VEGETATION RE-EXPOSED AFTER BURIAL BY ICE AND ITS RELATIONSHIP TO CHANGING CLIMATE IN THE SOUTH ORKNEY ISLANDS

By J. H. C. FENTON

ABSTRACT. At Signy Island, South Orkney Islands, and other localities in the maritime Antarctic, remains of former vegetation have recently been exposed after burial under semi-permanent snow patches that have now decreased in size. The relationship between snow-patch size and climate is considered and it is concluded that, until more is known about how these snow patches react to changes in the various climatic variables, it is difficult to identify any firm relationship between variation in their size and changes in climate. Re-exposed vegetation has been radiocarbon dated in order to determine the time of burial. It is concluded that on Signy Island the ice cover fluctuates around a mean close to the present-day levels and there have been at least three minor ice advances/retreats since A.D. 1450.

THE climate and glacial history of the maritime Antarctic during the last 500 years remain largely unknown; Collins (1976) has reviewed the evidence for past climatic changes with particular reference to Signy Island, South Orkney Islands (lat. 60°43′S, long. 43°38′W). He reported moss turves that have recently been exposed after burial under now shrinking semi-permanent snow patches. This paper considerably extends the list of sites at which vegetation has been re-exposed, both in the South Orkney Islands and elsewhere, and includes sites where vegetation is known still to be buried. Radiocarbon dating of the moss peat has provided a means of dating the burial of the vegetation; the possibility of relating these dates to past climatic changes is discussed with particular regard to what is known of the factors controlling snow-patch size.

THE SITES OF RE-EXPOSED VEGETATION

The locations of 35 sites, at which vegetation has recently been re-exposed on Signy Island, are shown in Fig. 1 and details of each are given in Table I. Details of re-exposed vegetation observed at other localities, two on Coronation Island, South Orkney Islands, and three on islands off the west coast of the Antarctic Peninsula, are given in Table II.

As the snow patches under which the vegetation has been buried have persisted for many seasons, most of the snow in them has been transformed into ice; at the present time the winter accumulation of snow often melts completely or becomes superimposed ice, so that at the end of the ablation season a surface of smooth ice is revealed. Although the ice adjacent to sites 13–19, 21–26 and 29–32 is connected to the small slow-moving McLeod Glacier, it is in fact stationary and is considered here as though it were a snow patch. This area south-east of McLeod Glacier is where re-exposed vegetation is most abundant. Fig. 2 illustrates a *Chorisodontium aciphyllum*-dominated moss bank in this area (site 24), the lower half of which has been buried by ice and subsequently re-exposed. In the foreground is the snow patch at the end of the ablation season with the re-exposed peat immediately above it; it is possible that there is some moss peat still buried. A surface sample of the peat nearest the ice edge has been dated at A.D. 1425–1535. The healthy living moss, which at the nearest is 4 m vertically above the ice level, is visible at the top and has probably never been covered by ice for it is above the lichen "trim line". The trim line is the line below which there are no lichens growing on the rocks, indicating that the rocks have recently been covered by snow or ice and have not yet been re-colonized by lichens. Hooker (1977) stated that colonies of the lichen *Rhizocarpon geographicum* growing above the trim line could be as much as 500–700 years old. Between the living and most recently exposed moss shown in Fig. 2 is an area where crustose lichens (visible as white specks and mainly of *Ochrolechia frigida*)

TABLE II. SITES OF OTHER RE-EXPOSED VEGETATION

Site number	*Locality*	*Altitude* (m)	*Distance of vegetation from nearest ice edge* (m)	*Dominant species*	*Notes*
36	Cape Hansen, Coronation Island, South Orkney Islands	*c.* 70	*c.* 5 (13 March 1974)	*Chorisodontium aciphyllum*	Dead turf *c.* 15 cm deep on gently sloping scree
37	Near Shingle Cove, Coronation Island, South Orkney Islands	*c.* 150	0 (March 1975)	*Polytrichum alpestre* *Chorisodontium aciphyllum*	A *c.* 10 m by 10 m moss bank on a 25° slope; *c.* 20 cm deep with dead moss nearest the ice edge extending to living moss away from it. Some moss still buried
38	Litchfield Island, Arthur Harbour, Anvers Island (lat. 64°45′S, long. 64°10′W)	*c.* 10	1–2 (vertical) (24 December 1975)	*Polytrichum alpestre*	A *c.* 15 m by 15 m moss bank on a 25° slope. Most of the bank is living though the lowest 3 m (vertically) has been killed by previous advance of a small semi-permanent snow patch
39	Bonaparte Point, Anvers Island (lat. 64°47′S, long. 64°05′W)	—	0–12 (7 February 1977)	*Polytrichum alpestre* with some *Chorisodontium aciphyllum*	Remains of the base of moss banks re-exposed by retreat of snout of Marr Ice Piedmont (see Smith 1981)
40	Galindez Island, Argentine Islands (lat. 65°15′S, long. 64°15′W)	5–30	See notes	See notes	Where *Polytrichum alpestre* moss banks terminate above snowdrifts, their edges have often been killed. There are also areas of dead re-exposed *Drepanocladus uncinatus* carpets, including one *c.* 15 m in diameter with 20–25 cm high hummocks of *Polytrichum alpestre*. There has been up to 2 m vertical retreat of snow (February 1976)

Table I. Details of sites of re-exposed vegetation on Signy Island in late summer, 1975

