ECOLOGY OF THE FRESH-WATER LAKES OF SIGNY ISLAND, SOUTH ORKNEY ISLANDS:

I. CATCHMENT AREAS, DRAINAGE SYSTEMS AND LAKE MORPHOLOGY

By Ronald B. Heywood

Abstract. Signy Island can be divided into six main catchment areas which are described with reference to their drainage forms, geology and botany. While drainage over the upland area is generally good, the lowlands remain extensively waterlogged throughout the summer months. Since the glacial debris and scree covering most of this area are in various stages of weathering and are affected by permafrost phenomena, the resulting substrate is unstable and constantly moving. Water running over much of the lower slopes and valley floors is of insufficient volume, force and frequency to form and maintain anything more than runnels in this unstable terrain. Sub-surface drainage is severely restricted by the clay-like properties of the finer soil particles and by the permafrost. Hence the water that cascades down the steep upper slopes does not collect into a stream-drainage system and it must percolate through or run over ground already waterlogged. Small fresh-water lakes occupy the more low-lying areas of the glacially overdeepened valleys. These lakes conform to a basic pattern of a steep-sided trough surrounded by a sub-lacustrine shelf of varying width. The trough, 3–6 m. in depth in the majority of the lakes, has a floor of gravel and silt broken by occasional jutting rocks. The shelf area, which rarely exceeds 1 m. in depth, is covered by a continuation of the surrounding scree and ground moraine. Some of the more important morphometric parameters of the lakes are given and possible origins of the lakes are discussed.

Before 1962 work on the fresh-water lakes in British Antarctic Territory had been confined to the collection and subsequent taxonomic evaluation of biological specimens. A study of the fresh-water ecosystem of Signy Island began during the 1961–62 southern summer when several small lakes were selected for general study. An interim report on the first 2 years of field work has been prepared (Heywood, 1967) and a more detailed analysis of the results will be presented in this series of papers.

Signy Island (lat. 60°43′S., long. 45°38′W.) is one of the South Orkney Islands group which lies on the Scotia Ridge, within the Antarctic maritime region (Holdgate, 1964), 560 km. east-north-east of the northern tip of the Antarctic Peninsula. The general climatic conditions in this sector of the maritime Antarctic have been discussed by Pepper (1954). Holdgate (1964) has pointed out the ecological significance of the annual temperature of the region, and other authors (Chambers, 1966*a*, *b*, 1967; Holdgate, Allen and Chambers, 1967) have commented on climatic aspects of Signy Island. The island lies in a zone dominated by an oceanic climate and the ameliorating influence of the surrounding ocean is shown by the relatively small temperature range (monthly mean temperature range +0·8° to −10·5° C; annual mean temperature −3·8° C). The oceanic influence is also responsible for the high annual mean cloudiness (7 oktas) and the low annual mean sunshine (1·5 hr./day). The amount of precipitation, mainly snow, is low (~ 40 cm./yr.), although the frequency is high (335 days/yr.). A regular series of depressions passes through the region north of Signy Island, resulting in the extreme windiness of the area (monthly mean varying from 12·0 to 17·6 kt. (6·2 to 9·1 m./sec.); annual mean 14·7 kt. (7·6 m./sec.)).

Signy Island is small, triangular-shaped, 19·4 km.^{2} in area and has a maximum height of 276·5 m. The summits of the hills are generally flat and connected by shallow cols near the centre of the island, forming an ice-covered plateau which covers about one-third of the island's area. The sharply defined edges of the plateau have been eroded by ice action. There is a coastal lowland area, which is extensive on the east coast but either discontinuous or absent on the west coast. The lowlands are usually snow-free during the summer but there are lobes of permanent ice and large isolated snowdrifts. Some parts (North Point, Stygian Cove, Spindrift Rocks, The Wallows, Elephant Flats and Gourlay Peninsula) are heavily colonized by birds and seals. Small bodies of fresh water lie on the plains and in the lower parts of glacially overdeepened valleys. The definition of Røen (1962) for the concept of "lake" in polar regions has been used in this study. A "lake" is a permanent standing body of fresh water which never freezes solid. Many of the fresh-water bodies were not visited during the winter and they have been grouped according to knowledge gained from the others. There are 16 lakes on Signy Island and numerous smaller water bodies.

Catchment Areas

Topography

Signy Island can be divided into six main catchment areas (Fig. 1, I-VI). The separate drainage basins in these areas are generally well defined because the main coastal topo-

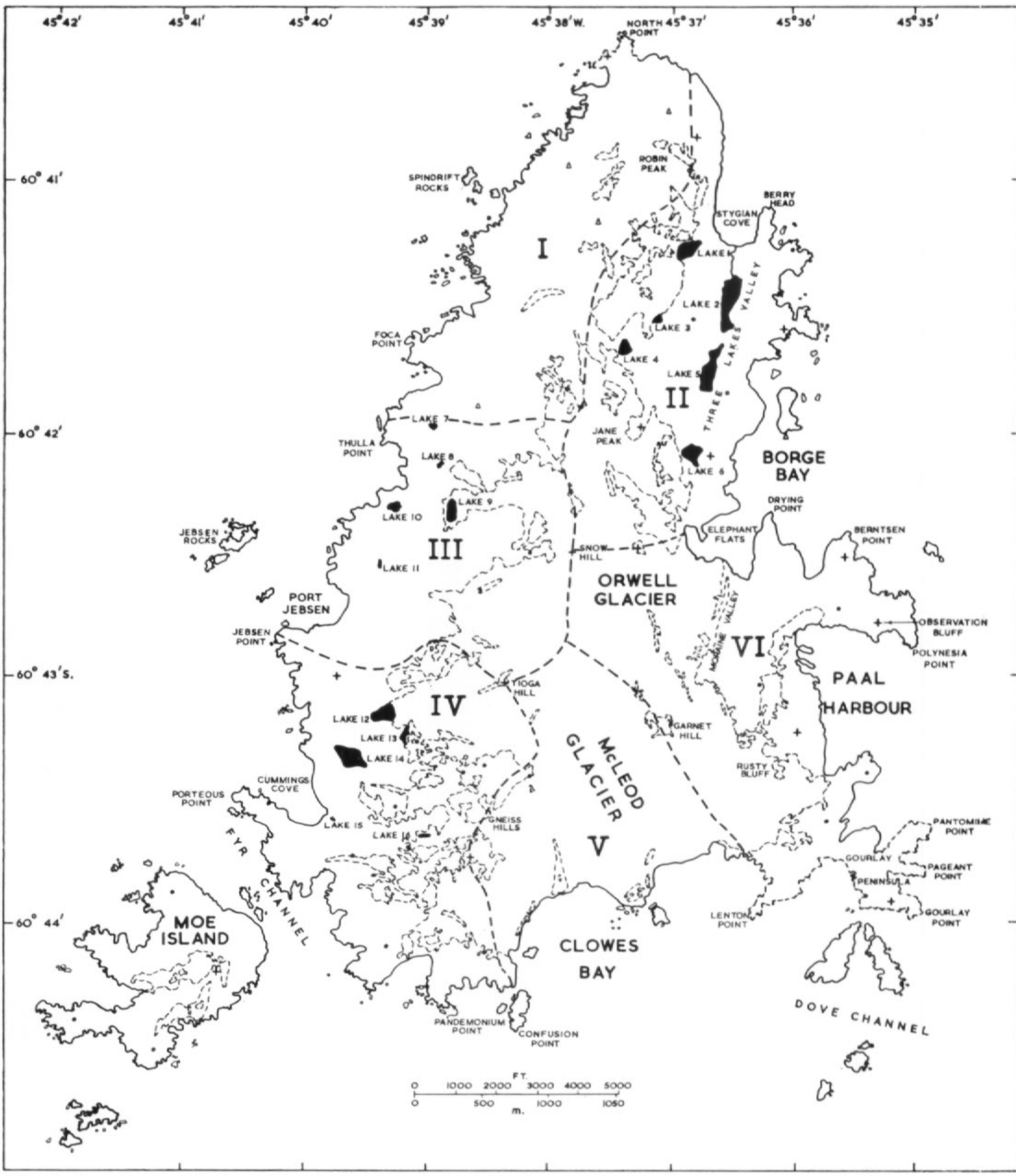

Fig. 1. Sketch map of Signy Island, South Orkney Islands, showing the limits of the six main catchment areas (I-VI) and the locations of the fresh-water lakes (1-16).

graphical features are small cirques separated by rugged frost-shattered spurs. The descriptive information given below has been drawn from several sources. Geological detail and certain spot heights were obtained from the map by Matthews and Maling (1967) but other heights were measured by aneroid barometer and additional topographical details were obtained from field notes and photographs.

