THE COLONIZATION OF VOLCANIC TEPHRA ON DECEPTION ISLAND BY PROTOZOA

By H. G. SMITH

ABSTRACT. 13 species of Protozoa (6 flagellates and 7 ciliates) were observed in samples of volcanic tephra collected from five sites on Deception Island following the eruptions in 1967, 1969 and 1970. The numbers of species observed in the samples were closely correlated with both the age and the per cent loss on ignition of the tephra. Samples containing moss were more species rich (particularly in ciliate species) than vegetation-free samples of the same age. It is suggested that the rate of colonization was limited by the low moisture content of the tephra. Colonization proceeded more quickly in tephra from the 1969 eruption than in that from the other eruptions; this was possibly owing to the pyroclasts from the 1969 eruption having a slightly different chemical composition.

VOLCANIC eruptions occurred on Deception Island, South Shetland Islands, in December 1967, February 1969 and August 1970 (Baker and others, 1969; Baker and McReath, 1971). Large areas of new, lifeless land surface arose, both as a result of fresh land created by submarine eruption and from the deposition on old surfaces of pyroclastic ejecta produced by marine and land eruptions. Such surfaces, where stable and when cool, became available for colonization by living organisms. From 1968 to 1973 a study was made of the colonization of the surface tephra by Protozoa at five sites (Fig. 1):

Two sites on the new island in Telefon Bay, created by the 1967 eruption.
A site in the area of fumaroles near the land centre of the 1967 eruption.

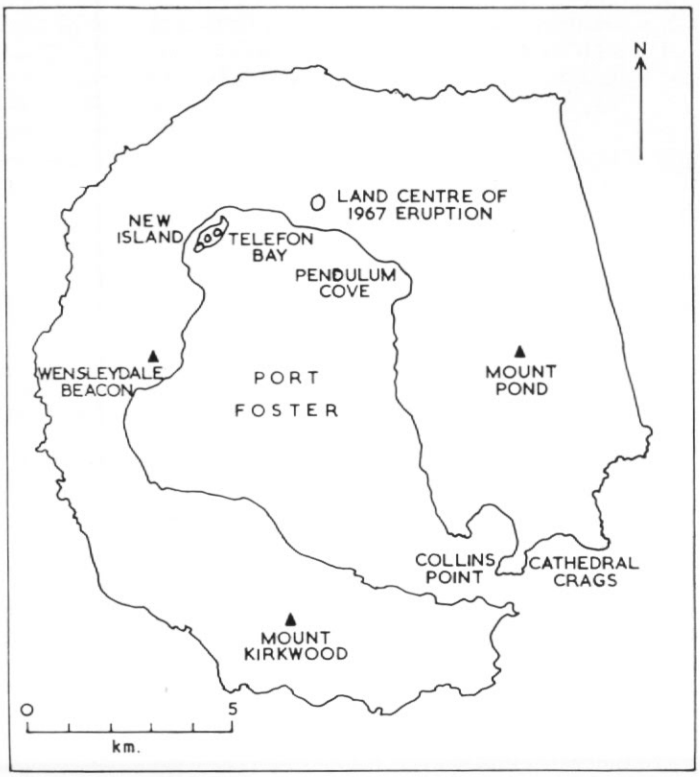

Fig. 1. Sketch map of Deception Island in December 1968, showing the positions of the new island in Telefon Bay and the land centre of the 1967 eruption (after Baker and others, 1969).

A site 200 m. north of Cathdral Crags.
A site 200 m. west of Collins Point.

Methods

Samples of tephra for protozoological examination were collected on four occasions:

I. 10 December 1968 (12 months after 1967 eruption).
II. 27 November and 11 December 1969 (9 and 10 months after 1969 eruption).
III. 18 December 1970 (4 months after 1970 eruption).
IV. 22 and 23 February 1973 (30 months after 1970 eruption).

At each site 500 g. samples of the 0–5 cm. horizon of tephra were taken from virgin untrodden ground, using a sterile trowel, and stored either in sterile Kilner jars or in unused polythene containers. The samples were stored at +4° C during transport to the Signy Island station or the United Kingdom for laboratory examination.

