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Report No. 63

A Glacial History of the South Shetland Islands, Antarctica

by

James E. Curl

Institute of Polar Studies
and
Department of Geology and Minerology

September 1980

The Ohio State University
Institute of Polar Studies
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ABSTRACT

A glacial geology program was conducted in the South Shetland Islands. Field investigations concentrated on Byers Peninsula, Fildes Peninsula and in coastal embayments.

The tentative glacial history reconstructed for the South Shetland Islands demonstrates at least two distinct ages of glaciation separated by a warmer climate interval that is interpreted as the Sangamon Interglacial. Radiocarbon dates and lichenometric ages suggest that two late Neoglacial advances occurred at approximately 1475 A.D. and 1720 A.D.. The ice margins have thinned gradually since the Neoglacial fluctuations probably in response to the secular warming trend that commenced recently and extended until about 1940.

Both the long-term and short-term glacial fluctuations in the South Shetland Islands appear to be broadly synchronous with world-wide climatic trends.

ACKNOWLEDGMENTS

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INTRODUCTION

Location

The South Shetland Islands are situated about 725 km south-east of Cape Horn and approximately 160 km north-west of the Antarctic Peninsula (Fig. 1). These islands are a land link between Antarctica and South America, and they extend in a line roughly parallel to the coast of the Antarctic Peninsula. Almost all of the South Shetland Islands are ice covered, except for two ice-free peninsulas: Byers Peninsula and Fildes Peninsula (Fig. 2). This report is concerned primarily with these two areas, although a significant portion of the field work was performed close to the ice margins or along the coastal embayments.

Scientific Setting and Nature of the Problem

Recent advances toward a glacial history of East Antarctica (east of the Transantarctic Mountains) have resulted from investigations made in the ice-free "oases" surrounding McMurdo Sound in the Ross Sea area. But to date, only a tentative partial chronology involving several recognizable glacial and non-glacial stages has been produced (Calkin, 1964; Denton and others, 1970; Hollin, 1962; 1964; 1965). In West Antarctica (including the Transantarctic Mountains) the search for a comparable glacial record has proved more complex. This complexity is partially due to the extremely rugged terrain and the absence of large ice-free areas.

In West Antarctica, the northern Antarctic Peninsula and adjacent sub-antarctic islands beyond the present limits of shelf ice are ideally located for investigations leading toward a history of Quaternary and possible older glaciations. The South Shetland Islands and the Antarctic Peninsula are the only austral land masses that cut across the zone of circumpolar westerlies that serve as a transition area between the circulation of lower latitudes and the polar heat sink (Adie, 1964; Lamb, 1964). This region extends northward to within about 750 km of South America and separates the maritime climate of the Bellingshausen Sea from the continental climate to the south and east. As a result of the climatic and geographic setting of this area, it is probable that the glaciers, especially in the South Shetland Islands, have been and are more sensitive to "short term" changes in southern hemisphere climatic patterns than the large, cold, buffered ice masses elsewhere in Antarctica. In the South Shetland Islands evidence of glacial advance and retreat is preserved in the form of moraines and interrelated isostatically and eustatically produced raised-marine beaches ideal for studies directed toward understanding the relationship between the glacial-climatic history of Antarctica and that of other southern continents.