Site number	Grid reference	Altitude (m)	Distance of vegetation from nearest ice edge (m)	Dominant species	Notes
1	102^1 048^2	80	Snow patch now almost vanished	*Chorisodontium aciphyllum*	The lowest 25 cm of this small moss bank has been blackened and killed by a previous advance of this snow patch
2	102^0 048^0	80	Snow patch now almost vanished	*Chorisodontium aciphyllum*	The lowest 25 cm of this small moss bank has been blackened and killed by a previous advance of this snow patch
3	102^9 047^4	20	25	*Drepanocladus uncinatus*	Most of this dead moss carpet now eroded by a melt stream
4	102^7 047^2	40	0–*c*. 5	*Polytrichum juniperinum*	Re-exposed rock outcrop *c*. 30 m by 25 m rising 2 m above the surrounding ice. Moss consists of dead *Polytrichum* turves up to 10 cm thick and species characteristic of marble knolls (all dead)
5	102^8 047^2	45	35	*Andreaea* sp.	Small patch of dead *Andreaea*
6	102^7 047^2	45	3 (vertical)	*Polytrichum* sp.	Dead moss on a rock platform above the ice edge; a small eroded patch of dead *Calliergon sarmentosum* nearby
7	102^6 047^1	40	0–20	*Andreaea* spp. *Calliergon sarmentosum* *Drepanocladus uncinatus* *Chorisodontium aciphyllum*	Extensive ice retreat here with dead re-exposed moss areas and some re-colonization by *Pohlia nutans*
8	102^6 047^0	40	*c*. 20	*Andreaea* spp. *Calliergon sarmentosum* *Drepanocladus uncinatus* *Chorisodontium aciphyllum*	Extensive ice retreat here with dead re-exposed moss areas and some re-colonization by *Pohlia nutans*
9	102^4 046^8	75	*c*. 5	*Chorisodontium aciphyllum*	Edge of a small moss bank has been killed
10	102^8 046^1	20	12	*Chorisodontium aciphyllum*	A 4 m by 10 m area of dead discontinuous moss turf
11	102^8 046^1	20	10	*Chorisodontium aciphyllum*	A 10 m by 4 m turf, mostly dead, although the moss more than 18 m from the ice edge still living
12	102^8 045^9	20	1	Not seen	A possible area of re-exposed moss but obscured by melt water
13	103^3 044^0	190	<5	*Andreaea* sp. *Himantormia lugubris* *Sphaerophorus globosus*	A moss–lichen community re-exposed during the 1974–75 summer
14	103^4 043^8	85	Still under ice; 1 m in from edge	*Chorisodontium aciphyllum*	Dead moss bank at least 20 cm deep and under 1.5 m of ice (4 April 1974) (Fig. 3)
15	103^4 043^8	85	0–6	*Chorisodontium aciphyllum*	Small moss turf continuous to the ice edge; some moss still buried under 65 cm of ice and moss more than 5 m from ice edge is still living
16	103^5 043^8	80	0–2	*Chorisodontium aciphyllum*	Dead turf *c*. 15 cm deep on level ground. Between 4 April 1974 and 7 April 1975, ice retreated 170 cm with some moss still under ice
17	103^5 043^8	80	0–7	*Chorisodontium aciphyllum*	Continuous shallow turf 10 cm deep; 1–2 m living moss at top of slope then 5 m dead turf to ice edge with some moss still buried (Fig. 3)
18	103^6 043^7	70	*c*. 1	*Chorisodontium aciphyllum*	A continuous turf, the lower *c*. 1 m of which has been killed
19	103^6 043^7	70	0–2	*Chorisodontium aciphyllum*	Re-exposed dead moss on a ledge vertically below a living moss bank. There was a vertical ice retreat of 1.5–2 m in the 1974–75 summer
20	102^9 043^5	104	0–1	*Drepanocladus uncinatus*	Dead carpet *c*. 1 m² on outcrop in McLeod Glacier, probably exposed in the 1974–75 summer. The ice has diminished by 3–4 m in thickness since 1965 (personal communication from R. I. L. Smith)
21	102^9 043^5	104	0–1	*Usnea antarctica*	Re-exposed on same outcrop as site 20; *Himantormia lugubris* also present. Both species presumed dead
22	104^0 043^6	20	0–15	*Drepanocladus uncinatus*	A 15 m wide moss carpet on gently sloping ground with some moss still buried
23	103^9 043^6	25	n.m.	*Chorisodontium aciphyllum*	A small moss bank, the upper half living and the lower half dead but now well away from the ice edge
24	103^9 043^5	35	0.5 (vertical)	*Chorisodontium aciphyllum*	A large moss bank on a 25° slope; re-exposed moss from the lower half is 15–20 cm deep; 4 m vertically above the ice level, the moss is living and deep enough to have a permafrost (at 25 cm) (Fig. 2)
25	103^8 043^5	40	n.m.	*Andreaea* spp. *Drepanocladus uncinatus*	Many small patches of dead moss in this area
26	103^7 043^4	45	0	*Chorisodontium aciphyllum*	Largest area of re-exposed moss on Signy Island consisting of a turf 10–15 cm deep and *c*. 20 m by 50 m in area, on level ground about 2 m vertically above the present ice level. On one side it leads into a living moss bank; on the other some moss is still buried but the majority is now re-exposed
27	103^7 043^3	45	Snow patch now vanished	*Chorisodontium aciphyllum*	The outer 10–30 cm of this bank has been killed by a previous ice advance (evidence from trim lines)
28	104^0 043^2	20	*c*. 3	*Andreaea* sp. *Drepanocladus uncinatus*	Dead and probably re-exposed moss patches around frost boils
29	103^6 043^3	25	*c*. 10	*Drepanocladus uncinatus*	Patches of dead moss carpet
30	103^6 043^2	20	*c*. 10	*Drepanocladus uncinatus*	Patches of dead moss carpet
31	103^5 043^2	20	0	*Calliergon sarmentosum*	Dead moss carpet with some moss still under ice
32	103^4 043^2	20	0	*Chorisodontium aciphyllum* *Calliergon sarmentosum* *Polytrichum alpinum*	Dead moss patches, some still under ice
33	101^4 042^4	100	0	*Polytrichum alpinum* *Andreaea* sp. *Drepanocladus uncinatus*	Dead moss patches, some still under ice
34	101^4 042^3	90	*c*. 1 (vertical)	*Chorisodontium aciphyllum*	Moss turf 10–15 cm deep, most of which is living though the lower edge is killed, the boundary being 2 m vertically above the present ice level; probably no more moss buried
35	101^5 042^3	80	0	*Chorisodontium aciphyllum*	Dead re-exposed moss extending to living moss; also dead *Drepanocladus* nearby, some still buried