The north-west catchment area (Fig. 1, I; 2·7 km.^{2}) lies on the dip slope of an eroded fault scarp which trends north—south through the centre of the island from Robin Peak (259 m. a.s.l.). Near Jane Peak (204 m. a.s.l.) the slope merges with a small plateau and col, south of which the terrain rises steeply to heights of 265 (Snow Hill) and 250 m. a.s.l. before continuing southward as the main plateau of the island. The southern boundary of this area is formed by a steep high ridge which trends towards Thulla Point from a rocky outcrop on the ice-clad flanks of Snow Hill.

In the north of the area subsidiary ridges of Robin Peak radiate across the main slope, which falls steeply to the 6–10 m. cliffs bordering most of the coast. South of Robin Peak the fault line is crossed by a wide col (107 m. a.s.l.) from which the ground slopes gently towards the coast. Between 15 and 60 m. a narrow plain extends as far south as Foca Point. A narrow valley with a steeply falling floor lies between ridges leading to Foca Point and Thulla Point, and a steep narrow gully, blocked by a coarse scree, leads from this valley to the col between Jane Peak and Snow Hill.

There is very little permanent ice within this area but a few semi-permanent snowdrifts persist on the flanks of Robin Peak. Melt water from ice near Jane Peak and Snow Hill is confined by the gully at the head of the valley and forms a stream which flows under scree before emerging to run through shallow channels on the lower slopes. There are no lakes in this catchment area.

The north-east catchment area (Fig. 1, II; 3·4 km.^{2}) has its inland boundary along the edge of the fault scarp from Robin Peak to the 230 m. buttresses above Elephant Flats (Fig. 2). Ridges radiating out from Jane Peak divide most of the area into four dissimilar valleys. There is also a narrow coastal strip.

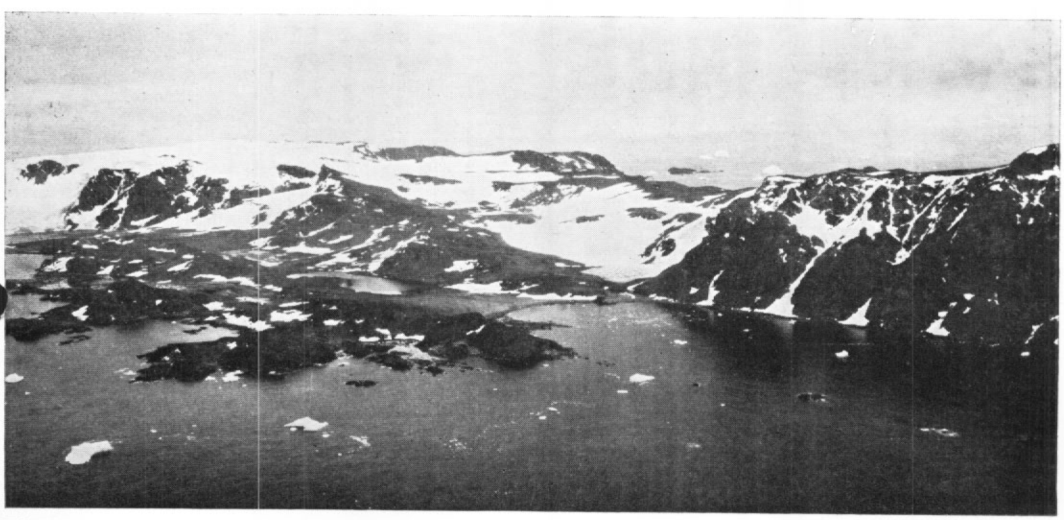

Fig. 2. Aerial photograph of the north-east catchment area (II) from the north-east. Berry Head is in the foreground. (Photograph by courtesy of the M.O.D. (Navy).)

A D-shaped valley trends northward from a cirque on the north face of Jane Peak, between the scarp face and the steep, narrow, irregular north ridge of Jane Peak. An ice-field, descending from the fault scarp, covers two-thirds of the valley. Lakes 1, 3 and 4 (Fig. 1) are interconnected by streams which flow beneath ice for most of their length.

Although the area parallel to the first valley is known as Three Lakes Valley, it is divided into two valleys by a low (30 m. a.s.l.) ridge, which is a rocky extension of Jane Peak covered by debris or a moraine. These valleys are described separately.

The floor of the trough-shaped northern valley is divided into two levels (14 and 4·5 m. a.s.l.) by a step covered by glacial debris. The north ridge of Jane Peak is terraced along the upper valley but it presents almost sheer bluffs to most of the lower valley floor. The eastern boundary is along the western edge of a coastal ridge (20 m. a.s.l.), which descends rapidly near the step and continues afterwards as a flat broad outcrop which forms an effective watershed, although it rarely attains a height of 1·5 m. above the valley floor. There is no permanent ice in this valley and only a few snowdrifts persist during the summer months under the Jane Peak ridge. Lakes 2 and 5 (Fig. 1), which are interconnected, occupy almost the entire areas of the upper and lower valley floors.

The floor of the valley south of the ridge bisecting the Three Lakes Valley area falls gently to sea-level at Elephant Flats. The western limit of the valley is formed by the almost sheer ice and rock face of Jane Peak and the steep ice-clad slopes of its southern shoulder. Low outcrops, seldom rising more than 6 m. above the valley floor, form the eastern boundary. Parallel outcrops, extending north–south, trisect the lower valley floor. Approximately one-tenth of the surface area of the valley is covered with ice. Lake 6 lies 140 m. from the northern limit of the valley (Fig. 1).

The fourth valley, which is roughly triangular in shape, lies on the southern flanks of Jane Peak and trends south-eastwards to Elephant Flats (Fig. 1). The fault scarp emerges from the ice of the col, between Jane Peak and Snow Hill, to form the north-east buttresses of Snow Hill which present sheer walls to the floor of the valley. A low ridge extending southwards from Jane Peak forms the eastern limit of the valley. Most of the valley is covered with ice but there are small scree exposures below the rock buttresses and where the buttresses and ridge meet near the narrow entrance of the valley. There are no lakes in the valley but throughout a normal summer there is a small stream. The floor of the valley slopes south and south-eastwards, and melt water drains to the foot of the buttresses. After running to the mouth of the valley, the stream dips under ice to emerge finally from an ice cave and discharge into Elephant Flats.

The coastal strip, which is very narrow for most of its length, consists of a few small beaches separated by low rugged knolls.

The west central catchment area (Fig. 1, III; 3·0 km.^{2}) lies between Thulla Point and Jebsen Point. It consists of a narrow coastal plain and a cirque separated by a small upland area formed by two parallel ridges and associated knolls extending westwards from the ice cap. There is a small valley on the coast at the foot of this upland area. Part of the ice cap lies within the catchment area and its high ramparts overshadow both the plain and the cirque.

The 700 m. long plain lies between the 40 and 30 m. contours on the dip slope of the ridge leading to Thulla Point, and it is bordered by a low, heavily faulted coastal ridge beyond which the terrain falls quickly to sea-level. A small ice-field falls through a narrow break in the ice cap's ramparts into the south-east corner of the plain. One other lobe of the ice cap descends to 80 m. between the two ridges of the upland area. The ice covers part of the northernmost ridge and it is bordered by a moraine, which is overshadowed by a sheer 100 m. rock face of the second ridge. The cirque is small and steep-walled, and most of its floor lies below the sea in Port Jebsen.

Approximately one-quarter of this area is ice-covered and a few semi-permanent snowdrifts lie on the plain. There is a small stream in the upland area where melt water, running off the ice-field, is confined by the moraine and the rock face to a narrow channel. Lakes 7, 8, 9, 10 and 11 occur in this area.

The south-west catchment area (Fig. 1, IV; 3·8 km.^{2}) lies south of a steep 200 m. high ridge extending from Tioga Hill to Jebsen Point (Fig. 3). The inland boundary of this area trends southward from Tioga Hill (276 m. a.s.l.) across a shallow col (225 m. a.s.l.) and the eastern summits of the Gneiss Hills. It consists of most of the Gneiss Hills and a large cirque between the northern flanks of the hills and the almost sheer southern walls of the ridge towards Jebsen Point.

A lobe from the ice cap still overhangs the north-east corner of the cirque and there are also lobes of permanent ice and semi-permanent snowdrifts on the Gneiss Hills. Considerable quantities of melt water from the ice cap are channelled down the col and form a stream which receives additional supplies of water from lakes 12, 13, 14, 15 and 16 as it runs across the cirque floor.