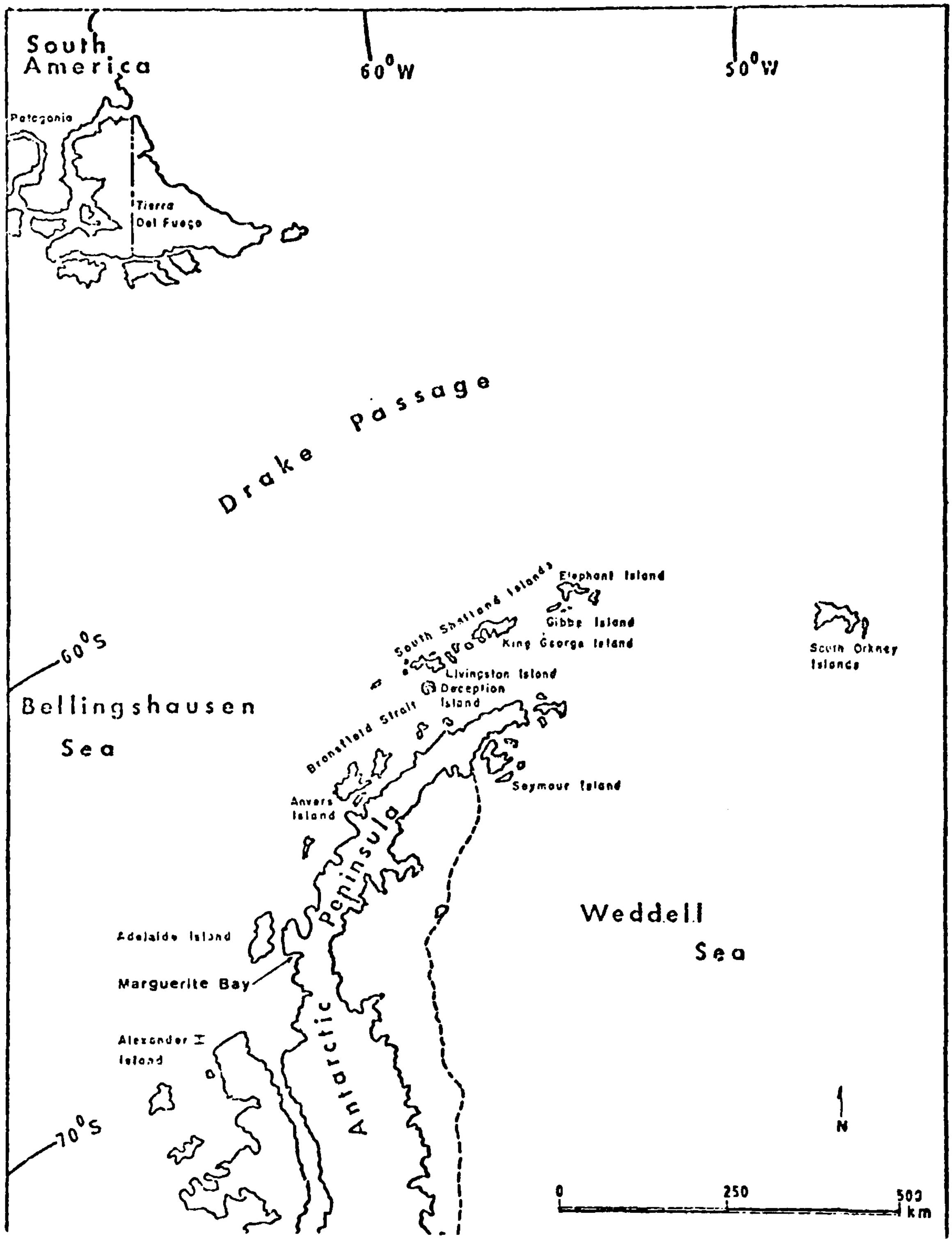

Fig. 1. Index map of the Northern Antarctic Peninsula and South America.