The following were determined for the samples from each site: species of Protozoa present, mean pH, mean moisture content—per cent dry weight (for samples collected in 1973 only), mean loss on igntion—per cent dry weight. Protozoa were cultured by inoculating about 10 g. of each sample on to agar in 9 cm. Petri dishes. The agar was prepared from distilled water extract of tephra (400 g./l., steamed for 2 hr.), 0·5 per cent NaCl and 1·5 per cent agar. The cultures were supplied with *Aerobacter aerogenes* (NCIB 418) as food source for Protozoa and kept moist with sterile 0·5 per cent NaCl solution. The cultures were examined daily for 7 days, then at the fifteenth and thirtieth days after inoculation. Species were identified morphologically.

Measurements of the physical properties of the samples were made on six sub-samples of tephra from each site, the results being expressed as means ±95 per cent confidence limits for each site. pH was determined using a glass electrode and a pH meter, with minimum moistening with distilled water if necessary. Sometimes steady readings could not be obtained and means were not calculated in these cases. Moisture was determined by oven drying at 100° C for 48 hr., and loss on ignition by ashing in a muffle furnace at 450–500° C for 10 hr.

Results

In all, 16 samples of tephra were collected on the four sampling occasions, their ages varying from 4 to 48 months. 13 species of Protozoa were recorded from these samples, six flagellates and seven ciliates:

Mastigophora

Oikomonas termo Ehrenberg
Polypseudopodius bacterioides Pusch
Bodo saltans Ehrenberg
Cercobodo agilis Martin
Cercomonas longicauda Stein
Sainouron mikroteron Sandon

Ciliata

Chilophrya sp. Kahl
Dileptus sp. Dujardin
Enchelys sp. Hill
Holophrya sp. Ehrenberg
Lacrymaria sp. Ehrenberg
Leptopharynx sphagnetorum (Levander) Mermod
Oxytricha pellionella Stein

The results may now be considered in detail and related to the sequence of volcanic activity at each site.

The new island in Telefon Bay

This island was created by submarine eruption in December 1967 (Fig. 1). Surface tephra (volcanic dust, ash and lapilli) were collected from two sites, A and B, on the island (Fig. 2), 12 months after the eruption (sampling occasion I). The island was apparently unaffected by the eruption in 1969 as it lay outside the 1 cm. isopach of tephra resulting from the second eruption and also north of the later fine ash fall (Baker and others, 1969); so samples of tephra collected from the same two sites in December 1969 (sampling occasion II) were considered to be 24 month old material of the 1967 eruption.

The eruption of August 1970, partly submarine, created a new strip of land across Telefon Bay, joining the island to the mainland, destroyed the north-western half of the island and

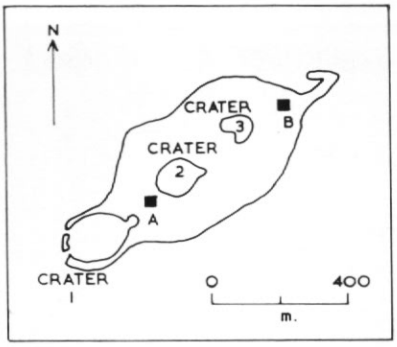

Fig. 2. Sketch map of the new island formed during the 1967 eruption in Telefon Bay, showing craters and sampling sites in December 1968 (after Baker and others, 1969).
■ Sites from which samples of tephra were collected for protozoological examination in December 1968 and December 1969.

truncated the south-eastern half at both ends (Baker and McReath, 1971). The remnant of the island lay within the 50 cm. isopach of tephra from the 1970 eruption, and in December 1970 the whole island was observed to be covered in new ash (personal communication from B. J. Peters). Samples of surface tephra were collected at this time from sites A and B (Fig. 3) on sampling occasion III.