n.m. Not measured.
* From D.O.S. 210 Signy Island with 1 km grid, second edition, 1975.

Table I. Details of sites of re-exposed vegetation on Signy Island in late summer, 1975

Site number	*Grid reference*	*Altitude* (m)	*Distance of vegetation from nearest ice edge* (m)	*Dominant species*	*Notes*
1	102^{1} 048^{2}	80	Snow patch now almost vanished	*Chorisodontium aciphyllum*	The lowest 25 cm of this small moss bank has been blackened and killed by a previous advance of this snow patch
2	102^{0} 048^{0}	80	Snow patch now almost vanished	*Chorisodontium aciphyllum*	The lowest 25 cm of this small moss bank has been blackened and killed by a previous advance of this snow patch
3	102^{9} 047^{4}	20	25	*Drepanocladus uncinatus*	Most of this dead moss carpet now eroded by a melt stream
4	102^{7} 047^{2}	40	0–*c.* 5	*Polytrichum juniperinum*	Re-exposed rock outcrop *c.* 30 m by 25 m rising 2 m above the surrounding ice. Moss consists of dead *Polytrichum* turves up to 10 cm thick and species characteristic of marble knolls (all dead)
5	102^{8} 047^{2}	45	35	*Andreaea* sp.	Small patch of dead *Andreaea*
6	102^{7} 047^{2}	45	3 (vertical)	*Polytrichum* sp.	Dead moss on a rock platform above the ice edge; a small eroded patch of dead *Calliergon sarmentosum* nearby
7	102^{6} 047^{1}	40	0–20	*Andreaea* spp. *Calliergon sarmentosum* *Drepanocladus uncinatus* *Chorisodontium aciphyllum*	Extensive ice retreat here with dead re-exposed moss areas and some re-colonization by *Pohlia nutans*
8	102^{6} 047^{0}	40	*c.* 20	*Andreaea* spp. *Calliergon sarmentosum* *Drepanocladus uncinatus* *Chorisodontium aciphyllum*	Extensive ice retreat here with dead re-exposed moss areas and some re-colonization by *Pohlia nutans*
9	102^{4} 046^{8}	75	*c.* 5	*Chorisodontium aciphyllum*	Edge of a small moss bank has been killed
10	102^{8} 046^{1}	20	12	*Chorisodontium aciphyllum*	A 4 m by 10 m area of dead discontinuous moss turf
11	102^{8} 046^{1}	20	10	*Chorisodontium aciphyllum*	A 10 m by 4 m turf, mostly dead, although the moss more than 18 m from the ice edge still living
12	102^{8} 045^{9}	20	1	Not seen	A possible area of re-exposed moss but obscured by melt water
13	103^{3} 044^{0}	190	<5	*Andreaea* sp. *Himantormia lugubris* *Sphaerophorus globosus*	A moss–lichen community re-exposed during the 1974–75 summer
14	103^{4} 043^{8}	85	Still under ice; 1 m in from edge	*Chorisodontium aciphyllum*	Dead moss bank at least 20 cm deep and under 1.5 m of ice (4 April 1974) (Fig. 3)
15	103^{4} 043^{8}	85	0–6	*Chorisodontium aciphyllum*	Small moss turf continuous to the ice edge; some moss still buried under 65 cm of ice and moss more than 5 m from ice edge is still living
16	103^{5} 043^{8}	80	0–2	*Chorisodontium aciphyllum*	Dead turf *c.* 15 cm deep on level ground. Between 4 April 1974 and 7 April 1975, ice retreated 170 cm with some moss still under ice
17	103^{5} 043^{8}	80	0–7	*Chorisodontium aciphyllum*	Continuous shallow turf 10 cm deep; 1–2 m living moss at top of slope then 5 m dead turf to ice edge with some moss still buried (Fig. 3)
18	103^{6} 043^{7}	70	*c.* 1	*Chorisodontium aciphyllum*	A continuous turf, the lower *c.* 1 m of which has been killed
19	103^{6} 043^{7}	70	0–2	*Chorisodontium aciphyllum*	Re-exposed dead moss on a ledge vertically below a living moss bank. There was a vertical ice retreat of 1.5–2 m in the 1974–75 summer
20	102^{9} 043^{5}	104	0–1	*Drepanocladus uncinatus*	Dead carpet *c.* 1 m² on outcrop in McLeod Glacier, probably exposed in the 1974–75 summer. The ice has diminished by 3–4 m in thickness since 1965 (personal communication from R. I. L. Smith)
21	102^{9} 043^{5}	104	0–1	*Usnea antarctica*	Re-exposed on same outcrop as site 20; *Himantormia lugubris* also present. Both species presumed dead
22	104^{0} 043^{6}	20	0–15	*Drepanocladus uncinatus*	A 15 m wide moss carpet on gently sloping ground with some moss still buried
23	103^{9} 043^{6}	25	n.m.	*Chorisodontium aciphyllum*	A small moss bank, the upper half living and the lower half dead but now well away from the ice edge
24	103^{9} 043^{5}	35	0.5 (vertical)	*Chorisodontium aciphyllum*	A large moss bank on a 25° slope; re-exposed moss from the lower half is 15–20 cm deep; 4 m vertically above the ice level, the moss is living and deep enough to have a permafrost (at 25 cm) (Fig. 2)
25	103^{8} 043^{5}	40	n.m.	*Andreaea* spp. *Drepanocladus uncinatus*	Many small patches of dead moss in this area
26	103^{7} 043^{4}	45	0	*Chorisodontium aciphyllum*	Largest area of re-exposed moss on Signy Island consisting of a turf 10–15 cm deep and *c.* 20 m by 50 m in area, on level ground about 2 m vertically above the present ice level. On one side it leads into a living moss bank; on the other some moss is still buried but the majority is now re-exposed
27	103^{7} 043^{3}	45	Snow patch now vanished	*Chorisodontium aciphyllum*	The outer 10–30 cm of this bank has been killed by a previous ice advance (evidence from trim lines)
28	104^{0} 043^{2}	20	*c.* 3	*Andreaea* sp. *Drepanocladus uncinatus*	Dead and probably re-exposed moss patches around frost boils
29	103^{6} 043^{3}	25	*c.* 10	*Drepanocladus uncinatus*	Patches of dead moss carpet
30	103^{6} 043^{2}	20	*c.* 10	*Drepanocladus uncinatus*	Patches of dead moss carpet
31	103^{5} 043^{2}	20	0	*Calliergon sarmentosum*	Dead moss carpet with some moss still under ice
32	103^{4} 043^{2}	20	0	*Chorisodontium aciphyllum* *Calliergon sarmentosum* *Polytrichum alpinum*	Dead moss patches, some still under ice
33	101^{4} 042^{4}	100	0	*Polytrichum alpinum* *Andreaea* sp. *Drepanocladus uncinatus*	Dead moss patches, some still under ice
34	101^{4} 042^{3}	90	*c.* 1 (vertical)	*Chorisodontium aciphyllum*	Moss turf 10–15 cm deep, most of which is living though the lower edge is killed, the boundary being 2 m vertically above the present ice level; probably no more moss buried