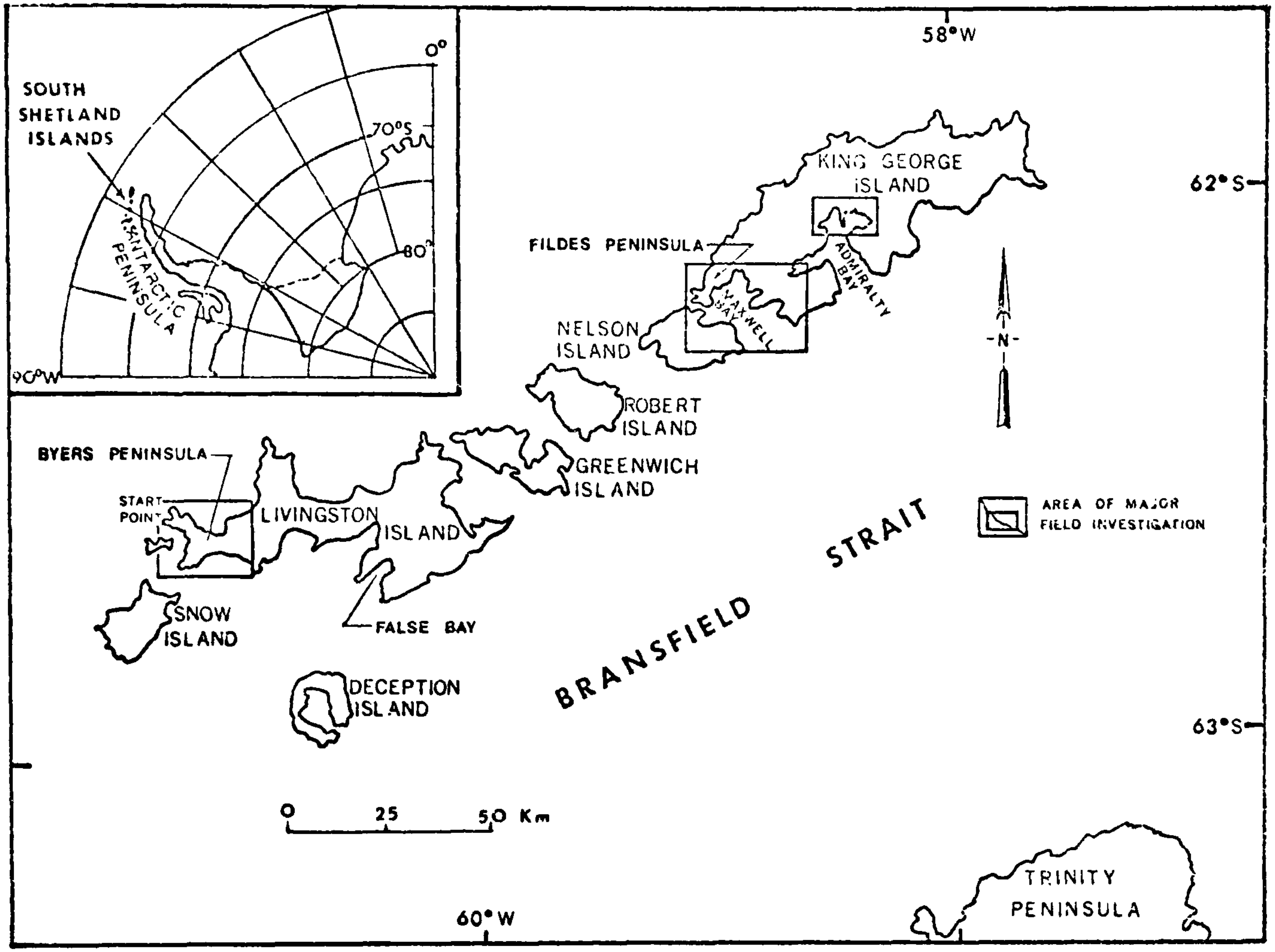

Fig. 2. Index map of the South Shetland Islands, Antarctica.

The purpose of this study was to determine the history of glacial events for the South Shetland Islands, where the behavior of small active glaciers, many of which terminate on land, should accurately reflect regional climatic and sea level variations.

The South Shetland Islands were selected as the site for this study because of their unique geographic position, accessibility, abundant evidence of glaciation, and the availability of a short climatic record (Pepper, 1954; Orheim, 1972).

Field investigations were conducted during the austral summer seasons of 1972-73 and 1973-74. The first season commenced December 16, 1972 and continued until severe storms forced evacuation from the islands on January 28. Subsequent field studies were begun January 10, 1974 and terminated February 15, when gales, snow storms and drifting ice became hazardous to the safe operation of the supporting vessel.

The field parties consisted of two members in 1972-73 and four members in 1973-74. All were transported to the South Shetland Islands from Tierra del Fuego aboard the National Science Foundation's R/V _Hero_. A network of strategically located equipment caches was established on each island of interest and the field work performed during a series of 2 to 14 day overland tent and/or Zodiac boat traverses between the supply bases. Transport between islands was accomplished with the aid of R/V _Hero_.

Primary field objectives included: (1) determining a history of glacial events based on the development of landforms and stratigraphic relationships; (2) local mapping and radiometric dating of moraines and related raised beaches on Livingston and King George Islands; and (3) lichenometric dating of "recent" moraines on Livingston Island.

In the field, maps were prepared by sketching on marine navigation charts or with an alidade and plane table. These maps are presented in the form of diagrams since no small-scale base maps and only limited aerial photographs were available.

Beach profiles below an altitude of 55 m were surveyed with a hand level and steel tape, while barometric elevations were corrected for temperature variation and adjusted for diurnal barometric changes showing on a 24 hour recording barograph stationed in the survey area.

All elevations were measured from actual sea level, are tide corrected, and are given in meters above "mean half-tide" as defined and recommended by the U.S. Coast and Geodetic Survey (Marmer, 1951). The "datum" references used are those included in the N.O.A.A. Tide Tables: High and Low Water Predictions 1972-74, East Coast of North and South

America Including Greenland (1973) and are also published on the U.S. Naval Hydrographic Office Charts (1960) that include the area under investigation.

Previous Work

The first documented record of discovery of the South Shetland Islands was made by William Smith, Captain of the brig Williams in February, 1819, but according to Captain J. Hornsburg (Mill, 1905), American sealers had been clandestinely catching in this region as early as 1812. Numerous brief accounts of the geology and physiography of the islands were entered in ships' logs during sealing and whaling operations between 1821 and about 1830.

Although his observations were made from aboard ship and at a distance, O. Holtedahl described the South Shetland Islands as being typically glacial features formerly in the sounds separating the island chain (Holtedahl, 1929). R.L. Nichols, a member of the Ronne Antarctic Expedition, (1947-48), was one of the first geomorphologists to investigate the Antarctic Peninsula region with his work in Marguerite Bay (Fig. 1). Nichols described a sequence of more than 20 well-developed raised beaches and erosional effects. Nichols' findings questioned Wright and Priestly's (1922) thesis for a late Tertiary build-up of an Antarctic ice age. Such a build-up following middle to late Tertiary volcanism could have preceeded the Pleistocene Glaciations of the rest of the world (Nichols, 1947).

