oldest site but all three profiles show very little evidence of mineral weathering.

This paper describes three soil profiles from Elephant Island, South Shetland Islands. The profiles were sampled by R. M. G. O'Brien during the course of general geomorphological investigations, which formed part of the scientific programme of the Joint Services Expedition, 1970–71. No previous pedological investigations had been carried out on Elephant Island or its near neighbours.

The three profile sites (Fig. 1) were selected with the object of obtaining a developmental

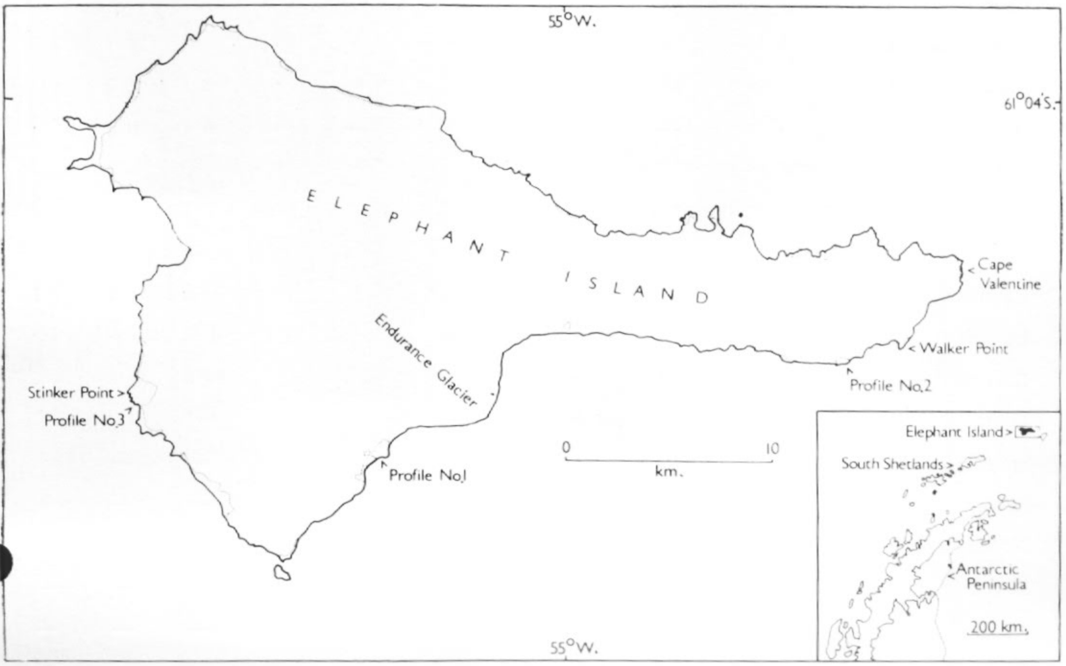

Fig. 1. Map of Elephant Island showing profile-site locations.

chronosequence from raw till, with polygonal patterned ground features outlined by sparse lichen growth, to raised beach material with a continuous moss-vegetation cover and slight indications of profile development. The intermediate site in the sequence is on older moraine with a moss–lichen cover, partially destroyed by recent penguin colonization. All three sites are underlain by continuous permafrost. The time interval since exposure to leaching is

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thought to range from several hundred years for the fresh till to perhaps 10,000 yr. for the raised beach material.

Chemical, physical and mineralogical analyses (Tables I–IV) have been carried out on bulk samples collected from all three profiles. For micro-morphological examination, thin sections were prepared from undisturbed samples. The profile descriptions are based on both field and laboratory examination.

TABLE II. PERCENTAGES OF MINERALS PRESENT IN THE FINE SAND FRACTION OF ELEPHANT ISLAND SOIL SAMPLES

Profile	*Elephant Island No. 1*				*Elephant Island No. 2*			*Elephant Island No. 3*		
Sample depth (cm.)	0–5	15–25	45–55	65–75	15–25	35–45	55–65	0–5	5–15	40–50
Quartz	29·9	29·6	29·1	20·5	18·0	20·1	21·9	2·6	9·0	18·5
K-feldspar	21·1	29·2	25·0	27·0	9·0	7·2	5·4	2·5	9·7	13·6
Plagioclase	—	—	—	—	0·4	0·5	*	—	—	—
Carbonate	0·4	1·9	2·2	4·6	—	—	—	*	—	—
Glass	—	—	—	—	0·4	1·4	0·5	*	—	*
Brown material	—	—	—	—	—	—	—	—	19·3	2·4
Muscovite	5·7	4·4	4·3	6·6	0·4	—	*	0·3	2·0	6·9
Biotite	—	—	—	—	—	—	—	0·4	0·2	0·5
Chlorite	22·8	14·7	16·6	19·6	*	*	*	2·0	6·7	11·3
Iron oxides	1·4	2·3	3·1	3·0	0·8	1·7	1·0	1·1	1·6	2·0
Augite	—	—	—	—	*	0·1	*	—	—	0·1
Hornblende	0·3	0·2	0·1	0·2	*	*	*	0·4	1·1	1·6
Epidote	9·7	9·4	8·6	8·2	0·1	0·1	0·1	0·9	8·9	9·5
Garnet	0·7	0·9	0·9	0·4	*	0·1	*	89·6	36·4	16·2
Tourmaline	0·1	*	0·1	0·3	—	—	—	—	0·2	0·1
Sphene	0·1	0·1	0·1	0·1	*	—	—	—	—	0·1
Apatite	0·1	0·1	—	—	—	—	—	—	—	—
Hypersthene	—	—	—	—	*	*	*	—	—	—
Zircon	—	—	—	—	—	—	—	—	—	—
Rutile	—	—	—	—	*	—	—	—	—	—
Composite	1·6	0·6	1·0	1·6	*	*	—	—	1·9	3·5
Weathered	6·3	6·7	8·9	8·1	70·9	68·8	71·1	0·3	3·1	13·8

* Present but <0·1 per cent.
— Not detectable within the limits of analytical determination.