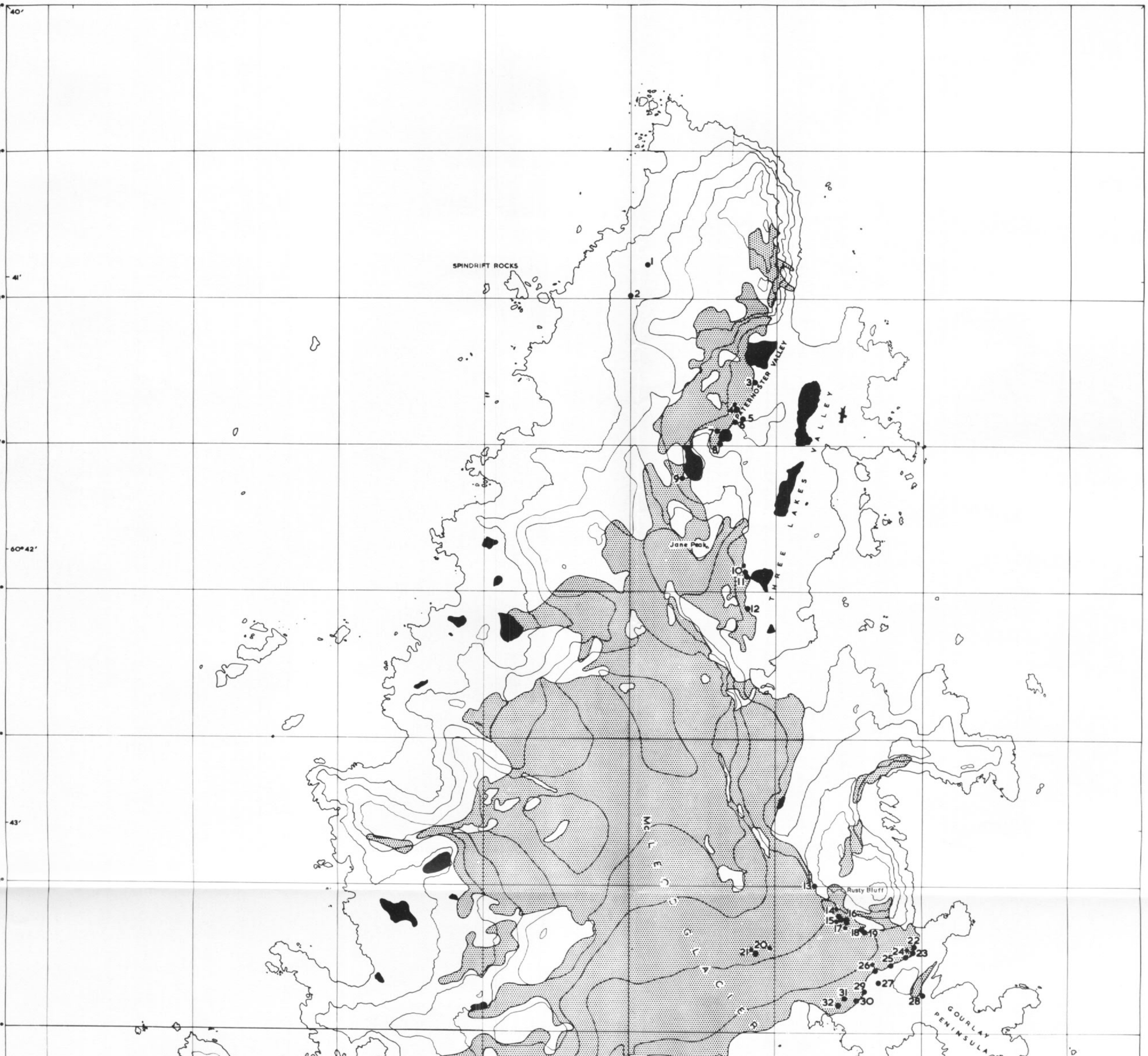

Fig. 1. Map of Signy Island showing the locations of the re-exposed sites listed in Table I. The asterisk (*) indicates a site with a radiocarbon date.

[face page 248

Fig. 2. Re-exposed site 24; the ... half of this *Chorisodontium* moss bank is still living, whereas the lower half has at one time been killed by ice advance. The pale rocks visible in the foreground are below the trim line. (Photograph taken 4 April 1974.)

and moss shoots have begun to colonize the dead moss, the first stage in the sequence of re-colonization described by Collins (1976).

Table I shows that a spectrum of community types, as found on Signy Island today (see Smith, 1972), has in the past been buried. In some localities the permanent ice edge is now well away from any re-exposed vegetation (e.g. sites 5, 10 and 11), whereas in others moss peat, visible where melt streams have eroded the ice, is still buried (e.g. site 14; Fig. 3).

Relationship between Climate and Snow-patch Size

Before attempting to relate dates of burial to past climatic changes, it is necessary to consider the relationship between climate and the presence of permanent snow patches. Climatic records for Signy Island have been maintained for the period 1947–present (Falkland Islands ..., Dependencies Meteorological Service, 1951–62; Pepper, 1954; British Antarctic Meteorological Service, 1964–70; Limbert and Loan, 1976*a*, *b*; Limbert, 1977*a*, *b*, 1979; British Antarctic Survey unpublished data) and there is also a complete record for nearby Laurie Island since 1904 (Servicio Meteorològico Nacional, Argentina, 1951; Limbert, 1974). The mean air temperature in December, January, February and March for 1948–75 was 0.0, 0.8, 0.9 and 0.1° C, respectively, and the mean annual air temperature for 1948–75 was −3.7° C (personal communication from D. W. S. Limbert). As these monthly means are near freezing point and diurnal fluctuations are slight, very minor changes in temperature will determine whether the precipitation falls as rain or snow, which will greatly influence the rate of summer ablation of the snow patches. The high degree of cloudiness of Signy Island is shown by the sunshine data, the annual mean for the period 1947–72 being 14.65% of the maximum possible (personal communication from D. W. S. Limbert).