Until recently most investigations of the South Shetland Islands have been concerned with bedrock, with only minor attention devoted to glacial and surficial geology. Marine-raised beaches and glacially reworked landscapes were observed by Andersson (1906), Ferguson (1921), Hattersley-Smith (1949), Bibby (1961), Ferrar (1962), Barton (1965), Aráya and Herve (1966), and Hobbs (1968), but these investigations were principally bedrock oriented. The geomorphological aspects of these accounts have been summarized by Adie (1964) and Nichols (1964) and emphasize the importance of the relationship between glacial history and sea levels, especially during the Late Tertiary and Quaternary of Antarctica. This is significant because, while eustatic changes are of a world-wide nature, isostatic changes are regional and may reflect partial deglaciation of the Antarctic continent (Adie, 1964). Commenting on the record of former sea levels and the shallow depth of the continental shelf of this region, Adie (1964) concludes, "This part of Antarctica has clearly suffered severe submergence to a depth of at least 305 m in the past." Here glaciation during the Pleistocene(?) subjected the peninsula region to heavy glacial loads. Minor fluctuations during deglaciation are preserved by a nearly complete record of minor sea-level changes (Adie, 1964).

Only in recent years have detailed glacial geologic field studies been conducted in the South Shetland Islands. As a result of a pedologic field study conducted on Livingston Island during the austral summer of 1968-69, Everett (1971) suggested that this island records at least three glacial events. During the oldest advance (Livingston Event) all areas of the island below about 200 m were covered by an expanded ice cap, which may have joined that of the adjacent islands. Based mainly on stratigraphic evidence, Everett noted that subsequent glacier advance (False Bay Event) probably did not exceed the limits of the present ice cover. A third minor, and probably relatively recent, glacial advance (Post-False Bay Event) was recorded in cirques and push moraines from which the ice has now receded (Everett, 1971). Although no attempt was made to establish a chronology of these episodes, Everett was the first to publish a description of this series of glacial events based on direct field observation.

John's (1972) and John and Sugden's (1971) conclusions from preliminary examination of marine and glacial features in many of the South Shetland Islands, were similar to those of Everett. Two distinct phases of glaciation were recognized, possibly separated by a warm climatic interval. In addition, John and Sugden reviewed the stages of landscape evolution in the light of similar evidence from elsewhere in the Antarctic Peninsula, Patagonia, and Tierra del Fuego. Their conclusions are in agreement with Mercer's (1968b) chronology for Patagonia.

Later investigations by John (1972) and Sugden and John (1973) on King George Island (Fig. 1) conducted concurrently with this study, did suggest a tentative partial glacial history. The older "major glaciation" (Livingston Event, Everett, 1971) was considered to be Illinoian or earlier, the non-glacial interval was Sangamon, and the "less intense glaciation" (False Bay Event, Everett, 1971) was Wisconsin.

GEOLOGIC AND CLIMATIC BACKGROUND

Geology

The bedrock geology of the South Shetland Islands is fairly well known from field investigations by Tyrell (1921), Adie (1955; 1957; 1962; 1964) Hawkes (1961), Barton (1965), Bibby (1961; 1965), Ashcroft (1972), and Hobbs (1968). These islands are an extension of the Scotia Arc (Fig. 3), a prominent and continuous arcuate submarine ridge linking Southern Patagonia with the Antarctic Peninsula (Adie, 1964).

The rocks range in age from Precambrian through Middle to Late-Tertiary in age and are composed of sediments, metasediments, volcanics, and a Late-Cretaceous to Tertiary (?) Andean Intrusive Suite. The geology is similar to that of the Antarctic Peninsula.

The oldest rocks (False Bay Schists) are medium grained regionally metamorphosed geosynclinal sediments exposed over a small area of Livingston Island where they dip steeply northward. Old well-indurated volcanic rocks occur on Livingston and King George Islands, but their relationship to the geosynclinal sediments is not clear (Barton, 1965). These volcanic rocks are older than the Andean batholiths, which form the central portion of both islands.

This central "core" of the islands (Andean intrusives) is overlain by a less dense metamorphic basement, above which Jurassic through Tertiary lavas have been extruded from vents parallel to the length of the islands. These vents mark the sites of tension faults (Ashcroft, 1972) and both faulting and volcanicity have continued intermittently until the recent.

Crustal Structure

Ashcroft (1972) suggested that the Upper-Paleozoic sediments, which occur on both the South Shetland Islands and the Antarctic Peninsula, were deposited in a single geosynclinal trough that subsequently underwent folding and plutonic intrusion. Later, as part of a regional process of continental drift, a portion of the Antarctic Peninsula moved northwestward relative to the peninsula, forming the South Shetland Islands.