TOPOGRAPHY AND CLIMATE

Elephant Island is located at lat. 61°S., long. 55°W. on the southern limb of the Scotia Ridge between Drake Passage and the Weddell Sea. The island measures about 40 km. from east to west and about 24 km. from north to south. The main topographic features are an

TABLE I. CHEMICAL AND PHYSICAL ANALYSES OF SOIL SAMPLES FROM ELEPHANT ISLAND

			Soil separates					*Exchangeable cations*						*pH*		*Organic fraction*				
Profile	*Sample depth* (cm.)	*Loss on ignition* (per cent)	*Sand* (per cent)	*Silt* (per cent)	*Clay* (per cent)	*U.S. sand* (per cent)	*U.S. silt* (per cent)	Ca (mg./100 g.)	Mg (mg./100 g.)	Na (mg./100 g.)	K (mg./100 g.)	H (mg./100 g.)	*Total soluble salts* (per cent)	H_2O	$CaCl_2$	C (per cent)	N (per cent)	C/N	$CaCO_3$ (per cent)	P (mg./100 g.)
Elephant Island No. 1	0–5	3·2	51	39	10	34	56	5·4	0·39	0·22	0·06	<0·1	0·019	8·2	7·5	0·33	0·04	8·3	1·5	220
	15–25	3·4	56	44	<1	41	58	22·5	0·47	0·22	0·08	<0·1	0·023	8·4	7·5	0·50	0·03	16·7	2·5	135
	45–55	4·0	52	47	<1	38	61	40·4	0·51	0·14	0·09	<0·1	0·023	8·5	7·6	0·61	0·05	12·2	3·0	195
	65–75	3·8	52	48	<1	36	63	39·8	0·55	0·14	0·10	<0·1	0·024	8·6	7·7	0·55	0·05	11·0	3·5	194
Elephant Island No. 2	0–5	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	1·2	0·27	0·26	0·79	15·0	0·049	n.d.	n.d.	2·80	0·42	6·7	Nil	5,075
	15–25	6·1	48	37	12	34	50	<0·01	0·06	0·62	2·54	15·2	0·018	4·3	3·6	1·14	0·42	2·7	Nil	8,350
	35–45	5·9	43	38	16	30	52	<0·01	0·06	0·42	1·16	16·2	0·017	4·2	3·6	1·52	0·34	4·5	Nil	5,962
	55–65	5·9	49	35	13	37	47	<0·01	0·10	0·37	2·47	15·4	0·018	4·2	3·5	1·25	0·44	2·8	Nil	8,475
Elephant Island No. 3	0–5	0·6	98	1	1	98	1	<0·01	0·06	0·07	0·02	1·0	0·007	5·4	4·7	0·22	0·02	11·0	Nil	89
	5–15	1·0	95	2	3	93	4	2·3	0·10	0·18	0·12	1·7	0·013	5·7	4·8	0·34	0·06	5·6	Nil	1,240
	40–50	4·2	87	10	6	67	25	1·8	0·35	0·35	1·11	4·8	0·030	5·0	4·3	1·68	0·30	5·6	Nil	1,700

n.d. Not determined.

TABLE III. CLAY MINERAL ANALYSES OF THE <2 μm. FRACTION OF ELEPHANT ISLAND SOIL SAMPLES

Profile	*Sample depth* (cm.)	*Chlorite*	*Mica*	*Mica/ vermiculite interstratified*	*Hornblende*	*Leucophosphite*
Elephant Island No. 1	0–5	+++	+			
	15–25	+++	+			
	45–55	+++	+			
	65–75	+++	+			
Elephant Island No. 2	15–25			+++		+
	35–45			+++		+
	55–65			+++		+
Elephant Island No. 3	0–5	+++	+		+	
	5–15	+++	+			
	40–50	+++	+			

+++ Dominant, >75 per cent.
+ Subordinate, 5–25 per cent.