Fig. 3. Aerial photograph of the south-west catchment area (IV) from the west. Porteous Point, with Cummings Cove behind it, is in the foreground. (Photograph by courtesy of the M.O.D. (Navy).)

The southern catchment area (Fig. 1, V; 2·5 km.^{2}) is formed by the valley of McLeod Glacier (Fig. 4). From the northern limit (approximately 250 m. a.s.l.), near the centre of the ice cap, the western boundary climbs Tioga Hill before extending across the eastern summits of the Gneiss Hills. The eastern boundary is formed by a slight rise in the ice cap, trending towards Garnet Hill (225 m. a.s.l.) and then falling steadily to the south coast near Lenton Point. The 1,900 m. long snout of McLeod Glacier presents 20–30 m. cliffs to Clowes Bay. The amount of ice-free terrain is very small, being limited to the crests of Garnet Hill and the Gneiss Hills.

The south-east catchment area (Fig. 1, VI; 4·0 km.^{2}) is bounded on the north and west by slight rises on the ice cap and the buttresses towering above Elephant Flats. The boundary then extends from Snow Hill south-eastwards through Garnet Hill to reach the coast near Lenton Point.

The fault scarp, which extends the length of the island, swings south-south-eastwards through this area, forming the eastern edge of the ice cap, and it dips sharply near Garnet Hill to form a col (130 m. a.s.l.) with the flanks of Rusty Bluff. The eastern and southern flanks of Rusty Bluff (217 m. a.s.l.) and its associated peaks fall almost sheer into Paal Harbour.

North of the col the scarp is separated from the coastal peaks by Moraine Valley. Scarp, col and peaks present steep walls to the valley floor, the ice-clad scarp face rising almost sheer for 150–180 m. A large part of the valley floor is covered by Orwell Glacier which flows through a break in the scarp face. The ice cap also spills over the scarp at the head of the valley. Scree of the inland slopes of the coastal peaks and glacier reduce the valley floor to a narrow strip at the foot of the glacier's lateral moraine.

Fig. 4. Aerial photograph of the southern catchment area (V) and part of the south-east catchment area (VI) from the south-east. Clowes Bay and Gourlay Peninsula are in the foreground. (Photograph by courtesy of the M.O.D. (Navy).)

South of the col the scarp merges with the flanks of Rusty Bluff to form a wide slope trending south and east which is covered by an extension of the ice cap. Gourlay Peninsula, a low-lying ice-free area of small headlands, is south-east of this slope.

The subsidiary peaks and ridges of Rusty Bluff follow the northern coastline of Paal Harbour and form a rocky headland dominated by Observation Bluff (108 m. a.s.l.). The northern flanks of the headland present a complex of scree-covered terraced ridges overlooking Borge Bay.

Melt water from the ice cap and Orwell Glacier drains into the V of the Moraine Valley floor and forms a stream but there are no lakes in this catchment area.

Geology

Signy Island is composed of regionally metamorphosed sediments, which are mainly garnetiferous quartz-mica-schists with subordinate amphibolites and marbles (Matthews and Maling, 1967). The amount of exposed rock is small and most areas are covered by glacial drift and scree. The amphibolite and marble outcrops are localized and they are only prominent on Jane Peak and in the coastal knolls bordering the valley of lake 6 in the north-east catchment area. They also occur in the faulted coastal ridge and the Thulla Point ridge of the west central catchment area, and in the Gneiss Hills in the south-west catchment area.

Flora

Initial studies on the terrestrial flora of Signy Island have already been published (Holdgate, 1964). Fine silt and mud are bare of vegetation except in very wet areas where they may have a

TABLE I. SOME MORPHOMETRIC PARAMETERS OF THE LAKES OF SIGNY ISLAND WITH DETAILS OF THEIR DRAINAGE BASINS

		Lake number		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Lake	*Morphology*	Shoreline form		sc	sre	t	sc	sre	sc	c	c	sc	i	e	sc	t	sre	c	
		Area—A	(m.^{2})	24,300	40,730	1,500	9,750	32,500	14,300	1,300	3,800		6,150	500	20,200	500	31,000	1,800	
		Length—l	(m.)	250	427	100	130	410	166	55	75	Surface frozen throughout the survey	90	60	190	25	270	55	
		Breadth—b_x	(m.)	150	137	50	100	100	155	35	60		50	15	140	20	160	30	
		Maximum depth—z_m	(m.)	n.d.	6·0	6·4	n.d.	3·5	3·5	4·0	n.d.		4·3	n.d.	15	n.d.	n.d.	n.d.	
		Development of shelf		Moderate	Moderate	Extensive	Small	Moderate	Extensive	Moderate	Extensive		Small	Very small	Small	Moderate	Moderate	Small	
		Height above sea-level	(m.)	10·0	4·5	43	60	14	26	41	35	30	6·0	60	45	60	35	2·0	
		Proximity of sea	(m.)	50	200	700	1,000	200	150	200	300	400	25	200	500	700	300	15	
		Exposure to winds		mex	ex	ex	sh	ex	mex	ex	ex	mex	mex	vsh	sh	mex	mex	ex	Not visited
Drainage basin	*Relative amounts of*	Ice (per cent)		50–95	None	50–95	5–20	None	5–20	None	<5	50–95	None	None	50–95	50–95	50–95	5–20	
		Snow (per cent)		tr	tr	tr	tr	tr	None	<5	<5	tr	tr	<5	tr	tr	tr	tr	
		Rock (per cent)		5–20	>95	5–20	50–95	>95	50–95	>95	50–95	<5	>95	>95	<5	<5	<5	50–95	
		Quartz-mica-schist (per cent)		>95	>95	>95	50–95	>95	50–95	50–95	>95	>95	>95	>95	>95	>95	>95	>95	
		Amphibolite (per cent)		tr	tr	tr	5–20	tr	tr	tr	tr	tr	<5	tr	None	<5	<5	tr	
		Marble (per cent)		tr	tr	tr	tr	tr	5–20	5–20	tr	tr	None	None	None	None	None	None	
	Overall vegetation cover	Total (per cent)		5–20	50–95	<5	<5	20–50	20–50	<5	<5	<5	<5	<5	<5	<5	<5	<5	
		Moss (per cent)		5–20	50–95	tr	tr	50–95	20–50	<5	<5	tr	<5	<5	tr	tr	<5	<5	
		Lichen (per cent)		50–95	20–50	>95	>95	20–50	50–95	>95	>95	>95	>95	>95	>95	>95	>95	>95	
Drainage water		Main source		Ice face; lake 3	Lake 5	Ice-field; lake 4	Ice face	Seepage	Ice face	Snow bank	Snow bank	Ice cap	Seepage	Seepage	Ice cap	Ice cap	Ice cap; lake 12	Ice cap; lake 14	
	Contamination by fauna	Total (per cent)		<5	5–20	tr	tr	tr	tr	<5	tr	tr	>95	tr	tr	tr	tr	20–50	
		Seal (per cent)		20–50	50–95	None	None	None	None	None	None	None	>95	None	None	None	None	>95	
		Bird (per cent)		20–50	20–50	>95	>95	>95	>95	>95	>95	>95	tr	>95	>95	>95	>95	tr	

Shoreline form
c Circular
sc Sub-circular
sre Sub-rectangular-elongate
e Elliptical
t Triangular
i Irregular

Exposure to winds
ex Exposed
mex Moderately exposed
sh Sheltered
vsh Very sheltered

n.d. Not determined
tr Trace

covering of blue-green algae, mainly *Phormidium* spp. Lichens, mainly *Usnea* spp., and a species of *Andreaea* colonize the stone stripes, scree and bare rock, but *Grimmia* mats replace this community on the marble outcrops. Moss stands have developed on slopes, ledges and promontories where the substratum is more consolidated. These stands are dominated by *Drepanocladus uncinatus* but *Acrocladium* spp. are abundant in the wetter areas. *Brachythecium* spp. are particularly common lining runnels where the water is fast-running, and *Pohlia* spp. and a *Bryum* are common associates of this community. *Tortula* and *Mniobryum* are predominant lining runnels in the wetter areas of the marble outcrops. Where soils are heavily contaminated by animals, the ground is bare of vegetation, but the alga *Prasciola crispa* is present where there is nitrogen-rich seepage water in the peripheral parts of these areas.

Drainage Systems

The formation and movement of ice play only a small part in the general drainage of Signy Island. Nunataks and ridges divide the ice cap into drainage basins which are so small that there is very little ice movement, even in the glaciers (Matthews and Maling, 1967). General observation suggests that the ice cap is retreating, because the ablation rate is far greater than the accumulation.