The present position of the islands and peninsula is the result of earlier drifting towards the southeast from the northwest. This movement was in response to sea-floor spreading of the Pacific Ocean in the vicinity of the subdued trench located in the Drake Passage northwest of the South Shetland Islands (Fig. 4). During this drifting process

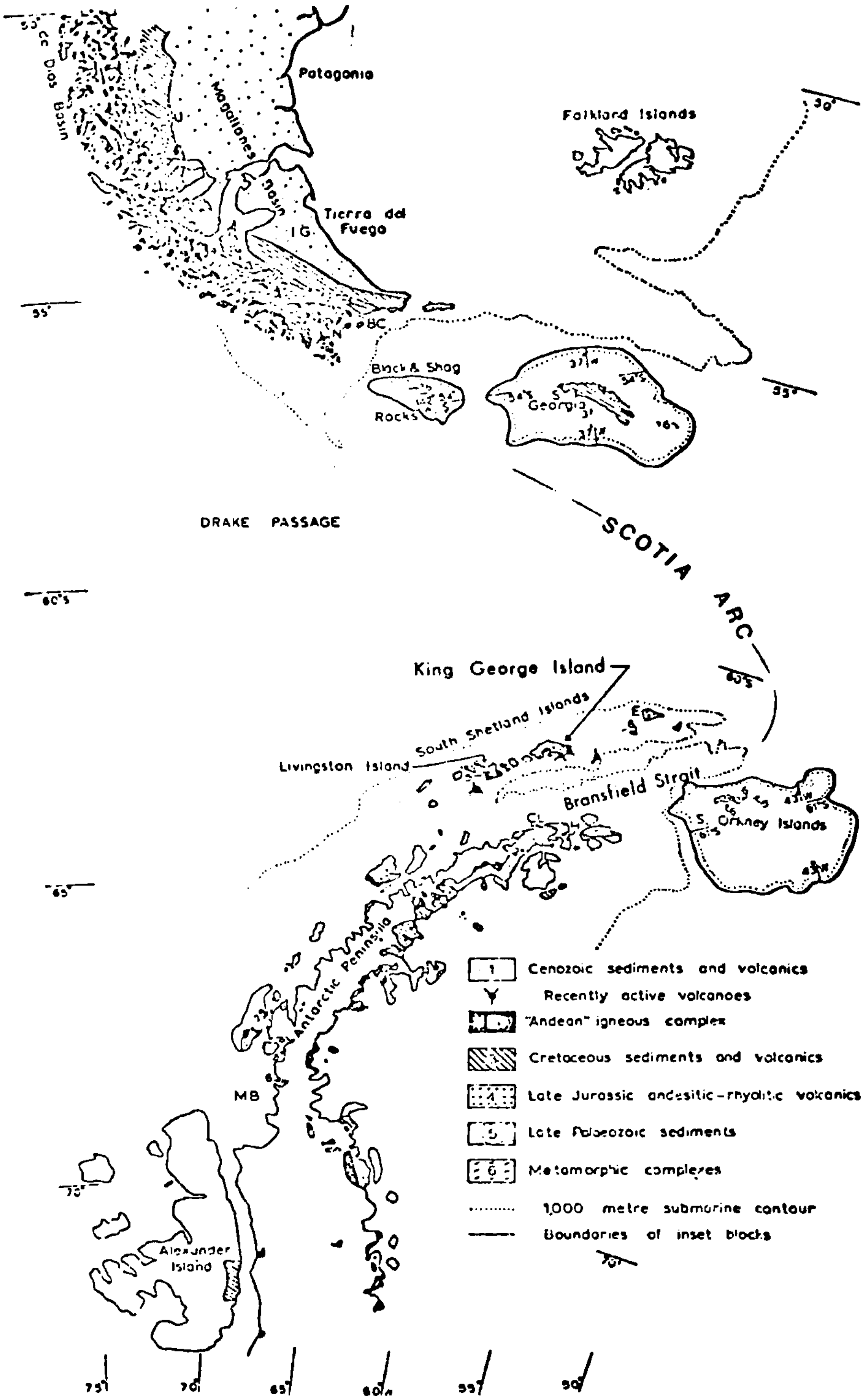

Fig. 3. Geologic map of the Scotia Arc region. After Elliot, 1975.