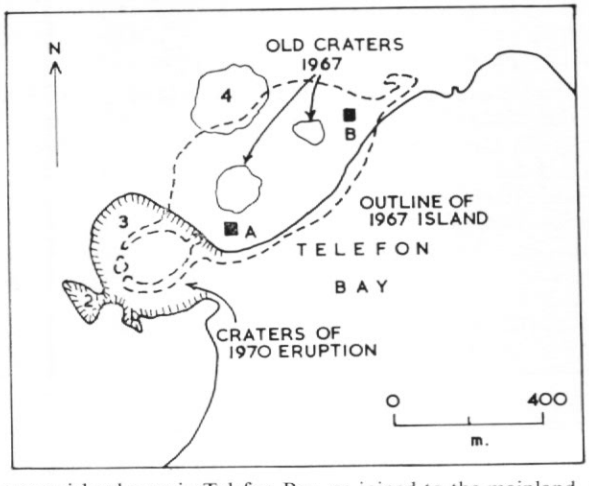

Fig. 3. Sketch map of the new island area in Telefon Bay, as joined to the mainland, in December 1970 (after Baker and McReath, 1971). The pecked line indicates the outline of the 1967 island. The craters of the 1970 eruption are also shown.
■ Sites from which samples of tephra were collected for protozoological examination in December 1970.

There has been no report of any volcanic activity since 1970, but on sampling occasion IV, in February 1973, the topography of the "island" had changed again, apparently because of slumping of solid material (personal communication from Sir Vivian Fuchs and M. R. A. Thomson). Samples of surface tephra were again collected from two sites (Fig. 4) chosen to correspond as closely as possible with sites A and B of previous sampling occasions. This material was considered to be 30 month old tephra from the 1970 eruption.

No Protozoa were recorded from samples collected at either site on sampling occasions I, II or III. In the samples collected on occasion IV, three small flagellate species were observed. No macroscopic vegetation was present in any of the samples and the loss on ignition of the

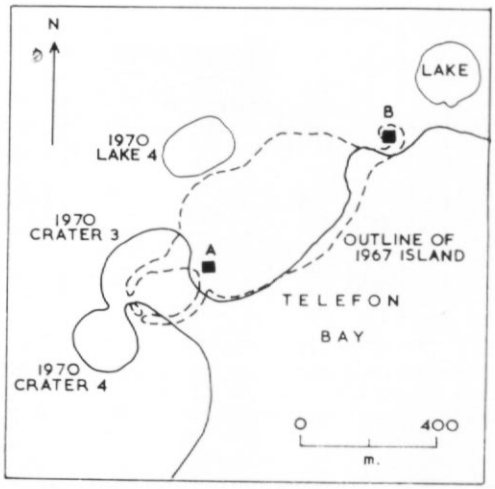

Fig. 4. Sketch map of the new island area in Telefon Bay, in February 1973 (personal communication from Sir Vivian Fuchs). The pecked line indicates the outline of the 1967 island.
■ Sites from which samples of tephra were collected for protozoological examination in February 1973.

material never exceeded 1 per cent except in the case of the sample from site A on sampling occasion IV. The results for samples from the two sites are summarized in Tables I and II.

Land centre of the 1967 eruption

In addition to the submarine eruption in Telefon Bay, a land centre of eruptive activity arose in December 1967 on the north side of Port Foster, about half-way between Telefon Bay and Pendulum Cove (Fig. 1). In December 1968 this was observed by Baker and others (1969) to have formed a water-filled crater 180 m. in diameter. To the south-west of this crater the ground was observed by Collins (1969) to be covered with ash and fragmenting bombs and lapilli through which fumaroles were continuously emitting steam. Here extensive areas had been colonized by moss species of the family Funariaceae, the colonization being facilitated, presumably, by the moisture and heat provided by the fumaroles (Collins, 1969). Like the new