TABLE IV. QUANTITIES OF MATERIAL IN THE SOIL SAMPLES FROM ELEPHANT ISLAND RETAINED BY AND PASSED THROUGH A 2 mm. SIEVE

Profile	*Sample depth* (cm.)	*Total sample weight* (g.)	*Weight of stones* (g.)	*Weight of fraction <2 mm.* (g.)	*Fraction <2 mm. as percentage of total sample*
Elephant Island No. 1	0–5	350·6	71·9	278·7	79
	15–25	339·5	78·0	261·5	77
	45–55	356·4	87·2	269·2	76
	65–75	454·4	111·1	343·3	76
Elephant Island No. 2	0–5	443·6	372·2	71·4	16
	15–25	250·9	106·1	144·8	58
	35–45	456·5	209·8	246·7	54
	55–65	652·0	377·8	274·2	42
Elephant Island No. 3	0–5	821·7	1·2	820·5	100
	5–15	598·7	186·0	412·7	69
	40–50	348·3	182·0	166·3	48

alpine spine, which rises to 970 m. altitude and is almost completely masked by snow and ice, and a precipitous coastline along which high cliffed headlands alternate with steep outlet glaciers or ice cliffs. More than 95 per cent of the land surface is permanently covered by snow and ice. Limited ice-free surfaces, usually bearing glacial drift or raised marine deposits, are found on top of the major coastal promontories. Geologically, the island is composed almost entirely of metamorphic rocks, mainly garnetiferous mica-schists and dark grey and chloritic green phyllites.

The climate of the island is maritime and shows relatively modest extremes of cold. Temperatures are characterized by low maxima and narrow ranges. The mean temperature for July, normally the coldest month, is thought to be about −10° C, and that for January, the warmest month, about 1° C (Pepper, 1954). An important feature of the thermal regime, in a pedogenic context, is the frequent freeze–thaw cycling of air temperatures throughout the year caused by changing pressure systems bringing air from different sources. Elephant Island lies in the Antarctic zone of most frequent cyclonic disturbance and, accordingly, high wind speeds, large total cloud amounts and substantial precipitation are other notable features of the climate. Mean annual precipitation in the interior is probably about 1,500 mm. water equivalent; the bulk of the precipitation falls as snow. Detailed meteorological data for Elephant Island have been published by O'Brien (1974).

Macro- and Micro-morphology of the Soil Profiles

Profile No. 1

Location. 2·5 km. south-east of Endurance Glacier (lat. 61°12′S., long. 55°10′W.).

Topography. Flat crest area at 190 m. a.s.l. South-west exposure. The site bears well-defined large sorted nets with miniature nets superimposed on the fine centres.

Parent material. Fresh till derived from quartz-mica-schist and garnetiferous quartz-mica-schist.

Vegetation. Sparse *Usnea antarctica* and *Drepanocladus uncinatus* in the coarse elements of the nets.

Drainage. Saturated at 65 cm. Permafrost table presumed to be at ca. 90 cm.

0–5 cm. Very dark grey-brown 10 YR 3/2 clay loam with gritty particles and small flakes of schist, no roots or organic debris, very moist, diffuse boundary.

5–13 cm. Very dark grey 10 YR 3/1 clay loam with appreciable quantities of coarse sand and flakes of schist, stiff and compact, no roots or other organic debris, moist, merges into

13–50 cm. Very dark grey 10 YR 3/1 clay loam with coarse sand and fragments of shaly schist, stiff and compact with some discontinuous horizontal fissuring giving a platy structure with some suggestion of break-down into coarse and medium angular to sub-angular blocky fragments, frequent angular to sub-angular schist stones with near-vertical orientation in the upper part of this horizon, no roots or other organic debris, moist, merges into

50–70 cm. Very dark grey 10 YR 3/1 clay loam with appreciable quantities of sharp gritty coarse sand, stiff and compact with traces of fine horizontal lamination, larger stones tend to be sub-rounded, glacially polished, and horizontally aligned, no roots or organic debris, moist to very moist, profile waterlogged at 65 cm.

The analyses confirm that this is an extremely immature soil. Free calcium carbonate is still present in all horizons sampled from the surface to 70±5 cm. but both total carbonate and exchangeable calcium values indicate that a leaching gradient has been initiated (Table I). Percentages of carbon (after correction for $CaCO_3$) and nitrogen are very low, and taken in conjunction with total phosphorus values suggest that the organic matter in No. 1 profile could be of avian rather than of plant origin. However, as the nitrogen values are so low, any such interpretation must be regarded as speculative.

Differential movement of fine material within the solum is a characteristic of the soils of cold regions (Chambers, 1966*a*; Ugolini, 1966; Wilimovsky and Wolfe, 1966); this has been confirmed experimentally by Corte (1961). The mechanical analyses carried out on the < 2 mm. fraction, together with values for the < 2 mm. fraction expressed as a percentage of the whole sample (Table IV), showed little evidence of textural differentiation within the solum, indicating that it had not been exposed to seasonal freeze–thaw processes long enough for any appreciable percentage of the fine material to be physically translocated down the profile. This is confirmed by examination of the soil thin sections which show that there is only a weak development of silt cappings (Romans and others, 1966) on the upper surfaces of some grit particles between 5 and 16 cm. below the surface (Fig. 2a). The orientation of these capped particles has not been greatly disturbed from the horizontal by current frost heaving though, near the surface, small stones up to 2 cm. long are vertically aligned. The 0–3 cm. surface layer has a very dense fabric interrupted only by scattered well-rounded circular bubble pores 0·3–0·9 mm. in diameter (Fig. 2b), and by some larger rounded pores which are elongated either horizontally or vertically. The structure of th s layer is consistent with intermittent surface freezing under bare-ground conditions. Circular or distorted sub-rounded bubble-like