The summer climatic regime of cloudiness, high humidity and low temperatures leads to a low ablation rate. It is probable that on Signy Island summer ablation is more important

Fig. 3. Site 14, where the moss peat (approximately under the ice-axe) was still buried under 1.5 m o[illegible]e on 4 April 1974, the date on which the photograph was taken.

than winter precipitation in controlling the balance of these snow patches; the ablation season is relatively short, 3 to 4 months, and thus a heavy snowfall in this period (which increases albedo as well as insulating the layers below) or the rare occurrence of heavy rain will have a disproportionate effect on the mass balance. Glaciological studies by Koerner (1964) at Hope Bay, northern Antarctic Peninsula, where the annual temperature regime is about 2° C cooler and where there is more than twice the sunshine recorded at Signy Island, have shown that what determines the height of the firn line at the end of the ablation season is not winter precipitation but the frequency of snowfalls, föhn conditions and violent south-south-west winds during summer. Similarly, studies by LaChapelle (1965) on a maritime temperate glacier in the Rocky Mountains showed that the type of spring and autumn precipitation, when the mean temperature is around freezing, disproportionally affects the glacier's budget for that year. Thus, snow patches will be particularly sensitive to small year-to-year changes in the summer climate.

There is also the possibility of a feed-back mechanism affecting the size of these snow patches; after a year of exceptional ablation, the snow patch becomes smooth, often dirty ice, the snow and firn having all melted. Thus, albedo is considerably reduced and the amount of winter accumulation will be less, since the dry winter snow is readily blown off the smooth ice by strong winds. Increased summer ablation, combined with less winter accumulation, may thus result in a positive feed-back situation; this process can occur over one or two seasons (Hoinkes, 1964) but whether it can occur over a longer period is unknown. Bradley and Miller (1972) also mentioned the possibility of the reverse situation occurring: positive feed-back reinforcing the ice advance. Thus it could be tentatively suggested that ice advance and retreat can occur without significant climatic changes.