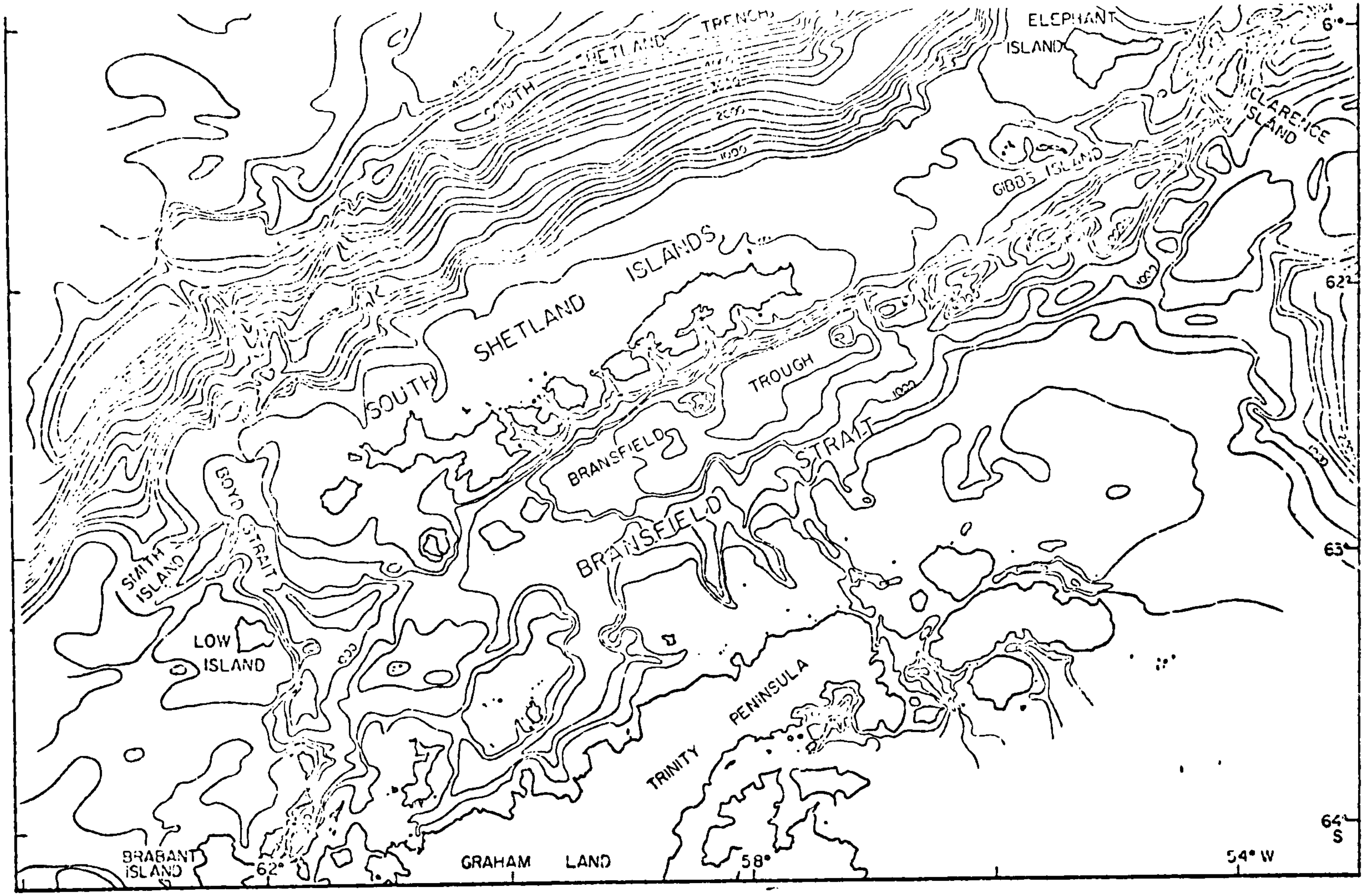

Fig. 4. Bathymetric contour map of the Bransfield Strait area. Contours at 250 m intervals. From Griffiths and others, 1964.

(toward the southeast) from the spreading center, Tertiary rifting in the Bransfield Strait produced a marginal trough over oceanic crust (Fig. 5) and separation of the South Shetland Islands from the Antarctic Peninsula occurred contemporaneously with the development of the trough.

This now inactive spreading center in the Drake Passage has magnetic anomalies associated with it that are at least 20 million years old. The mildly alkaline volcanism in the vicinity of Deception Island is probably related to the further opening and subsidence (along the subduction zone) of the Bransfield Trough (Ashcroft, 1972; Davey, 1972). This volcanic activity has been suggested by Barton (1965) to have persisted spasmodically from at least the Cretaceous or early Tertiary until contemporary times, as evidenced by eruptions on Deception Island as recently as 1971.

Andean Orogeny

The main uplift of the South Shetland Islands probably took place in early Tertiary time (?) as a result of the Andean Orogeny accompanied by major batholithic intrusions and associated block and transcurrent faulting (Ashcroft, 1972).

Magnetic, gravity, and seismic data further characterize the northern margin of the Bransfield Strait as a major fault or fault zone. A Bouguer anomaly of + 130 mgal was associated with about a 2.5 km minimum upthrow of the South Shetland Islands relative to the Bransfield Trough that is believed to have occurred contemporaneously with the emplacement of the Andean granodiorite batholiths (Griffiths and others, 1964; Ashcroft, 1972). On the southeast side of Bransfield Strait, similar normal faults were associated with the block uplift of Trinity Peninsula (Fig. 5).