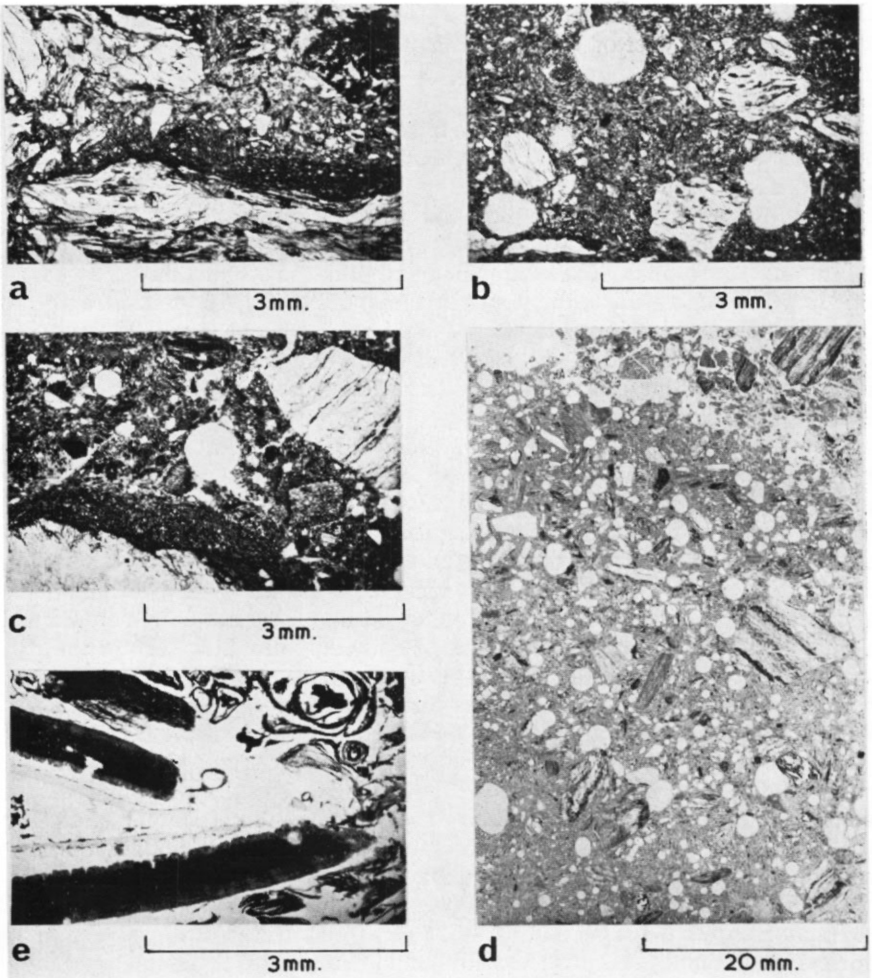

Fig. 2. Photomicrographs of soil thin sections prepared from Elephant Island samples.
a. Profile No. 1. Silt capping on rock fragment at ca. 12 cm.
b. Profile No. 1. Circular bubble pores at ca. 1 cm.
c. Profile No. 2. Silt cappings and circular bubble pores at ca. 36 cm.
d. Profile No. 2. Distribution of circular bubble pores between 25 and 30 cm.
e. Profile No. 2. Egg-shell fragments incorporated within surface moss mat.

pores of different sizes are present throughout the profile. Very slight staining on the upper surfaces of rock fragments at ca. 37 cm. is suggestive of slight translocation of colloidal organic matter.

Mineralogical analysis of the fine sand fraction (Table II) indicated no marked trends in mineral distribution within the profile. The dominant minerals at the 20–30 per cent level are quartz, potash feldspar and chlorite, followed at the 5–10 per cent level by epidote, muscovite and weathered (unidentified) minerals. Clay-mineral analyses (Table III) show that chlorite is the dominant clay mineral with subordinate amounts of mica. There is nothing to suggest that the clay fraction has been produced other than by straight-forward physical disintegration of the parent rock. Rock fragments identified in the soil thin sections included quartz-mica-schist, chlorite-schist, garnetiferous quartz-mica-schist, granulite and hypersthene.

Profile No. 2

Location. 3·5 km. south-west of Walker Point (lat. 61°08′S., long. 54°42′W.).

Topography. Bevelled rocky spur 120 m. a.s.l. South-east exposure.

Parent material. Till derived from dark grey and green phyllites.

Vegetation. Biotically eroded turf of *Polytrichum alpestre* and *Chorisodontium aciphyllum*. Considerable surface contamination by penguin excrement and regurgitated krill.

Drainage. Saturated at 60 cm.

5–0 cm. Eroded moss mat, with some pink and white surface staining.

0–5 cm. Dark brown 7·5 YR 3/2 to very dark grey-brown 2·5 Y 3/2 gritty silt loam, very stony, most of the stones are small angular fragments of dark shaly schist in the 1–4 cm. size range with fine material deposited on the upper surfaces, occasional roots and fragments of plant debris present, clear change into

5–45 cm. Dark grey-brown 2·5 Y 4/2 gritty silt loam, compact with platy structure, vesicles present, stony, most stones smaller than 5 cm., no roots or other organic material, moist, merges into

45–60 cm. Dark grey-brown 2·5 Y 4/2 gritty silty fine sandy loam, stiff and compact, with discontinuous horizontal fissuring, stony, with angular pieces of dark schist, no roots or organic debris, moist, becoming wet at 60 cm.