The relationship between climate and mass balance of glaciers has been discussed by Hoinkes (1964) and Sugden and John (1976); the former stated that attempts to relate the overall budget of glaciers to any single climatic variable have not been too successful. For example, Lliboutry (1953) noted glacier advances in Patagonia in spite of higher summer temperatures; he attributed this to increased cloudiness and precipitation. Unlike glaciers, snow patches respond immediately to changes in climate because there is no time lag induced by mass transfer (glacier movement) as occurs in glaciers; indeed, because they normally exist near the equilibrium line, they are particularly sensitive to climatic changes. Bradley and Miller (1972) have reported the advance of snow patches on Baffin Island concurrent with a lowering of summer temperature and increased precipitation; on the other hand, nearby glaciers continued to retreat. On Signy Island, the mean annual air temperature since 1950 has been slightly higher than in the previous 50 years (Limbert, 1974) but sometime during the period 1950–60 (see below) several areas of vegetation were buried (sites 4, 20, 26 and 34) and are only now (mid-1970's) being re-exposed. Thus there is no direct correlation here between annual average air temperature and changes in snow cover. It should be noted that changes in mean annual air temperature on Signy Island are primarily due to changes in winter temperature, the means for the summer months showing little year-to-year change (Limbert, 1974). However, since 1959 there has been an increase in the precipitation frequency as well as a period of reduced sunshine (1963–68) to about 12% of the maximum possible (personal communication from D. W. S. Limbert), both of which will influence snow-patch size. Unfortunately, the accuracy of radiocarbon dating is such that the exact date of burial cannot be determined so that in this case no correlation between time of burial and any specific meteorological data can be made.

Other evidence that no great climatic change is needed to affect the size of semi-permanent snow patches is the fact that immediately prior to burial there seems to have been no change in the growth rate of the moss. In shoots of *Pohlia nutans* dissected out of a *Chorisodontium aciphyllum* moss bank, which has recently been re-exposed (site 24), annual growth segments were clearly visible, including etiolated growth of 2 mm in the last year, suggesting that shoot production continued under the snow before ceasing altogether. The year prior to this the growth was 2–3 mm and the year before that it was 3–5 mm, these increments being similar to the average for healthy *Chorisodontium* (Baker, 1972; Fenton, 1980). The growth rate of *Polytrichum alpestre* from a re-exposed bank has also been measured (site 37); here it cannot be certain whether the present re-exposed surface is exactly the same as the old pre-burial surface, although it will be within 1 or 2 cm of it. At this site, the annual growth increment at the surface varies from 3 to 4 mm, again similar to the present-day mean (Longton, 1970; Fenton, 1980); in the previous year it averaged 1–4 mm.

The pattern of ice retreat at some of the re-exposed sites has been traced over three seasons using fixed stakes at the ice margin; the total retreat of the permanent ice for the 1974–75 summer at site 17 was 95 cm, whereas at sites 24 and 25 there was no retreat. This was because of a storm in late February when much snow drifted against the latter two sites but none against site 17. During 1975–76 summer there was no ice retreat at any of the sites at the south-east of McLeod Glacier probably because of snowfalls throughout March 1976; this contrasts with the 1973–74 summer when the ice retreated 60 cm in the last 3 weeks of March 1974. It appears that the weather during March will be the most critical in determining the current year's balance of these snow patches and that the rate of ice retreat will vary from season to season. It should be noted that a given change in snow depth will expose or cover a greater area of substrate on level as opposed to sloping ground.

Thus, in an area like Signy Island, where air temperatures in the ablation season fluctuate around a mean within 1 deg of 0° C, snow patches will be particularly sensitive to minor changes in one or more of the climatic variables and it is even possible that they react to year-to-year changes too small to be easily detectable in the meteorological records. Until more is known about their response to climatic change, it will be difficult to correlate variations in their size with any particular climatic change.

Date of Burial of Vegetation

The approximate date of burial of the vegetation was determined by radiocarbon dating samples taken from the top of the exposed surface and as near the ice edge as possible or, in one instance (site 15), from under the ice. All but one of the radiocarbon dates determined fall within the "modern" category. Unfortunately, this results in ambiguity for, because of the burning of fossil fuels since the eighteenth century, a given ^{14}C determination can result in two different dates (Pennington and others, 1976). Table III lists the possible age ranges into which the samples fall (the ranges are a function of the accuracy of the dating), for most samples there being two possible ages. The Signy Island samples fall into three groups: one relatively old sample dated at A.D. 1425–1535, eight samples dated in the period 1700–1940 and four post-1950 samples. These results are illustrated graphically in Fig. 4.