TABLE I. RESULTS FROM TEPHRA COLLECTED FROM THE NEW ISLAND IN TELEFON BAY (SOUTH-WEST END): SITE A

Sampling occasion	*Date*	*Age of tephra* (months)	*Composition*	*pH*	*Moisture* (per cent dry weight)	*Loss on ignition* (per cent dry weight)	*Protozoan species recorded*
I	10.12.68	12	Dust, ash, lapilli	4·8±1·0	—	0·09±0·02	None
II	11.12.69	24	Dust, ash, lapilli	*c.* 6·2	—	0·19±0·10	None
III	18.12.70	4	Dust, ash, lapilli	6·8±0·1	—	0·31±0·13	None
IV	22.2.73	30	Dust, ash, lapilli	7·2±0·2	13·1±1·1	1·1±0·9	*Oikomonas termo* *Cercomonas longicauda* *Sainouron mikroteron*

TABLE II. RESULTS FROM TEPHRA COLLECTED FROM THE NEW ISLAND IN TELEFON BAY (NORTH-EAST END): SITE B

Sampling occasion	*Date*	*Age of tephra* (months)	*Composition*	*pH*	*Moisture* (per cent dry weight)	*Loss on ignition* (per cent dry weight)	*Protozoan species recorded*
I	10.12.68	12	Dust, ash, lapilli	4·7±0·3	—	0·14±0·05	None
II	11.12.69	24	Dust, ash, lapilli	*c.* 6·0	—	0·23±0·11	None
III	18.12.70	4	Dust, ash, lapilli	6·5±0·2	—	0·28±0·06	None
IV	22.2.73	30	Dust, ash, lapilli	7·2±0·2	19·4±1·4	0·55±0·06	*Sainouron mikroteron* *Cercomonas longicauda*

island, the land centre was unaffected by the 1969 eruption (Baker and others, 1969), so that in December 1969 the tephra of the 1967 eruption were still at the surface and were observed to contain the same moss (personal communication from T. G. Davies). A sample of the moss together with the 24 month old tephra in which it was growing was collected at this time (sampling occasion II).

In contrast to the vegetation-free tephra of the same age on the new island, which contained no Protozoa, six species of Protozoa (three flagellates and three ciliates) were recorded from this material which had a lower pH (5·5) and a greater loss on ignition (2·1 per cent dry weight) (Table III).

TABLE III. RESULTS FROM TEPHRA COLLECTED FROM THE LAND CENTRE OF THE 1967 ERUPTION

Sampling occasion	*Date*	*Age of tephra* (months)	*Composition*	*pH*	*Moisture* (per cent dry weight)	*Loss on ignition* (per cent dry weight)	*Protozoan species recorded*
I	—	—	—	—	—	—	—
II	11.12.69	24	Dust, ash, with moss (Funariaceae)	5·5±0·5	—	2·1±0·5	*Oikomonas termo* *Polypseudopodius bacterioides* *Cercobodo agilis* *Chilophrya* sp. *Enchelys* sp. *Oxytricha pellionella*
III	—	—	—	—	—	—	—
IV	22.2.73	30	Dust, ash, lapilli	6·3±0·1	10·8±0·4	0·57±0·08	*Oikomonas termo* *Cercomonas longicauda* *Sainouron mikroteron*

As a result of the eruption in August 1970, the land-centre crater lake was obliterated by a lahar (Baker and McReath, 1971) and the fumarole area covered by new ash and lapilli. Like the new island area, this area lay within the 50 cm. isopach and was observed in February 1973 to contain no macroscopic vegetation (personal communication from M. R. A. Thomson); a sample of the 30 month old tephra of the 1970 eruption was collected at this time (sampling occasion IV). This material had similar properties to that collected at the same time from the new island, except for a lower pH, and the same three protozoan species were recorded from it. The results for samples collected from the 1967 land centre are summarized in Table III.

Cathedral Crags and Collins Point

The eruption of February 1969 occurred along fissures on the western slopes of Mount Pond (Fig. 1). The pyroclastic ejecta produced by this eruption were, unlike the ash produced by the 1967 and 1970 eruptions, large lapilli and were deposited over an area extending due south of the eruptive fissure (Baker and others, 1969). Both of the sites sampled for protozoological investigation (one 200 m. north of Cathderal Crags; the other 200 m. west of Collins Point) lay between the 5 and 10 cm. isopachs. A later fall of fine ash was distributed in area south-west of the fissures, extending over Mount Kirkwood and Wensleydale Beacon, so that the Cathedral Crags site lay about 1·5 km. east of the south-east limit of the fine ash fall, whilst the Collins Point site lay just within this limit (Baker and others, 1969).