Drainage over the upland areas of the island is good. Water runs freely off the ice, and the steep upper slopes of the plateau and high ridges, which are usually bare of rock debris or covered only by coarse scree, are well-drained. But most of the lower slopes and lowlands are covered by glacial debris or earlier moraines (the cirque in the south-west catchment area), which are in various stages of decomposition. Over extensive areas frost-shattering and solifluction have produced a fine mineral soil or an aggregate of mineral soil and rock particles. The resulting substrate is constantly moving and the water running over most parts is never of sufficient volume, force or frequency to form and maintain anything more than shallow runnels. The slopes, plains and valleys are too small for a sufficient number of the runnels to merge and provide the hydraulic power necessary for the excavation and maintenance of a stream bed. There are a few places where the natural relief of the terrain collects melt water and confines it to a narrow course, forming a stream, and all the lakes have outflow streams; in general, water draining over the slopes and lowlands is not collected by a stream drainage system. It must percolate through or run over the surface of the substrate. The clay-like properties of the finer particles hinder the seepage of sub-surface water, and permafrost (40–200 cm. below the surface) prevents percolation into the sub-soil. The lowlands, therefore, are poorly drained and they remain waterlogged throughout the summer months because the frequency of precipitation is high, and the rapid melting of ice and snow give rise to a greater amount of available water than the figures for the precipitation suggest. After periods of heavy precipitation, and in the vicinity of ice lobes and snow patches, water often flows over the surface of the ground along well-defined seepage courses. Evaporation of water from the soil is considerably reduced by the humidity which is usually as high as 80 per cent. The prevailing winds do not increase the rate of evaporation because, being oceanic, they already have a high moisture content. Evaporation is further restricted in some areas by overlying stands of moss.

Morphology of the Lakes and their Basins

Some general information on the fresh-water lakes of Signy Island is given in Table I. Descriptions of shoreline forms and definitions of morphometric parameters are after Hutchinson (1957, p. 165, 171). The values of the parameters for lakes 2 and 6, obtained by measurement and calculation after plane-table surveys, are accurate to $\pm$ 1 per cent. The values given for lakes 1, 4, 5, 8, 10, 12, 14 and 15 are based on helicopter aerial photographs taken by the Royal Navy in January 1965. Although vertical control was poor and the photographs were distorted by tilting, comparison of the photographs with plane-table surveys suggested that distortion was slight over areas as small as the lakes. Therefore, an accuracy of $\pm$ 5–10 per cent is claimed for the parameters of these lakes. Because the remaining lakes were still ice-covered at the time of the air photography, the values given are based on estimations made in the field using the "pacing out steps" method and they are of limited accuracy.

In the column headed "Exposure to winds" an attempt has been made to take into consideration the direction of the prevailing winds and the percentage of winds from other compass points (Pepper, 1954, p. 39) as well as field observations.

All the lakes conform to one pattern, a steep-sided trough surrounded by a sub-lacustrine shelf of varying width. A continuation of the surrounding slopes, covered by glacial debris or scree, forms the main shore type but low rock outcrops, cliffs, snowdrifts and ice may form part of the shoreline. For all the lakes the shoreline is one of submergence and it appears to be unaffected by hydromechanical activity; there is no evidence of beach formation such as gradation of particles from the water's edge (Hutchinson, 1957, p. 178). It is known that the erosive power of wave-action is determined more by the size of the waves than by the duration of wave-action. It is therefore evident that, although prevailing high winds over Signy Island produce considerable periods of wave-action, the smallness of the lakes reduces the erosion effect of the waves to negligible proportions. Thus all changes in shoreline have been caused by external forces—solifluction, stone movement, moraine damming and falling scree—and in all the lakes the sub-lacustrine shelf area appears to have resulted from the further deepening of the lake by one or other of these agents.

The scree and glacial debris continue beyond the water-line to cover the shelf and the small to large boulders are sometimes interspersed with patches of gravel and silt. Silting is generally confined to areas where seepage courses and runnels lead water into the lake, i.e. where water runs to the lake with sufficient force to carry small particles but with insufficient force to produce currents in the lake water to sweep the silt into the trough, as occurs where a stream enters a lake. The depth of water over the sub-lacustrine shelf rarely exceeds 1 m. The floor of the lake trough is generally covered by gravel and silt, overlain by organic debris and penetrated by occasional large boulders. It was only possible to investigate the sediments in the trough by dredging. This was an unsatisfactory method because only surface layers, which were of predominantly organic matter, were removed and the true ratio of inorganic to organic material in the sediments must await investigation by coring techniques. The amount and nature of the transported organic debris reflects the dominant vegetation type, its abundance over the drainage basin and the destructive force of the water flowing through it.

Each lake is fed by seepage of sub-surface water, surface water running in seepage courses and runnels from ice lobes and snow banks, and by precipitation falling over the lake surface. Some of the lakes are interconnected. The drainage basins are generally small but all the lakes receive sufficient water to maintain a constant and often considerable outflow throughout the summer months.

Lakes 2, 3, 6, 7 and 10 were chosen for the ecological study and they are described in detail. When selecting lakes for such a study one is obviously guided by the apparent variety in morphological, physico-chemical and biotic factors, as revealed by preliminary observation, but on Signy Island the over-riding factor had to be the summer and winter accessibility of the site. The considerable amount of equipment necessary for work on the lakes could only be transported by boat and pack during the summer months, and rough seas prevented regular visits to the west coast areas during this period. In winter the equipment was usually manhauled by sledge but work on the west coast was then limited by time (if using a sea-ice route) or by the low cloud base (if using an overland route). Final selection of the lakes for study was made after the experience of the 1962 winter:

i. Lake 2; to be sampled at least monthly.
ii. Lakes 3 and 6; to be sampled bi-monthly.
iii. Lakes 7 and 10; to be sampled every 6 months.

Accurate outline maps for lakes 2 and 6 were drawn by plane-table survey but field sketch maps illustrate the other lakes. A portable, transistorized echo-sounder (Hecta depthmeter; accuracy $\pm$ 1 per cent) became available for the bathymetric survey of lake 2. Soundings were taken along a series of transects marked by stakes fixed into the plane-table survey. Horizontal distances were determined by a measured rope line. This technique is not the most accurate method of survey but it was the only one possible under the conditions of climate, labour and material. In areas where transects crossed, soundings were in close agreement and the results of the survey were considered accurate enough for the calculation of morphometric parameters. The surface area and volume were calculated by a National-Elliot 803 computer with a standard library programme based on the estimation of volumes by the trapezium rule. The remaining lakes were surveyed bathymetrically by sounding line. Although horizontal control was poor (counting oar strokes along parallel transects), a reasonable assessment of the morphology of lakes 3 and 6 was obtained.

Lake 2 (4·5 m. a.s.l.) occupies most of the lower level of the northern valley of the Three Lakes Valley area in the north-east catchment area (Figs. 1 and 5). The step to the upper

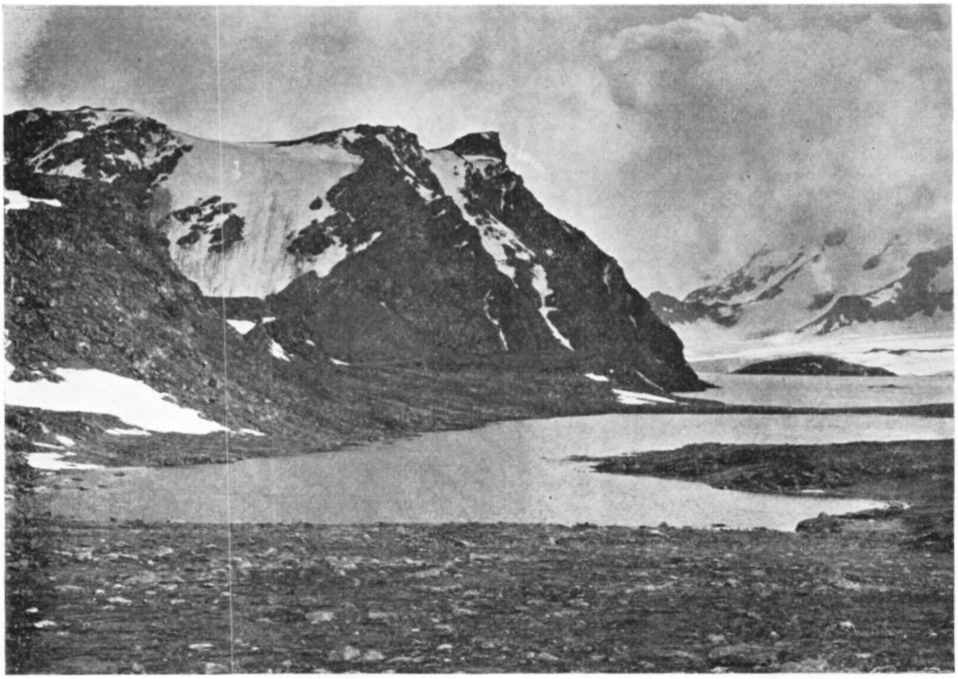

Fig. 5. Lake 2 in Three Lakes Valley, viewed from a point above the southern shore.