It was not until intrusion of the Andean Intrusive Suite that the islands and peninsula achieved much of their present elevation, and for the first time several islands of the South Shetland Archipelago emerged above the sea (Barton, 1964).

The oceanic trench (Bransfield Trough) fronting the South Shetland Islands appears to represent the latest stage of island arc formation in this area. At the present time, the only active area of the Scotia Arc appears to have shifted northeastward to the South Sandwich Islands (Barker and Griffiths, 1972; Dalziel and Elliot, 1972; 1973; Elliot, 1975).

This evidence suggests that the major period of block faulting and uplift in the South Shetland Islands probably ceased, or was reduced considerably, soon after uplift of the Andean Orogen in the Antarctic Peninsula. Although occasional volcanism (related to the Bransfield Trough) has persisted until the present, more recent vertical adjustments

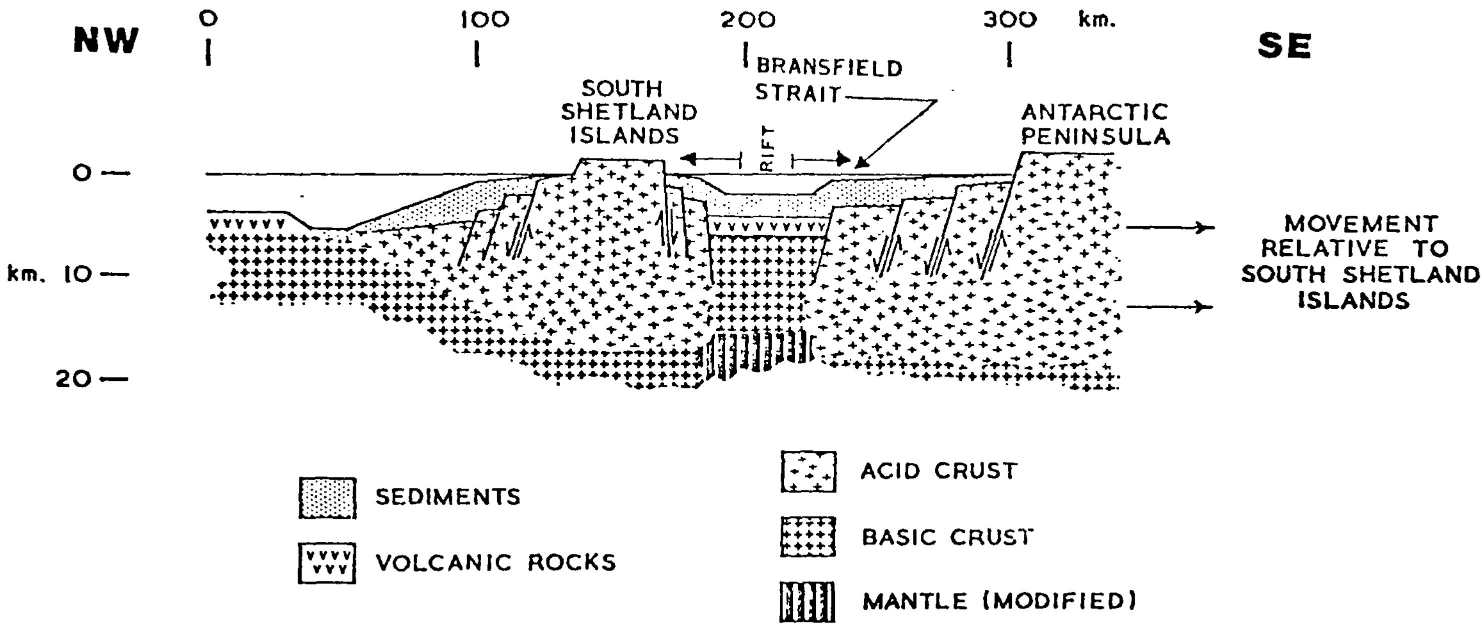

Fig. 5. Schematic diagram illustrating the hypothetical origin of the Bransfield Strait by a process of rifting. After Ashcroft, 1972.

other than those produced by glacio-isostatic and eustatic influences are not indicated.

Stratigraphy

The stratigraphic succession of Livingston Island is broadly comparable with that of King George Island (Table 1). But sediments of Cretaceous age are apparently absent on Livingston Island and it would appear that at this time the island was above sea level (Hobbs, 1968).

Towards the end of the Oligocene, renewed volcanic activity occurred. The occurrence of conglomerates and sandstones interbedded with tuffs, lavas, andesitic agglomerates and basalts suggests that many of these volcanic eruptions occurred in a shallow submarine environment. At different times this submarine ridge must have risen above sea level resulting in the growth of a considerable vegetative cover during Oligocene-Miocene times (Hobbs, 1968).