Samples of tephra from these sites were first collected in November and December 1969 (sampling occasion II); no Protozoa were observed in the large cinder-like lapilli from Cathedral Crags but two small flagellate species were recorded from the ash from Collins Point, although this material was only 10 months old.

The southern half of Deception Island was unaffected by the eruption in August 1970 (Baker and McReath, 1971), so samples of tephra collected from these sites in December 1970 (sampling occasion III) and in February 1973 (sampling occasion IV) were considered to be material from the 1969 eruption. The numbers of species recorded from the samples showed increases with each successive sampling, the numbers in the samples from Collins Point being always greater than in those from Cathedral Crags. The sample collected from Collins Point in February 1973 comprised shoots of the moss *Polytrichum alpinum* intimately mixed with fine volcanic ash. The regeneration of *Polytrichum alpinum* through volcanic ash at Collins Point, following the 1967 eruption, has been described in detail by Collins (1969); he described this species as the most efficient, of the mosses common on Deception Island, at growing up through an ash covering to reach a new surface. Nine species of Protozoa (four flagellates and five ciliates) were recorded from this sample, which had a loss on ignition of 13·7 per cent, compared with five species (two flagellates and three ciliates) in the vegetation-free sample collected at the same time from Cathedral Crags, which had a loss on ignition of only 1·3 per cent.

The results for all of the samples collected from the Cathedral Crags and Collins Point sites are summarized in Tables IV and V.

Discussion

Rate of colonization

Pooling the results from all five sites, there is a clear correlation between the numbers of species of Protozoa recorded from the samples and the age of the tephra from which the samples were taken (rank correlation: $\rho = 0{\cdot}724$, $P < 0{\cdot}01$) (Fig. 5). A linear regression line plotted through the points for vegetation-free tephra ($y = -1{\cdot}08 + 0{\cdot}114x$) intercepts the y-axis at a negative value. This indicates that there was a lag phase before the new tephra began to be colonized by Protozoa. Chemical analyses of bombs produced by the three eruptions on Deception Island (Baker and others, 1969; Baker and McReath, 1971) showed them to be composed of dark scoriaceous glass (alumina and silica together constituting 71–78 per cent) with small amounts of Fe^{+++}, Fe^{++}, Mg^{++}, Ca^{++}, Na^{+}, K^{+}, Ti^{++++}, Mn^{++} and phosphate. Therefore, many of the necessary mineral elements for living organisms were present in the tephra from the time of deposition, but the essential elements C and N were absent. Accordingly, once the tephra had cooled to temperatures suitable for living organisms, the first ones

TABLE IV. RESULTS FROM TEPHRA COLLECTED FROM CATHEDRAL CRAGS

Sampling occasion	*Date*	*Age of tephra* (months)	*Composition*	*pH*	*Moisture* (per cent dry weight)	*Loss on ignition* (per cent dry weight)	*Protozoan species recorded*
I	—	—	—	—	—	—	—
II	27.11.69	9	Large lapilli	—	—	0·04±0·01	None
III	18.12.70	22	Large lapilli	6·3±0·2	—	0·04±0·01	*Cercomonas longicauda*
IV	23.2.73	48	Disintegrating lapilli	6·3±0·1	19·6±1·6	1·33±0·14	*Oikomonas termo* *Polypseudopodius bacterioides* *Chilophrya* sp. *Dileptus* sp. *Oxytricha pellionella*