valley presents a 100 m. long, debris-covered slope to the southern lake shore, and beyond the northern shore the ground falls gently over a distance of 200 m. to sea-level in Stygian Cove. The Jane Peak ridge follows the western shoreline very closely and for most of this distance the rock rises sheer for 45–50 m. from within a few metres of the water's edge. The narrow level strip along the shore is mostly covered by steep mounds of scree. The ridge recedes from the shore at each end of the lake where small areas of more level ground lie above low subsidiary ridges trending at right-angles to the main ridge. Although they are only 1–2 m. higher than the lake, these subsidiary ridges deflect away from the lake water which at the northern end is lost to the outflow stream, but which at the southern end is re-directed to enter the south-west corner of the lake. The low outcrop forming the eastern limit of the valley is often part of the shoreline and it is seldom more than 4 m. away.

This lake receives water from the outflow stream of lake 5 and its drainage basin therefore consists of the whole valley, an area covering $4 \cdot 4 \times 10^5$ m.^{2}. The small areas of level ground and the gentle slope bordering the south, east and west shores of lakes 2 and 5 are covered with luxuriant stands of moss. Practically all the water entering these lakes flows through or under moss during part of its course.

Although the prevailing winds over Signy Island generally have a westerly component, the mass of Coronation Island lying immediately to the north promotes localized north-north-easterly winds that sweep down the Three Lakes Valley area. Lake 2 is particularly exposed to winds from this quarter and during periods of very high winds the north basin of the lake may lie within the spray zone of Stygian Cove.

Lake 2 has a surface area of 40,730 m.^{2} and its outline is sub-rectangular-elongate (Hutchinson, 1957). The trough of the lake is formed by two basins, which differ considerably in area, depth and general form (Fig. 6; Table II), connected by a narrow channel. Sub-

TABLE II. MORPHOMETRIC PARAMETERS* OF LAKE 2, SIGNY ISLAND

	North basin	*South basin*	*Whole lake*
Length—l (m.)	270	103	427
Breadth—b_x (m.)	140	95	137
Mean breadth—$\bar{b} = A/l$ (m.)	99	86	95
Area—A (m.^{2})	26,800	8,875	40,730
Mean depth—$\bar{z}$ (m.)	2·3	1·7	2·0
Maximum depth—z_m (m.)	6	4	6
Number of cryptodepressions	3	None	3
Depth of cryptodepressions (m.)	1·5	—	1·5
Volume—V (m.^{3})	62,395	15,775	86,100
Development of volume—$\bar{z}/z_m$	0·38	0·42	0·33
Shoreline—L (m.)	—	—	1,230
Development of shoreline—$D_L = L/2\pi^{\frac{1}{2}}A$	—	—	1·7

* As defined by Hutchinson (1957).

lacustrine ridges, knolls and troughs form a complex pattern in the southern basin and a continuation of the main trough extends in a narrow deepening V through the channel into the northern basin where it broadens and deepens, and is bisected by a submerged bar elongated along the main axis of the lake. Along the southern shore the lake bottom plunges immediately over large boulders to the floor of the trough but elsewhere there is a relatively wide shelf. The small amount of silt on the shelf is mainly confined to the west coast. Dredge samples from the trough contained varying amounts of both transported and *in situ* organic material; the larger amounts were found in the southern basin near the inflowing stream. The sub-lacustrine ridges and bars are of bare rock and very little debris was obtained from these areas.

Lake 3 (43 m. a.s.l.) occupies a depression at the foot of the ice-field descending from the fault scarp in the north-east catchment area (Fig. 1) and it is 560 m. from the crest of the scarp. North of the lake the ground rises 3 m. in a distance of 125 m. before falling away to lake 1, the slight slope being covered partly by an extension of the ice-field and partly by scree from the Jane Peak ridge. This ridge rapidly loses height (from 91·5 to 61·0 m. a.s.l.) and as it borders the lake it is crossed by a narrow col (52 m. a.s.l.) about 80 m. from the eastern shoreline. The southern shore lies under the rock lip and associated knoll at the entrance of the cirque. Part of the lip is covered by scree from the Jane Peak ridge.

The catchment area of the lake covers $3 \cdot 6 \times 10^5$ m.^{2} and it includes the catchment area of lake 4, the outflow of which drains into lake 3. The substrate of this area is mainly ice. Lichens dominate the sparse vegetation and there are only very small isolated areas of moss. The lake receives most of its water from lake 4 and the ice-field. The actual amount of water entering the lake was not measured but in an average summer there is a constant outflow of water from the northern apex, the stream flowing under the ice to lake 1. The lake is sheltered from southerly winds but the local topography deflects all other winds into the valley and the deflection often results in increased turbulence.

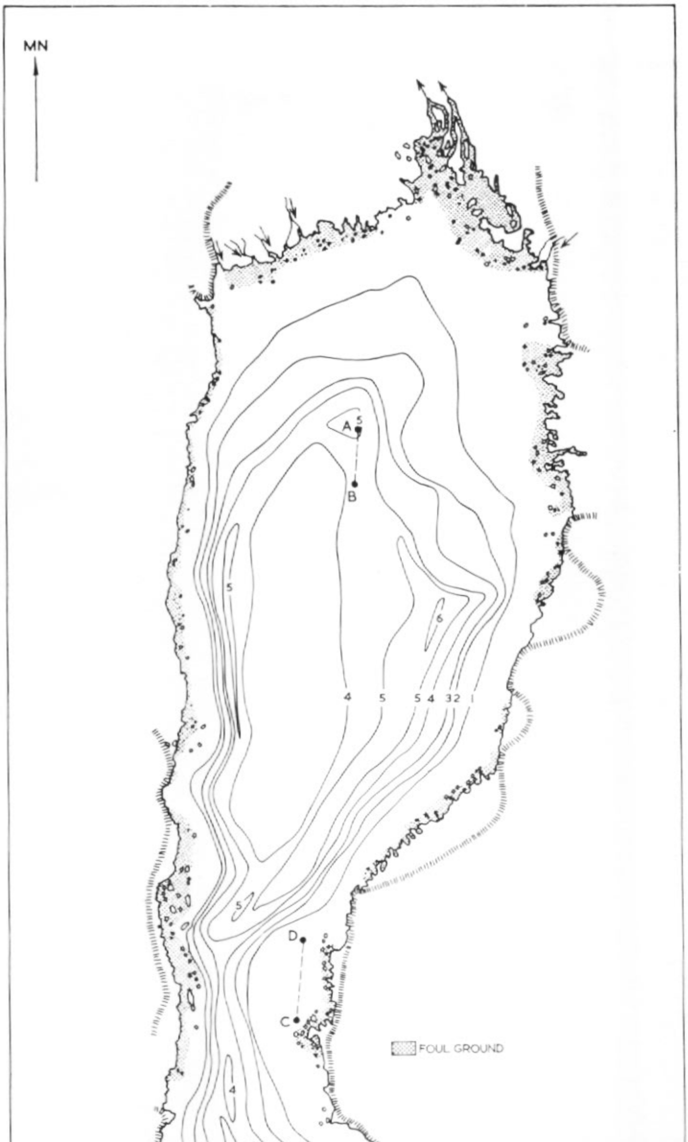

Fig. 6. Outline of lake 2 in Three Lakes Valley, showing the bathymetric contours in metres. A, B, C, D, E and F mark the sampling stations. (From a plane-table survey by M. W. Holdgate.)

Lake 3 is triangular in outline (Fig. 7), approximately 1,500 m.^{2} in surface area and consists of a steep-sided trough surrounded on three sides by a wide sub-lacustrine shelf. The western shoreline is formed by a wall of ice, which falls sheer to the bottom of the trough and through which the inflowing stream enters the lake at depths of 5·2 and 5·9 m. The shelf is covered by finer glacial material than is generally present in other lakes. The lake water is very clear and use of a water telescope revealed that the floor of the trough, which has a maximum recorded depth of 6·4 m., is almost featureless. No large boulders penetrate the bottom deposits but there are small areas of bare rock. It is not known whether the bottom deposits form a thick layer over a boulder-strewn floor or a thin layer over a level floor. Thick growths of green filamentous algae were seen over most areas of the trough and these formed the main component of dredge samples. The amount of organic matter present was small in comparison with other lakes examined and the *in situ* organic material was far more abundant than that transported.