For most of the sites, including the two on Coronation Island (both are within 4 km of the north-east of Signy Island), there are two periods in which the ice advance could have taken place, *c.* 1720–1850 or *c.* 1900–40. What evidence is there in favour of either of these? At site 15, a moss bank much of which is still buried by ice, a sample from the surface of the buried moss has been dated at either 1733–1843 or 1900–35 and a sample from the base as either 1814–1944 or 1850–1910. Now, unless the moss bank has been grossly distorted by the ice advance, and observations of other re-exposed moss banks suggest this is unlikely, the surface of the moss bank must be younger than the base. In this case, the younger radiocarbon ages must be the correct ones, i.e. the general ice advance was in the period 1900–40. On the other hand, a sample from a *Chorisodontium* turf 30 cm deep (site 10/11) has been dated at either 1661–1731 or 1900–35 (Collins, 1976). This sample was taken from the base of the turf and there must have been about 100 years' growth before the moss was buried, assuming an annual growth increment of 3 mm year^{-1} (Collins, 1976), so that the date of burial must have been in the period 1761–1831 as a date of 2000–35 is obviously impossible. In this case, the older radiocarbon date must be the correct one, i.e. the ice advance must have been in the period 1720–1850. Thus there is conflict of results and all that can be concluded is that there were one or even two ice advances in the period 1720–1940.

The four sites dated as post-1950 may, as stated above, be correlated with a period of increased precipitation frequency even though the mean temperature was slightly higher than in the previous 50 years. This increase in snow-patch size must have been very temporary, for Collins (1976) gave evidence of extensive ice retreat in 1961. This supports the statement given above that the size of a snow patch is very sensitive to small changes in climate.

The oldest radiocarbon date, 1425–1535 at site 24 (Fig. 2), appears slightly anomalous; the sample was taken from the surface of the moss nearest the ice edge and must reflect the

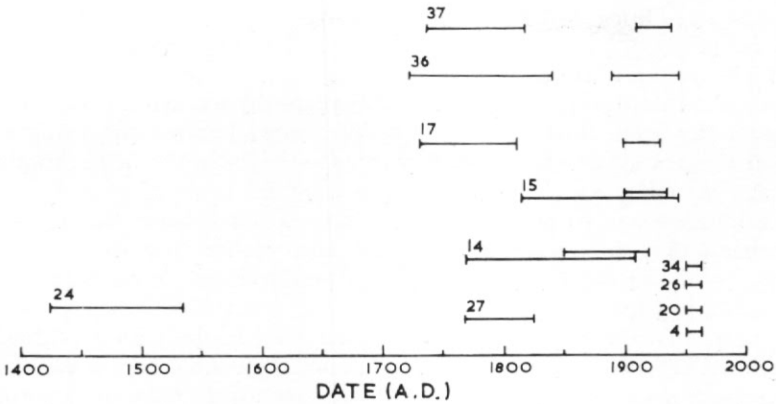

Fig. 4. Dates of burial of re-exposed moss on Signy and Coronation Islands. The numbers refer to the sites listed in Table I.

TABLE III. DATES OF BURIAL OF RE-EXPOSED VEGETATION

Site number	*Possible dates of burial* (A.D.)	*Notes and sampling date*
4	Post-1950	Sample taken from a turf *c.* 10 cm thick (20 March 1975)
10/11*	1661–1731 or 1935–50	These dates give the age of the base of a 30 cm deep turf; *c.* 100 years growth would have taken place before burial (data from Collins (1976))
14	1770–1910 or 1850–1920	Sample taken from moss >20 cm thick still under 1.5 m of ice (4 April 1974)
15	1733–1843 or 1900–35	Sample from surface of moss turf still under 65 cm of ice (4 April 1974)
15	1814–1944 or 1850–1910	Sample from base of moss turf (4 April 1976)
17	1731–1811 or 1900–30	(7 April 1975)
20	Post-1950	(4 March 1975)
21	1799–1909 or 1850–1910	This date may reflect the age of the lichen, which could be 50–200 years old, rather than the date of burial (7 April 1975)
24	1425–1535	(7 April 1975)
26	Post-1950	Sample taken *c.* 4–5 m from the ice edge (7 April 1975)
34	Post-1950	Sample taken *c.* 2 m from ice edge and 0.5 m vertically above it (7 April 1975)
36	1722–1842 or 1890–1945	(13 March 1974)
37	1738–1818 or 1910–40	(17 April 1975)
39	1270–1565	Dates from Smith (1981) (7 January 1977). The dates probably relate to the commencement of moss-bank development rather than time of removal by the advancing ice sheet

* Uncertain whether sample from site 10 or 11.

time at which it was buried and killed, although it is surprising that since that time it has never been re-colonized or eroded. This suggests either that it has been buried until the present day or that it has been so near the ice margin that re-colonization has not been able to occur. This would suggest that during the past 400–500 years the ice margin must have remained near the present-day level, fluctuating only a few metres because the living moss on this bank, which at the nearest is 4 m above the ice edge, is above the lichen trim line and can never have been buried. These slight fluctuations have left some areas of ground free from permanent ice long enough to be colonized by mosses and lichens; the depth of the moss turf would suggest that this ground would have been ice-free for about 100 years before a slight change in one or more climatic variables produced an ice advance of the order of a few metres and killed the vegetation.

Thus, it appears that there has been one such advance in the period 1425–1535, at least one in the period 1720–1940 and another in the period 1950–61. There may, of course, have been other advances since 1425 which have not been recorded. Since the growth rate of the moss at the time of burial was similar to present-day growth rates, it seems probable that the climate was also similar. In addition, growth-rate studies on *Polytrichum* and *Chorisodontium* moss banks have shown that there could not have been major changes in climate over the past 200 years and that a particular *Chorisodontium*-dominated moss bank on the west coast of Signy Island, which has been studied in detail, has probably been growing continuously for *c.* 1 000 years (Fenton, 1980). The base of another moss bank in the same area has been dated at 4 801±300 years B.P. (Fenton and Smith, 1981); thus, parts of Signy Island must have been ice-free and favourable for moss growth for the past *c.* 5 000 years. It may perhaps be concluded, therefore, that no major climatic changes have occurred in the past 5 000 years, although minor fluctuations in climate may have altered the area of permanent snow on Signy Island. It is probable that small changes in the amount of snow cover occur continuously around a mean within a few metres of the present-day level, although, until the main factors responsible are determined, it is not possible to correlate changes in snow-patch size with changes in any specific climatic variable.