TABLE V. RESULTS FROM TEPHRA COLLECTED FROM COLLINS POINT

Sampling occasion	*Date*	*Age of tephra* (months)	*Composition*	*pH*	*Moisture* (per cent dry weight)	*Loss on ignition* (per cent dry weight)	*Protozoan species recorded*
I	—	—	—	—	—	—	—
II	11.12.69	10	Dust, ash, lapilli	*c.* 6·4	—	0·53±0·42	*Cercobodo agilis* *Sainouron mikroteron*
III	18.12.70	22	Dust, ash, lapilli	6·5±0·4	—	0·15±0·07	*Cercobodo agilis* *Sainouron mikroteron*
IV	23.2.73	48	Dust, ash, with shoots of moss (*Polytrichum alpinum*)	5·5±0·3	56·8±9·4	13·7±3·8	*Oikomonas termo* *Bodo saltans* *Cercomonas longicauda* *Sainouron mikroteron* *Enchelys* sp. *Holophrya* sp. *Lacrymaria* sp. *Leptopharynx sphagnetorum* *Oxytricha pellionella*

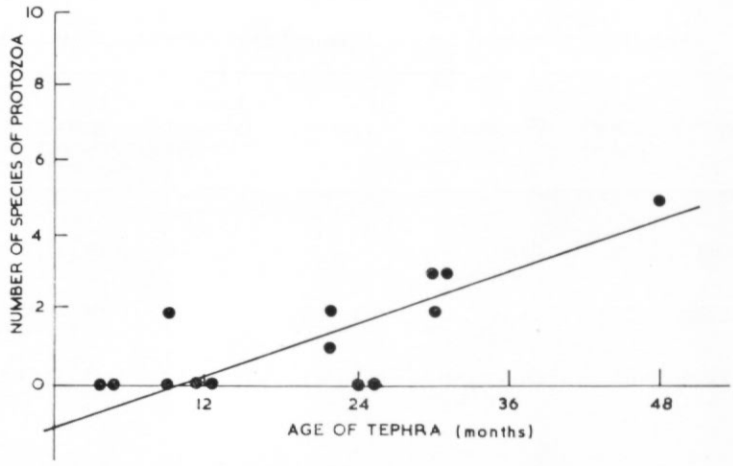

Fig. 5. Association between the numbers of species of Protozoa inhabiting vegetation-free volcanic tephra on Deception Island and the age of the tephra.

to colonize it must have been, presumably, nitrogen-fixing autotrophs, probably bacteria or blue-green algae. (Microbiological analysis of eight samples from the new island and the nearby mainland collected in January 1969 (Cameron and Benoit, 1970) showed that aerobic and anaerobic bacteria, fungi and yeasts were present in the 13 month old tephra, two of the samples containing bacteria which grew on a nitrogen-free medium. Henriksson and others (1972) showed that pioneer blue-green algae were fixing nitrogen in the juvenile soil on the volcanic island of Surtsey, Iceland.) Once an adequate supply of nitrogenous and organic matter had been built up in the tephra, saprophytic and bacteriophagous organisms could then colonize. From the present data it seems likely that, in the absence of colonization by mosses, the cooling of the tephra and microbial pioneer colonization occupied the first 9 months after deposition of the tephra. After this time it appears (Fig. 5) that the tephra aquired colonizing species of Protozoa at an arithmetic rate of 1·4 species per year, at least for the first 4 years.

The numbers of species of Protozoa in the samples are also closely correlated with the loss on ignition of the tephra (rank correlation: $\rho = 0{\cdot}802$, $P < 0{\cdot}001$) as shown in Fig. 6; it is

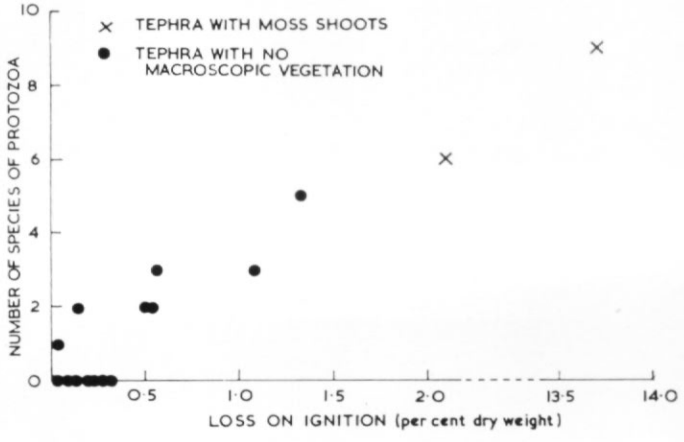

Fig. 6. Association between the numbers of protozoan species inhabiting volcanic tephra on Deception Island and the loss on ignition of the tephra.