Fig. 7. Field-sketch outline of lake 3, showing the bathymetric contours in metres. The sampling station is marked by A.

Lake 6 (26 m. a.s.l.) is on the southern slope of the ridge bisecting the Three Lakes Valley area (Fig. 1). The crest of the ridge is on the 30 m. contour 140 m. from the lake, and the valley floor continues to fall beyond the lake. Jane Peak rises above the north-west corner of the valley in an almost sheer wall of ice and rock. The southern shoulder and ridge of the peak fall in steep ice-covered slopes and approach to within 2 m. of the lake's western apex. The lake occupies almost the whole width of the valley floor and only 30 m. of gently rising ground separate the lake from the crest of the outcrop forming the eastern limit of the valley.

The drainage basin of the lake is $1·65 \times 10^5$ m.^{2} in area. Luxuriant stands of moss cover the slope north of the lake and extend around the eastern shoreline. The amounts of water entering the lake from the various sources were not measured but casual observation suggests that after the initial thaw the lake receives most of its water from the ice face. Melt water flows over the surface of a wide silt-covered area north-west of the lake. There are large quantities of green filamentous algae in this running water. In a normal summer there is a constant and considerable outflow of water from the southern end of the lake. The lake is sheltered when the wind in the drainage basin has a westerly component (p. 33).

Lake 6 is sub-circular in outline (Figs. 8 and 9), has a surface area of 14,300 m.^{2} and a maximum depth of 3·5 m. Its shoreline has been modified by human activity; early in the present

Fig. 8. Lake 6 viewed from the southern shoulder of Jane Peak (the north-west). The sharply defined trough is clearly visible.

century Norwegian whalers constructed a low dam on the glacial debris along the south and south-south-west shoreline. The dam was dry-built of local material and as the artificial dam merges with the natural shore there are no indications of the original shoreline but the extension of the shelf in the southern corner of the lake appears to be the result of the Norwegian activities. The shelf is wide around most of the lake but at the western apex, within 1 m. of the shoreline, the lake bottom falls over large boulders to the floor of the trough. Where water from the ice face drains into the lake the shore and shelf are covered with fine silt. Marble debris lies over the eastern shelf and this part of the lake basin may be formed by a marble outcrop. The lake water is clear and use of a water telescope revealed that the walls of the trough are steep, often lined with large boulders, several of which jut through the sediments over the trough floor. The organic fraction of the upper sediment layer is predominantly moss and blue-green algae, there being more *in situ* than transported material. The surface of the sediments is covered with luxuriant growths of green filamentous algae.

Lake 7 (41 m. a.s.l.) occupies most of a small depression on the northern boundary of the west central catchment area (Fig. 1). The depression is separated from the main coastal plain by a low ridge 2 m. above the lake surface and approximately 20 m. from the southern shoreline. East of the lake a buttress of the ice cap presents a sheer 60 m. face within 2 m. of the shore and the ridge extending towards Thulla Point also skirts the lake shore; the ground rises steeply to the crest only 30 m. away. The western shoreline is formed by a low narrow tongue of scree which separates the lake from a small subsidiary pool, beyond which the terrain falls away with increasing steepness to the 5–10 m. cliffs bordering the seashore.

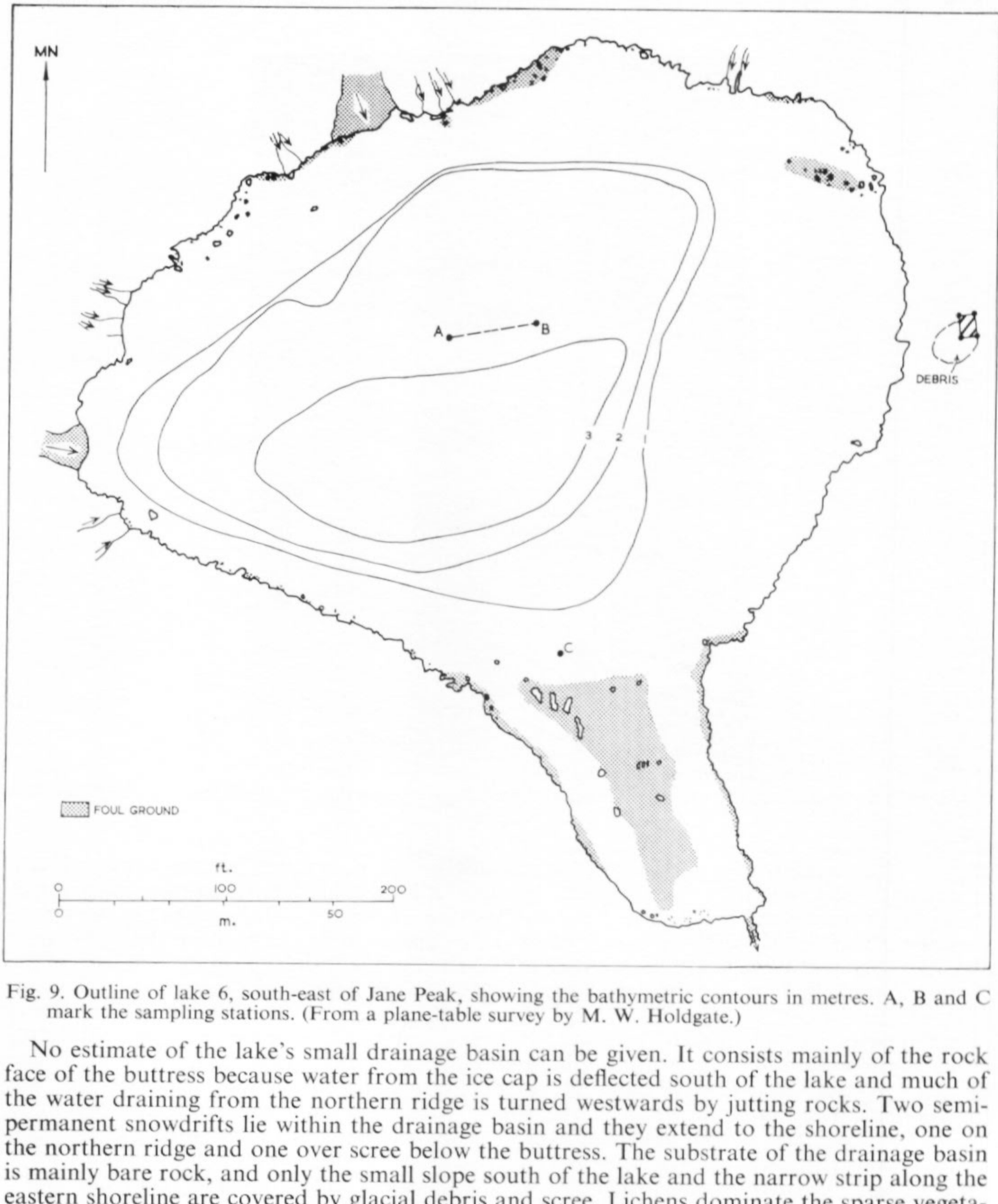

Fig. 9. Outline of lake 6, south-east of Jane Peak, showing the bathymetric contours in metres. A, B and C mark the sampling stations. (From a plane-table survey by M. W. Holdgate.)

No estimate of the lake's small drainage basin can be given. It consists mainly of the rock face of the buttress because water from the ice cap is deflected south of the lake and much of the water draining from the northern ridge is turned westwards by jutting rocks. Two semi-permanent snowdrifts lie within the drainage basin and they extend to the shoreline, one on the northern ridge and one over scree below the buttress. The substrate of the drainage basin is mainly bare rock, and only the small slope south of the lake and the narrow strip along the eastern shoreline are covered by glacial debris and scree. Lichens dominate the sparse vegetation and mosses are rare except over a small area near the south-west corner of the lake.

Hence most of the inflowing water drains over snow or bare rock. The ridge north of the lake is colonized by giant petrels (*Macronectes giganticus*) and some of the water draining through this colony enters the lake.

The amount of water entering the lake was not measured but field observations suggest that it was small in comparison with most other lakes. In the absence of precipitation, the lake receives most of its water from the adjacent snowdrifts. Water from the lake percolates slowly through scree into the subsidiary pool, which receives additional water from the northern ridge and from the surrounding waterlogged moss stands. A small stream flowing from the pool also receives water from the waterlogged coastal slopes and it branches to form two comparatively large streams before reaching the seashore.