No free carbonate and virtually no exchangeable calcium (except in the surface layer) are present in this profile. All the horizons sampled are acid with uniformly low pH values (Table I). Nitrogen, exchangeable sodium and exchangeable potassium levels are high throughout the profile and show no obvious trends. Total phosphorus values are extremely high. Carbon : nitrogen ratios are low compared with those of Scottish soils. Low carbon : nitrogen ratios associated with low pH, high total phosphorus and high exchangeable potassium values have been described as typical of the effects of sea-bird excreta on soil in a moist oceanic environment (Ward, 1961; Blakemore and Gibbs, 1968). It is very difficult to highlight any features in the chemical analyses, apart from the relatively high percentage of carbon in the surface sample, as being pedologically significant. The rest of the results can only be described as wholly consistent with the observation that "every conceivable habitable space on the surrounding slopes of rock and moraine was occupied by . . . nesting penguins" (Burley, 1971).

The relative maturity of this profile compared with No. 1 profile is indicated by a slight preferential concentration of silt and clay between 15 and 45 cm. (Table I). In fact, the whole $<$ 2 mm. fraction shows the same tendency (Table IV). However, this preferential concentration of fine material is much less pronounced than in comparable Scottish soils. On stable sites within the alpine zone in Scotland, where the ground was formerly exposed to severe frost action, a well-developed dense silty layer is present within the solum and extends to 90 cm. or more below mineral ground surface (Romans and others, 1966). Soil thin sections from No. 2 profile show the presence of thin silt cappings (Fig. 2c) on grit particles from a few centimetres below the moss mat to the base of the sectioned profile at 40 cm. The normal orientation of these capped particles has been somewhat disturbed from the horizontal throughout the profile. These characteristics confirm that there has been a slight translocation of fine material down the profile, and some subsequent frost disturbance of the solum to at least 40 cm. Well-developed circular or slightly distorted bubble pores are an intermittent feature of the microfabric throughout the profile. They are particularly clearly developed between 25 and 30 cm. (Fig. 2d).

The surface moss mat is much disturbed and is interspersed with grit, sand and crushed (calcite) egg-shell (Fig. 2e). Occasional fungal spores (Fig. 3a) are present. Rock fragments incorporated within the mat are locally coated with dark brown opaque material high in colloidal organic matter showing shrinkage cracks. As seen in similar circumstances within the A horizon of alpine soils in Scotland, the biotite in the affected rock fragments is blackened, opaque and strongly weathered. Immediately below the moss mat, silt cappings on rock frag-

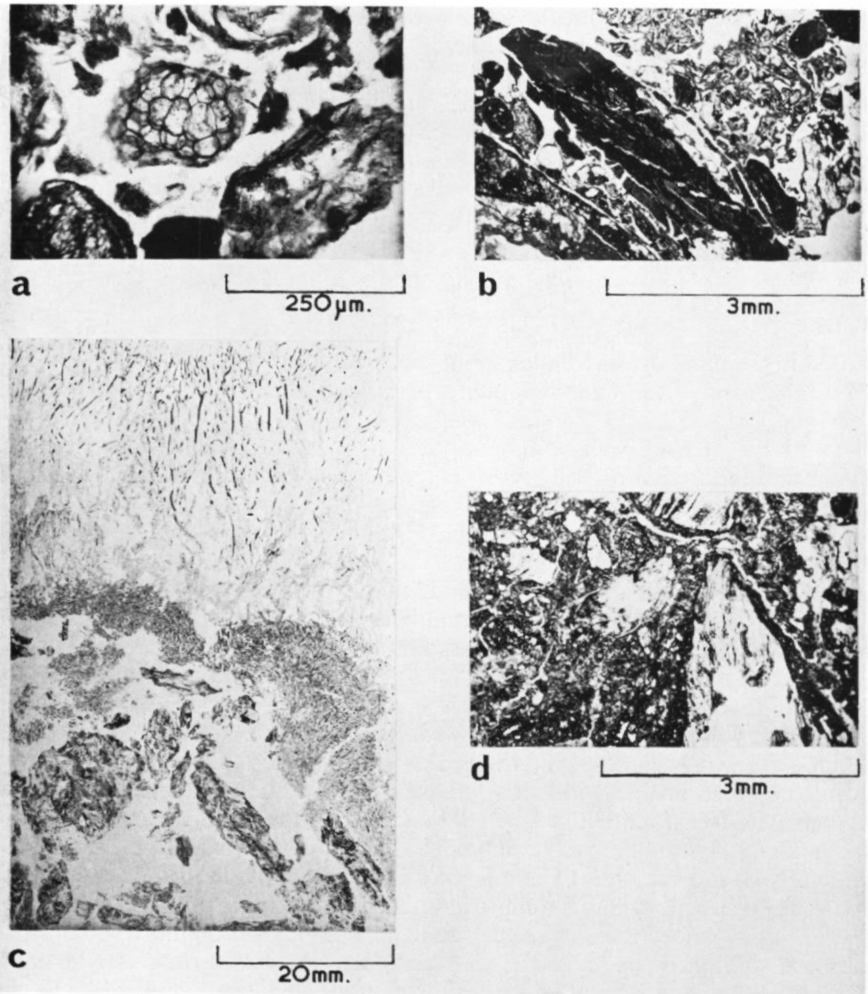

Fig. 3. Photomicrographs of soil thin sections prepared from Elephant Island samples.
a. Profile No. 2. Fungal spore at ca. 6 cm.
b. Profile No. 2. Coatings on rock fragments with high content of colloidal organic matter at ca. 8 cm.
c. Profile No. 3. Surface moss mat with slightly weathered mineral horizon below.
d. Profile No. 3. Silt cappings with disturbed orientation at ca. 29 cm.