therefore possible that the rate of colonization by Protozoa was determined by the rate at which organic matter accumulated in the tephra. This rate itself may have been limited by the low moisture content of the tephra which was less than 20 per cent dry weight in all the moss-free samples collected on sampling occasion IV. Observations made by Collins (1969) in December 1968 indicated that lack of moisture was the main factor limiting colonization of the new island in Telefon Bay by mosses; Brock (1972) recorded that the distribution of living organisms on Surtsey, Iceland, seemed closely associated with the availablility of moisture.

Tephra in which mosses were present contained more species of Protozoa than did vegetation-free tephra of the same age, indicating that colonization by mosses influenced considerably the ability of terrestrial Protozoa to inhabit the tephra. It is suggested that the moss had this influence both because it provided more suitable niches for species of Protozoa arriving on the tephra independently of the moss as wind-borne cysts, and also because colonizing moss propagules, whether arriving aerially or growing up to the moss surface from below, would probably have carried microbial organisms with them.

Composition of the colonizing fauna

The five small species of flagellate, *Oikomonas termo*, *Polypseudopodius bacterioides*, *Cercobodo agilis*, *Cercomonas longicauda* and *Sainouron mikroteron*, appear to have been the pioneer protozoan colonizers of vegetation-free tephra on Deception Island. The first four of these species have been recorded from established terrestrial habitats in the maritime Antarctic (Smith, 1972, 1973) and from many other regions of the Earth (Sandon, 1927). In particular, *O. termo* and *C. longicauda* have wide ecological amplitudes and are extremely common and widespread in terrestrial habitats; it is therefore not surprising that they should be among the pioneer colonizers of a newly created habitat. *Sainouron mikroteron* is a much more rare species but it was one of four species recorded by Smith (1970) from a sample of tephra collected in 1968 from Surtsey, Iceland. It is therefore possible that this species is particularly well adapted to colonizing volcanic tephra.

Ciliate species occurred only in the three samples which had the highest values for loss on ignition; in two of the samples (land centre, sampling occasion II; Collins Point, sampling occasion IV), this was obviously associated with the presence of mosses. It seems likely that quantities of organic matter in the tephra greater than 1·3 per cent are an essential pre-requisite for the tephra to hold water micro-films large enough to accommodate cells the size of these ciliate species (30–80 μm.). The species recorded are common inhabitants of moss and soil; however, *Lacrymaria* sp. has not previously been recorded from the Antarctic.

Differences between the eruptions

If the data on the samples of tephra from the three euptions are considered separately, it is clear that colonization by Protozoa proceeded more quickly in the tephra from the 1969 eruption than in those from the 1967 and 1970 eruptions. The sample of tephra collected from Collins Point in December 1969 (sampling occasion II) contained two species of Protozoa, although it was only 10 months old (and most of those winter months), whereas no species at all were recorded from the samples of 1967 tephra collected from the new island, even when it was 24 months old. Similarly, the samples of 1970 tephra collected from the new island and the land centre contained only three species 30 months after the eruption. This difference suggests that some property of the 1969 tephra, not shared by those of the 1967 and 1970 eruptions, hastens the rate of colonization by living organisms. Evidence that this property may be the mineral nutrient status of the tephra is provided by data on the chemical composition of volcanic bombs produced by three eruptions (Baker and others, 1969; Baker and McReath, 1971). These indicate that several sampled bombs from the 1967 and 1970 eruptions, collected from the new island and the land centre, are very similar to one another, but different from bombs from the 1969 fissure. The 1969 bombs are richer in Fe^{+++}, Fe^{++}, Mg^{++} and Ca^{++} but poorer in Na^{+}, K^{+} and P_2O_5 than the 1967 and 1970 bombs. It is therefore possible that slight differences in the relative proportions of mineral ions could have created conditions in the 1969 tephra in which biological colonization could proceed at a faster rate.

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