The lake is very exposed to the prevailing winds and the buttress may increase the turbulence over the surface of the lake through eddy formation. The ice cap affords good protection from easterly winds.

With a sub-circular outline (Figs. 10 and 11), the surface area of the lake is approximately

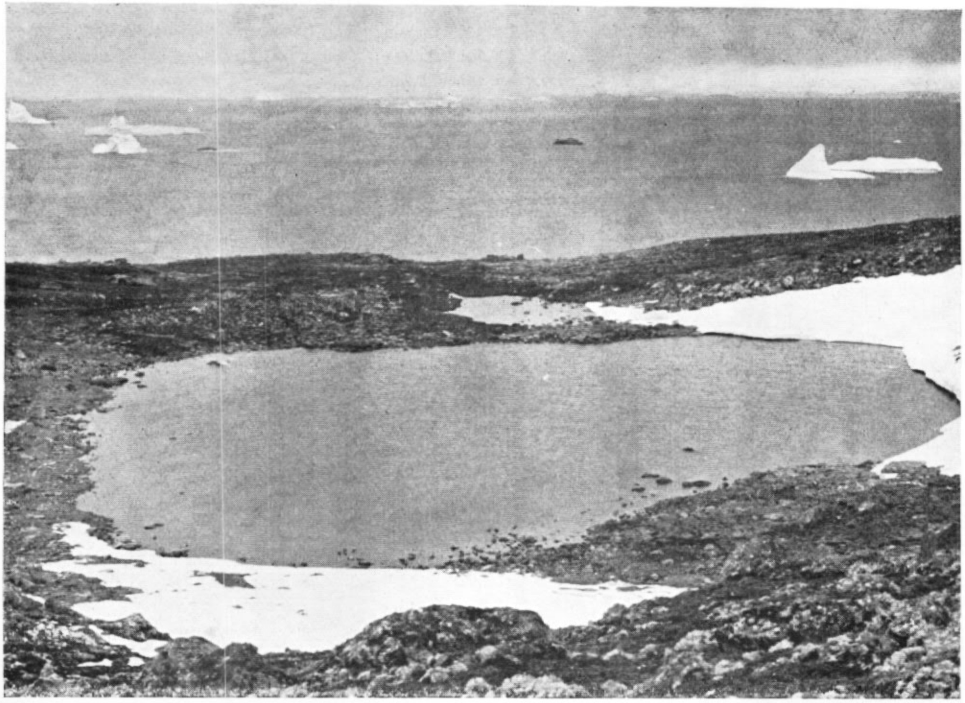

Fig. 10. Lake 7, east of Thulla Point, viewed from a point on the buttress of the ice cap to the east.

1,300 m.^{2}. The snowdrift along the northern shore terminates in a 30 cm. high edge, below which rock falls steeply to the floor of the trough, but a wide shelf borders the remaining shores. The scree forming the western limit of the lake is rarely more than 30 cm. high and is only 1 m. wide. The floor of the trough, which has a maximum recorded depth of 4 m., is covered with thick sediment and is featureless. An examination of dredge samples showed that the upper layers of sediment were predominantly organic, mainly a blue-green algal mat with very little moss or lichen. The samples also showed that the sediment is covered with green filamentous algae.

Lake 10 (6 m. a.s.l.) occupies a depression at the entrance of a small valley trending parallel to the coast at the foot of the upland area of the west central catchment area (Fig. 1). Immediately north of the lake the ground falls away through a narrow gap leading to a sea cove

10 m. from the lake shore. An extension of a coastal ridge borders the north and west shores of the lake and its east shore is defined by a stepped cliff (30 m. a.s.l.) which recedes south-eastwards beyond the lake to merge with ridges which overlook the head of the valley 70 m. from the southern shore of the lake.

It is difficult to estimate the size of the small drainage basin because the lake receives a considerable amount of water from some north- and west-facing slopes of the complex of ridges forming the upland area. It includes no permanent ice but a snowdrift persists throughout the summer months in a gully in the south-east corner of the valley.

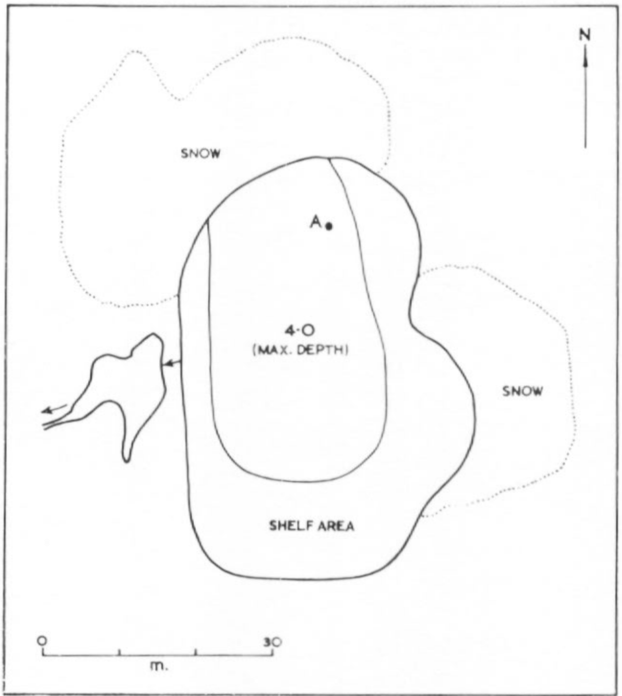

Fig. 11. Field-sketch outline of lake 7, showing the area of the sub-lacustrine shelf and the maximum recorded depth. The sampling station is marked by A.

The sparse vegetation is dominated by lichens. Elephant seals (*Mirounga leonina*) haul out in the valley and their excreta and moulted fur combine with the glacial debris and scree to form a reasonably stable, fine soil. Most of the water entering the lake drains across this contaminated ground which supports a little vegetation, mainly the alga *Prasciola crispa*. The drainage water pollutes a small subsidiary pool which appears to support little life other than blue-green algae. A small stream running through a band of coarse scree connects the pool with the lake. The amount of water entering the lake is not known but there is a constant flow of water throughout the summer months in the small stream which leaves the lake and runs into the cove through the narrow gap. The lake is well sheltered from easterly winds but it is exposed to all winds having a westerly component, and the narrow gap increases the turbulence of winds from the north and north-west.

The lake, which is irregular in outline (Figs. 12 and 13), has a surface area of 6,150 m.^{2}. A narrow shelf borders most of the shoreline but along the east shore the stepped cliff falls to the floor of the trough. The boulders covering the shelf are interspersed with large amounts of silt, which is an extension of the fine soil covering most parts of the valley. The main feature of the trough, which has a maximum recorded depth of 4·3 m., is a series of parallel bars of silt or silt-covered rock, each less than 1 m. high and striking east—west. The dredge samples showed

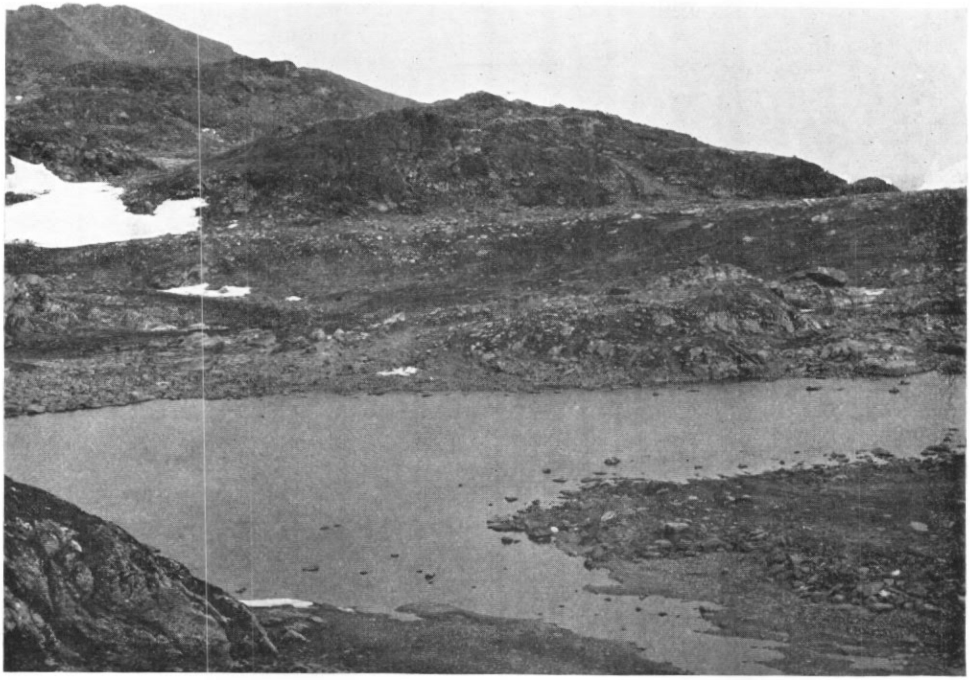

Fig. 12. Lake 10, south-east of Thulla Point, viewed from above the narrow gap north of the lake.