ments are coloured dark brown and show shrinkage cracks (Fig. 3b) but remain translucent. Fairly strong colour and some cracking of the cappings are present to the base of the profile and reflect the translocation of appreciable quantities of colloidal organic matter, but evidence of mineral weathering is negligible. It is evident that, despite the large quantities of colloidal organic matter passing through the profile and the very low pH, mineral weathering and soil-profile development are less advanced than in the highest parts of the alpine zone in Scotland above 1,200 m.

The fine sand fraction mineral analyses (Table II) again show no marked trend in mineral distribution throughout the profile. The most notable feature is the high percentage (about 70 per cent) of weathered (unidentified) material in the three horizons examined. The absence of any significant variations in mineral content between horizons is indicative of direct derivation from the parent rock. Apart from the large percentage of weathered material, quartz at the 20 per cent level and potash feldspar at the 5–10 per cent level are the only other minerals present in significant quantities. The dominant clay mineral (Table III) is an interstratified mica/vermiculite believed to be directly derived from the parent rock, with subordinate amounts of leucophosphite (potassium iron phosphate hydrate)—a mineral which has been previously identified in guano deposited by sea-birds (Axelrod and others, 1952). Rock fragments identified in the soil thin sections include mica-chlorite-schist with narrow granite veining, chlorite-schist, mica-schist and a fragment of graphically intergrown quartz/orthoclase. Small crystals of an exfoliated mineral resembling vermiculite are sometimes present in the granite veins.

Profile No. 3

Location. 0·5 km. south-east of Stinker Point (lat. 61°14′S., long. 55°30′W.).

Topography. Extensive level wave-cut platform at ca. 60 m. a.s.l. with patterned ground features.

Parent material. Sandy raised beach material derived from mica-schists and phyllites.

Vegetation. Continuous shallow carpet of *Drepanocladus uncinatus* broken in places by th bare erupting centres of large non-sorted circles.

Drainage. Profile waterlogged between 45 and 55 cm. depth.

10–0 cm. Moss mat.

0–5 cm. Black 10 YR 2/1 loamy sand to sand, single-grain structure, very few stones, some organic staining, plant debris and bone fragments present, moist, clear change into

5–20 cm. Very dark grey 10 YR 3/1 coarse sand, many stones and boulders present, stones are mainly flattened angular pieces of schist with sharp to sub-rounded edges and weak silt cappings, numerous soft dark-stained bone fragments, clear change into

20–45 cm. Very dark grey 5 Y 3/1 silty loamy sand, numerous flattened angular pieces of dark schist, massive and wet, profile waterlogged at 45 cm.

This is a composite profile with a surface sample of sand from one site and two other samples taken at 5–15 cm. and 40–50 cm., respectively, from a nearby profile pit. The parent material is a sandy raised beach deposit. None of the samples examined contained any free carbonate and pH values are low (Table I), though consistently about one unit higher than in No. 2 profile, suggesting that this soil must have been leached for some considerable time. The exchangeable cation values are within the range encountered in Scottish soils. The two sub-surface samples contained penguin bone fragments and, in view of the relatively low nitrogen and potassium values, the high total phosphorus levels in these samples can be reasonably ascribed to bone rather than guano. The levels are comparable with those found in samples from some archaeological sites but are much higher than is usual in either semi-natural or cultivated Scottish soils. The rather lower total phosphorus level in the 5–15 cm. sample compared with the 40–50 cm. sample is due to removal of bone fragments to provide material for possible ^{14}C dating.

The mechanical analyses indicate that increasing quantities of silt and clay are present in the lower horizons. The results are consistent with translocation of the fine fraction by repeated frost action but non-uniform deposition of beach material could be a contributory factor. In the soil thin sections, silt cappings are present on small stones and grit particles from a few centimetres below the surface moss mat to at least 34 cm. The cappings are more distinctive than those present in either No. 1 or No. 2 profiles and increase gradually in thickness with depth. They do not show the cracking (associated with high content of colloidal organic matter) seen in No. 2 profile. The cappings show some disturbance from horizontal orientation throughout (Fig. 3d). Below the uppermost few centimetres of the mineral soil, the fabric is quite dense and it seems that translocation of fine material has been more extensive and frost disturbance of the solum greater than in the other two profiles. Circular bubble pores are less prevalent in this profile, particularly in the 10 cm. lying immediately below the moss mat, but lower down they tend to concentrate in distinctive bands.

The undisturbed surface moss mat (Fig. 3c) is underlain by a 2 cm. band of rock fragments, some slightly humus-stained, and interstitial fine material, which includes some slightly weathered biotite in the upper 1 cm. Occasional silica spicules and diatoms are present. There are slight indications of the development of secondary aggregates which may be associated with soil-profile development. Below 2 cm. the fabric becomes more dense and its features are those associated with periglacial processes. Evidence of leaching and incipient profile development are present on this site but, as in No. 2 profile, the stage of development is less advanced than that found in the highest parts of the alpine zone in Scotland.