ACKNOWLEDGEMENTS

I must particularly thank Dr D. D. Harkness of the Scottish Universities Research and Reactor Centre, East Kilbride, for providing and commenting on the radiocarbon dates. I am also very grateful to D. W. S. Limbert and Dr R. I. Lewis Smith, and Dr N. J. Collins (Institute of Terrestrial Ecology) for advice during the preparation of the manuscript.

MS received 23 August 1978

REFERENCES

BAKER, J. H. 1972. The rate of production and decomposition of *Chorisodontium aciphyllum* (Hook. f. & Wils.) Broth. *British Antarctic Survey Bulletin*, No. 27, 123–29.

BRADLEY, R. S. *and* G. H. MILLER. 1972. Recent climatic change and increased glacierization in the eastern Canadian Arctic. *Nature, Lond.*, **237**, No. 5355, 385–87.

BRITISH ANTARCTIC METEOROLOGICAL SERVICE. 1964–70. *Annual meteorological tables, 1960–63*. Stanley, Falkland Islands, British Antarctic Survey.

COLLINS, N. J. 1976. The development of moss-peat banks in relation to changing climate and ice cover on Signy Island in the maritime Antarctic. *British Antarctic Survey Bulletin*, No. 43, 85–102.

FALKLAND ISLANDS AND DEPENDENCIES METEOROLOGICAL SERVICE. 1951–62. *Annual meteorological tables, 1951–59*. Stanley, Falkland Islands, Government Printing Office.

FENTON, J. H. C. 1980 The rate of peat accumulation in Antarctic moss banks. *J. Ecol.*, **68**, No. 1, 211–28.

————. *and* R. I. L. Smith. 1981. Distribution, composition and general characteristics of the moss banks of the maritime Antarctic. *British Antarctic Survey Bulletin*, No. 51, 215–36.

HOINKES, H. C. 1964. Glacial meteorology. (*In* ODISHAW, H., *ed. Research in geophysics*. Cambridge, Mass., MIT Press, 391–424.)

HOOKER, T. N. 1977. *The growth and physiology of Antarctic lichens*. Ph.D. thesis, University of Bristol, 188+10 pp. [Unpublished.]

KOERNER, R. M. 1964. Glaciological observations in Trinity Peninsula and the islands in Prince Gustav Channel, Graham Land, 1958–60. *British Antarctic Survey Scientific Reports*, No. 42, 45 pp.

LACHAPELLE, E. 1965. The mass budget of Blue Glacier, Washington. *J. Glaciol.*, **5**, No. 41, 609–23.

LIMBERT, D. W. S. 1974. Variations in the mean annual temperature for the Antarctic Peninsula, 1904–72. *Polar Rec.*, **17**, No. 108, 303–06.

———. 1977*a*. Climatological summary for 1973. *British Antarctic Survey Bulletin*, No. 45, 131–37.

———. 1977*b*. Climatological summary for 1974. *British Antarctic Survey Bulletin*, No. 45, 139–45.

———. 1979. Climatological summary for 1975. *British Antarctic Survey Bulletin*, No. 47, 129–35.

———. *and* R. S. B. LOAN. 1976*a*. Climatological summary for 1971. *British Antarctic Survey Bulletin*, No. 44, 31–37.

———. *and* ———. 1976*b*. Climatological summary for 1972. *British Antarctic Survey Bulletin*, No. 44, 39–45.

LLIBOUTRY, L. 1953. More about advancing and retreating glaciers in Patagonia. *J. Glaciol.*, **2**, No. 13, 168–72.

LONGTON, R. E. 1970. Growth and productivity of the moss *Polytrichum alpestre* Hoppe in Antarctic regions. (*In* HOLDGATE, M. W., *ed. Antarctic ecology*. London and New York, Academic Press, 818–37.)

PENNINGTON, W., CAMBRAY, R. S., EAKINS, J. D. *and* D. D. HARKNESS. 1976. Radionuclide dating of the recent sediments of Blelham Tarn. *Freshwater Biol.*, **6**, No. 4, 317–31.

PEPPER, J. 1954. *The meteorology of the Falkland Islands and Dependencies, 1944–1950*. London, Falkland Islands and Dependencies Meteorological Service.

SERVICIO METEOROLÒGICO NACIONAL, ARGENTINA. 1951. *Datos climatologicos y geomagneticos Islas Orcadas del Sud, periodo 1903–1950*. Buenos Aires, Servicio Meteorològico Nacional, Ser. B, Secc. 1ª, Pt. 1ª, No. 11.

SMITH, R. I. L. 1972. Vegetation of the South Orkney Islands with particular reference to Signy Island. *British Antarctic Survey Scientific Reports*, No. 68, 124 pp.

———. 1981. Plant succession and re-exposed moss banks on a deglaciated headland in Arthur Harbour, Anvers Island. *British Antarctic Survey Bulletin*, No. 51, 193–99.

SUGDEN, D. E. *and* B. S. JOHN. 1976. *Glaciers and landscape*. London, Arnold.