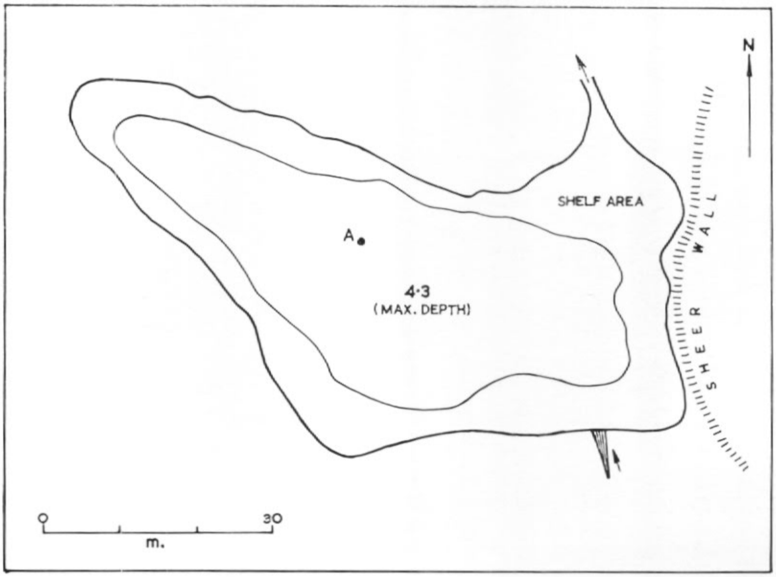

Fig. 13. Field-sketch outline of lake 10, showing the area of the sub-lacustrine shelf and the maximum recorded depth. The sampling station is marked by A.

that the amount of moss and lichen debris is very small compared with the amount of blue-green algal debris, and that broken anostracan egg cases contribute substantially to the upper sediments. The ratio of organic to inorganic material in the samples is approximately 1 : 1, and this suggests that the sediments are mainly inorganic and that the amount of organic matter is in fact small.

Origins of the lakes

Although a detailed geomorphological investigation is necessary before the origin of a lake can be discussed with any degree of certainty, general field observations suggest that several forms of glacial activity were involved in the formation of the lake system of Signy Island.

Lake 3 is clearly a proglacial lake of type 24e* (lakes dammed by ice), but it is not known whether the depression it occupies was either pre-glacial or excavated by ice. The topographic configuration of the valley suggests that should the ice-field retreat the water would not drain away but move west towards the fault scarp. At the time of the 1947–50 geological survey of Signy Island (Matthews and Maling, 1967) a second proglacial lake occupied a basin, consisting entirely or partly of ice, on the north shoulder of Jane Peak. However, by 1962 the walls of this basin had breeched and the water had drained away.

Lakes 4 and 12 (Fig. 14) have the significant features of cirque lakes (type 27a). They

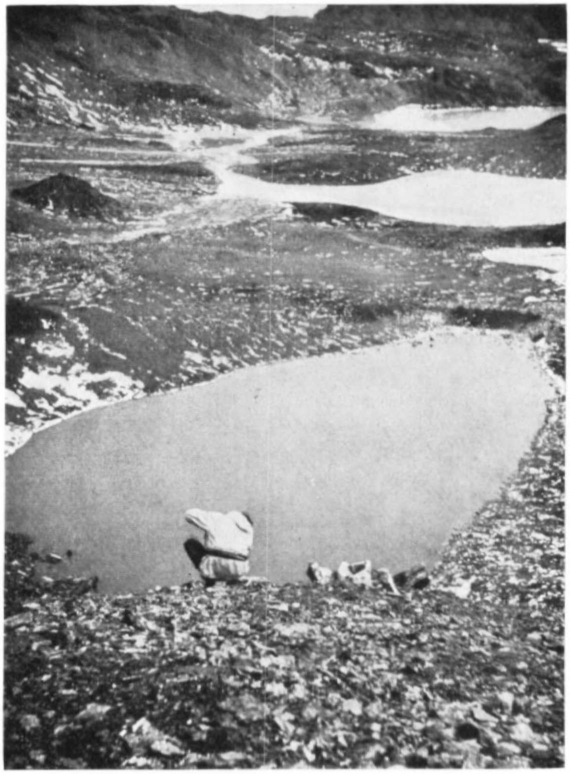

Fig. 14. Lakes 12 and 13 viewed from the ridge extending west to Jebsen Point. (Photograph by B. J. A. Goodman.)

occupy small but well-defined amphitheatres at the heads of glacial valleys. The entrances to the amphitheatres are blocked by low rocky outcrops and there is some evidence of moraines.

Several of the lakes may be ice-scour lakes (type 26). The morphology of lake 2 and the topography of its basin suggest that the lake occupies a depression formed by the ice scour of

* Types as defined by Hutchinson (1957).

fracture zones and/or shatter belts in a pre-glacial valley or plain. Matthews and Maling (1967) have reported that the buttresses forming the east face of Robin Peak and almost overhanging this part of Three Lakes Valley show evidence of glacial smoothing for only about 100 ft. (30·5 m.) a.s.l. The morphology of lake 5 appears to have been modified by heavy silting, but one outstanding feature is a residual island in the lake formed by a knob of resistant rock. This also appears to be an ice-scour lake and therefore the term "paternoster lake" (type 28a) is perhaps appropriate for lakes 2 and 5.

Lake 1 lies in the very narrow entrance of a relatively wide valley, and this topography suggests that the lake may also occupy an ice-scoured depression of the "glint" type (type 29).

Lake 11 is worthy of special note because it occupies a depression that may not have been excavated by ice. This steep-sided depression lies in a fold of a ridge overlooking the cirque east of Port Jebsen. It appears to have been formed as a result of damming by scree, stone movement or even lateral moraines at both ends of the fold.

Most of the other lakes appear to occupy drift basins—irregularities in ground moraine (type 34) or kettles (type 38). The thickness of glacial debris over the coastal lowlands of Signy Island is unknown, but it appears to be a thin veneer in such areas as the coastal plain of the west central catchment area and the cirque behind Cummings Cove. This might indicate that some of the lakes in these areas occupy irregularities largely determined by pre-glacial relief. However, the steep sides of the troughs present in these lakes are more characteristic of the ice-contact slopes of kettle lakes.

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REFERENCES

CHAMBERS, M. J. G. 1966*a*. Investigations of patterned ground at Signy Island, South Orkney Islands: I. Interpretation of mechanical analyses. *British Antarctic Survey Bulletin*, No. 9, 21-40.

————. 1966*b*. Investigations of patterned ground at Signy Island, South Orkney Islands: II. Temperature regimes in the active layer. *British Antarctic Survey Bulletin*, No. 10, 71-83.

————. 1967. Investigations of patterned ground at Signy Island, South Orkney Islands: III. Miniature patterns, frost heaving and general conclusions. *British Antarctic Survey Bulletin*, No. 12, 1-22.

HEYWOOD, R. B. 1967. The freshwater lakes of Signy Island and their fauna. (*In* SMITH, J. E., *organizer*. A discussion on the terrestrial Antarctic ecosystem. *Phil. Trans. R. Soc.*, Ser. B, **252,** No. 777, 347–62.)

HOLDGATE, M. W. 1964. Terrestrial ecology in the maritime Antarctic. (*In* CARRICK, R., HOLDGATE, M. *and* J. PRÉVOST, *ed. Biologie antarctique*. Paris, Hermann, 173-79.)

————., ALLEN, S. E. *and* M. J. G. CHAMBERS. 1967. A preliminary investigation of the soils of Signy Islands, South Orkney Islands. *British Antarctic Survey Bulletin*, No. 12, 53-71.

HUTCHINSON, G. E. 1957. *A treatise on limnology. Vol. I. Geography, physics, and chemistry*. New York, John Wiley and Sons, Inc.; London, Chapman and Hall Ltd.

MATTHEWS, D. H. *and* D. H. MALING. 1967. The geology of the South Orkney Islands: I. Signy Island. *Falkland Islands Dependencies Survey Scientific Reports*, No. 25, 32 pp.

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

RØEN, U. I. 1962. Studies on freshwater Entomostraca in Greenland, II. *Meddr Grønland*, **170**, Pt. 2, 1-249.