The predominant mineral in the fine sand fraction of the upper horizon is garnet (Table II). Below the surface, garnet (though decreasing in concentration with depth) is still a dominant mineral along with quartz at the 10–20 per cent level, potash feldspar at 10–15 per cent, epidote at about 10 per cent and chlorite and weathered (unidentified) material at the 5–15 per cent level. This assemblage seems to combine the characteristics of No. 1 and No. 2 profiles, with concentrations of nearly pure garnet sand spread locally over the surface. On separating the heavy minerals from the rest of the fine sand, part of the chlorite is found in the heavy and part in the light fraction. Chlorite is an important element in the fine sand from both No. 1 and No. 3 profiles but it is very scarce in No. 2 profile. In No. 1 profile the proportion of chlorite separating with the light mineral fractions shows little variation throughout the profile. In No. 3 profile the proportion in the light fraction is very high at the surface and decreases with depth, which may indicate increased physical weathering at the surface. X-ray examination of the clay fraction showed that chlorite is the dominant clay mineral in all horizons and mica is subordinate, but it provided little evidence of any increased structural disorder in clay minerals near the surface. Rock fragments identified in the soil thin sections include garnetiferous mica-chlorite-schist, spotted schist, quartz and granite-pegmatite veining, and one fragment of magnetite-schist.

Discussion

Soils in the ice-free areas of Elephant Island appear similar to those described from sites of comparable age and aspect on Signy Island, South Orkney Islands (Allen and Heal, 1970; Ugolini, 1970), though no profiles were available for comparison with the more brown earth-like soils occasionally developed on favourable north-facing slopes on Signy Island. Although horizon differentiation is absent or only very weakly developed in the Elephant Island soils, chemical analyses suggest that leaching has occurred to at least 60 cm. Free carbonate is affected quite rapidly, being absent from No. 2 and 3 profiles and significantly leached from the active layer of the most recently exposed profile No. 1. Exchangeable base levels are variable and subject to intermittent replenishment by penguin excreta. The distribution of minerals in the fine sand and clay fractions shows that mineral weathering has been extremely limited. This is confirmed by micro-morphological examination, which indicates the absence (No. 1 and No. 2 profiles) or the ephermeral presence (No. 3 profile; Fig. 2c) of any traces of mineral–humus aggregate formation despite the presence of effective amounts of colloidal organic matter in No. 2 profile. An interesting sidelight on the low level of mineral weathering is the rapid translocation of massive amounts of phosphorus to at least 60 cm. in No. 2 profile without any indication of phosphate fixation.

Frost action is the most important pedogenic factor on Elephant Island under prevailing climatic and edaphic conditions. Ice-free areas of the island are exposed to intense freeze–thaw action, and the soils can be classified as highly frost-susceptible according to accepted fine material content, grain-size distribution and moisture-content criteria (Beskow, 1947).

The frequency of freezing and thawing is an important factor in the effectiveness of periglacial processes and frequent freeze–thaw cycling of air temperature is a conspicuous feature of the climate of Elephant Island, particularly during the summer period. In February and March 1971, 34 air-temperature depressions to or below 0° C and 15 ground-frost cycles at 3 cm. depth were recorded at the Elephant Island meteorological station. Ground freezing was mainly of short duration (less than 24 hr.), small amplitude (absolute minimum −1·7° C) and only superficially effective. Dowel-heave measurements in a patterned ground area near to the Elephant Island No. 1 profile site revealed an average cumulative frost heave of 3·1 cm., and a maximum value of 16·9 cm., during the February–March period. These values are high by any standard. Observations on neighbouring Signy Island, South Orkney Islands (Chambers, 1966b), showed that below a depth of approximately 10 cm. only the annual cycle of freezing and thawing is experienced.

Periglacial action on Elephant Island finds surface expression in a full range of large- and small-scale sorted and non-sorted patterned ground and solifluction phenomena, while within the solum cryogenic features include vertically orientated rock fragments, evidence of a downwards translocation of fine material, bubble pores or vesicles and platy structure. The platy structure is well developed in profiles Nos. 1 and 2, where discontinuous platy aggregates 2–3 mm. thick are separated by thin fissures and voids. The plates become thicker and develop a weak blocky structure with depth. The form and density of the fissuring suggests an origin in sirloin freezing (Higashi, 1958) and the development of ice lenses. The absence of horizontal fissuring from profile No. 3 probably reflects the relatively coarse texture of the constituent mineral soil (Table I).

The circular bubble pores or vesicles seen in the soil thin sections represent a weak development of the vesicular structure which is a common feature of frost-active soils in polar regions (Kubiena, 1953; Ugolini, 1966).

The mechanism of bubble-pore formation is not yet fully understood. Springer (1958) has reported the formation of similar spheroidal vesicles in the surface layer of desert soils. He regarded them as transitory and unstable, easily destroyed but quickly reconstituted after re-wetting the dry powdered soil. His material was strongly alkaline (pH 8·3–9·3) and therefore readily dispersable on wetting. The raw unweathered soils of Elephant Island are also easily dispersed, and it may be significant that bubble pores were absent only from the surface layer of No. 3 profile where slight horizon differentiation was observed. Bubble pores have not so far been recorded in Scottish soils, even within the alpine zone where a frozen crust 30–45 cm. deep is formed during the winter months on sites above 760 m. A few circular pores have been seen in a thin section from an Icelandic soil profile sited on an exposed ridge at about 620 m.

Micro-morphological and macro-morphological examination of cryogenic features in the three profiles corroborates the chemical, mineralogical and other physical evidence relating to the relative maturity of the profiles. In profile No. 1 significant cryogenic effects are largely confined to near-surface layers (even the well-developed sorted circles at the surface are essentially superficial floating forms). It is evident that the raw till on this site has been exposed to the action of periglacial processes for a much shorter period than either the moraine on which profile No. 2 was sited, or the raised beach where the composite No. 3 profile was obtained.

Profile No. 1 was excavated only a few hundred metres from the margin of a small cirque tributary to Endurance Glacier. The till has a raw fresh appearance and merges with and is superficially indistinguishable from the morainic debris immediately adjacent to the ice margin. Its deposition can, therefore, reasonably be assigned to the most recent (Neoglacial) glacial re-advance. Tentative evidence from nearby King George Island, South Shetland Islands (Sugden and John, 1972), places maximum Neoglaciation in the period 500–750 yr. B.P. but correlation with the late eighteenth century re-advance postulated by Mercer (1970) in South America may prove more acceptable.

Profile No. 2 was also situated near to, but about 50 m. above, the margin of a small glacier. In this case, however, there were marked contrasts in the depositional form and appearances of the profile parent material and more recently deposited material from the lateral moraine. The apparent age contrast has been confirmed by lichenometric data (paper in preparation by R. M. G. O'Brien). This profile site is similar in altitude, aspect and topography to a site on Walker Point, about 3·5 km. to the north-east, from which basal material from a deep bed of *Polytrichum alpestre–Chorisodontium aciphyllum* peat has yielded a radiocarbon date of 1,515±40 yr. B.P. Similar peat beds on Signy Island have been dated at ca. 1,800 yr. B.P. (personal communication from N. J. Collins). It would appear that the beginnings of peat formation coincided with a marked climatic amelioration (characterized by reduced cyclonic disturbance and drier conditions) recognized by Auer (1956, 1958) in Patagonia. Auer's Dry Period, beginning ca. 2,240 yr. B.P., can be related to a preceding major glacier re-advance in the same region during the period ca. 2,700–2,200 yr. B.P. and it is tentatively suggested that the Elephant Island No. 2 profile site was exposed at the close of this glacial interlude.

The 60 m. raised beach at Stinker Point, in which the composite No. 3 profile was excavated, is the highest and best developed of a series of raised shoreline features which have not been disturbed by glaciation subsequent to their formation. Above 60 m. on Elephant Island, a succession of older platforms, all displaying evidence of over-riding glaciation, extends up to 120 m. above present sea-level. The situation appears to be analogous to that described by Sugden and John (1972) in the South Shetlands Island proper, where the highest undisturbed raised beach, at 54 m., has been assigned to the closing phases of the main Weichselian glaciation, while higher, older residual beaches are supposed to have formed in an Eemian non-glacial interval. According to Mercer (1970), Weichselian deglaciation in Patagonia may have been under way by 11,000 yr. B.P. In support of this proposition, radiocarbon dates obtained by Sugden and John (1972) suggest that, in the South Shetland Islands, deglaciation was well advanced and post-glacial isostatic re-adjustment substantially completed by ca. 9,000 yr. B.P. It seems likely then that the Elephant Island No. 3 profile site has been exposed to the elements for about 10,000 yr., though during this time pedogenesis has been very slow and may have been intermittently inhibited by *névé* cover during periods of minor glacial re-advance.

Conclusions

This paper describes three soil profiles from Elephant Island and attempts to establish their current pedogenic status, the nature of present-day pedogenic processes and the normal course of profile development in this outer oceanic zone of Antarctica. All three soils examined show very limited mineral weathering and little profile development, even where the parent material has been exposed to subaerial weathering processes for a considerable time, but all have been modified in varying degrees by frost action. It is suggested that the extreme weakness of pedogenic expression in the soils may be partly due to the inhibition of chemical weathering by low ambient temperatures, and partly to the frost-action process of heaving, displacement, collapse and sorting which forcibly impede profile development. These opposed trends may be cyclic. Occasional cessation of cryopedogenic processes (frost heaving/churning) during periods of climatic amelioration allows pedogenesis to proceed, the incipient profile development being subsequently cancelled out by renewed periglacial activity.

Smith (1960), whilst describing solifluction effects on a bare-ground site in South Georgia, has commented that the upper 20 cm. of the profile was somewhat orange in colour "recalling the B horizon of a podzol", and has speculated that the area may have carried a moorland plant association prior to climatic deterioration in the past few centuries. It is evident from his paper that permafrost was absent from the solum to a depth of at least 2 m. and that his site was sloping, unlike those on Elephant Island. The ochreous A/B horizon described by

Smith may perhaps represent the stage at which chemical weathering can start on mineral surfaces already physically damaged by frost action (as in the upper 10 cm. of the Elephant Island No. 3 profile), after a slight rise in mean annual temperature and a relaxation or cessation of periglacial activity.

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