Tertiary Fossil Floras

On King George Island, fossil plant fragments of *Nothofagus*, *Araucaria*, and *Equisetum* are found scattered through volcanics and sediments. No marine fossils have yet been found in these sediments (Barton, 1964) which exhibit ripplemarks, suncracks, and current bedding.

During the period of deposition of the plant beds, sedimentation was probably local and non-marine, suggesting deposition in shallow fresh-water lakes or streams in a temperate environment. Adie (1962) and Barton (1964; 1965) conclude that the climate of the islands has become much cooler since deposition of these plant beds.

By Pliocene or Pleistocene times the climate had become sufficiently cold for the establishment of permanent ice caps. At least once during this time the sea covered part of Livingston and King George Islands, and a littoral conglomerate interbedded with volcanics (Williams Point conglomerate and Lions Rump Group) that contained *Pecten* and other marine organisms was deposited (Barton, 1964).

Vulcanism continued spasmodically through the Pleistocene, terminating on King George and Livingston Islands in recent times after the formation of numerous small ash and scoria cones (Barton, 1965).

Present Ice Cover

The most important effect of the climate is the present ice cover. The South Shetland Islands are almost totally covered by ice. Broad low ice domes dominate landscape of gentle relief and in many places extend

Table 1.

Stratigraphy of Livingston and King George Islands. From Hobbs, 1968.

	Livingston Island	King George Island (modified after Hawkes (1961) and Barton (1965))
Recent	Glacial deposits Raised beaches	Penguin Island Group
Pliocene	Williams Point conglomerate	Lions Rump Group
Miocene Oligocene	(Dykes) Younger Volcanic Group (andesitic tuffs and lavas with interbedded conglomerates and sandstones)	Point Hennequin Group Fildes Peninsula Group Ezcurra Inlet Group Dufayel Island Group
Late Cretaceous to early Tertiary	Andean Intrusive Suite	Andean Intrusive Suite
Upper Cretaceous (Lower-Middle Campanian)		
Lower Cretaceous (Aptian)		
Upper Jurassic	Older Volcanic Group	Jurassic volcanic rocks
Middle Jurassic		
Triassic	Plant-bearing boulders within Younger Volcanic Group	
(?)Carboniferous	Miers Bluff Series	
Early Paleozoic		
(?)Precambrian	False Bay schists	Basement Complex

to the coast, where ice calving produces sharp ice cliffs (Fig. 6). In mountainous areas, valley and cirque glaciers occur, many of which also terminate at or near the sea (Fig. 7).

Several peninsulas adjacent to the ice domes are presently ice-free. Byers Peninsula of Livingston Island is the most extensive. King George Island has several ice-free areas, the largest of which are Fildes Peninsula and Barton Peninsula. Many other ice-free peninsulas and embayments fringe the coastline on both islands.

The summit altitudes of the ice caps measured during this study were: The Rotch Ice Dome, 350 m; ice dome east of Fildes Peninsula, 280 m; and the ice cap above the Stenhouse Glacier, Admiralty Bay, 600 m (all altitudes by Paulin altimeter).

Effect of Recent Climate on the Ice Cover

Glaciological studies were conducted in the South Shetland Islands by G. Hattersley-Smith in 1948-49; H.M. Nobel, 1958; M.J. Stansbury, 1959-60; and by O. Orheim, 1968-74. Continental Antarctica is generally unsuitable for directly inferring variations in annual net mass balance with variations in temperature, because with minor exceptions, little or no ablation occurs and the annual balance at a given site is controlled almost completely by precipitation (snow accumulation).

Orheim (1972) demonstrated that this is not the case in portions of the northern Antarctic Peninsula including the South Shetland Islands. Summer temperatures are well above melting and produce enough melting to cause many of the glaciers to terminate on land. Here variations in the annual balance are controlled more by temperature related ablation in summer than by snow accumulation in winter. Orheim's study implies that long-term variations in the climate should be reflected by variations in the glaciers.

Mass balance measurements made previously and during this study on Deception, Livingston, and King George Islands show that all glaciers below an altitude of about 500-600 m are temperate. The firn line varied from below 100 m on the Stenhouse Glacier, Admiralty Bay, and on Huntress and Charity Glaciers, False Bay, to between 100-200 m on cirque glaciers of the same islands. Measurements of the net annual accumulation for the ice cap above Admiralty Bay (600 m) were between 75-100 cm of water equivalent per year. The Stenhouse Glacier, a large valley glacier (1,500 m x 2,100 m), is fed by this ice cap, which at its lower limit discharges into Admiralty Bay.

The velocity measured near the terminus of the Stenhouse Glacier was about 150 cm day^{-1}, so the major budget loss for this glacier was mainly

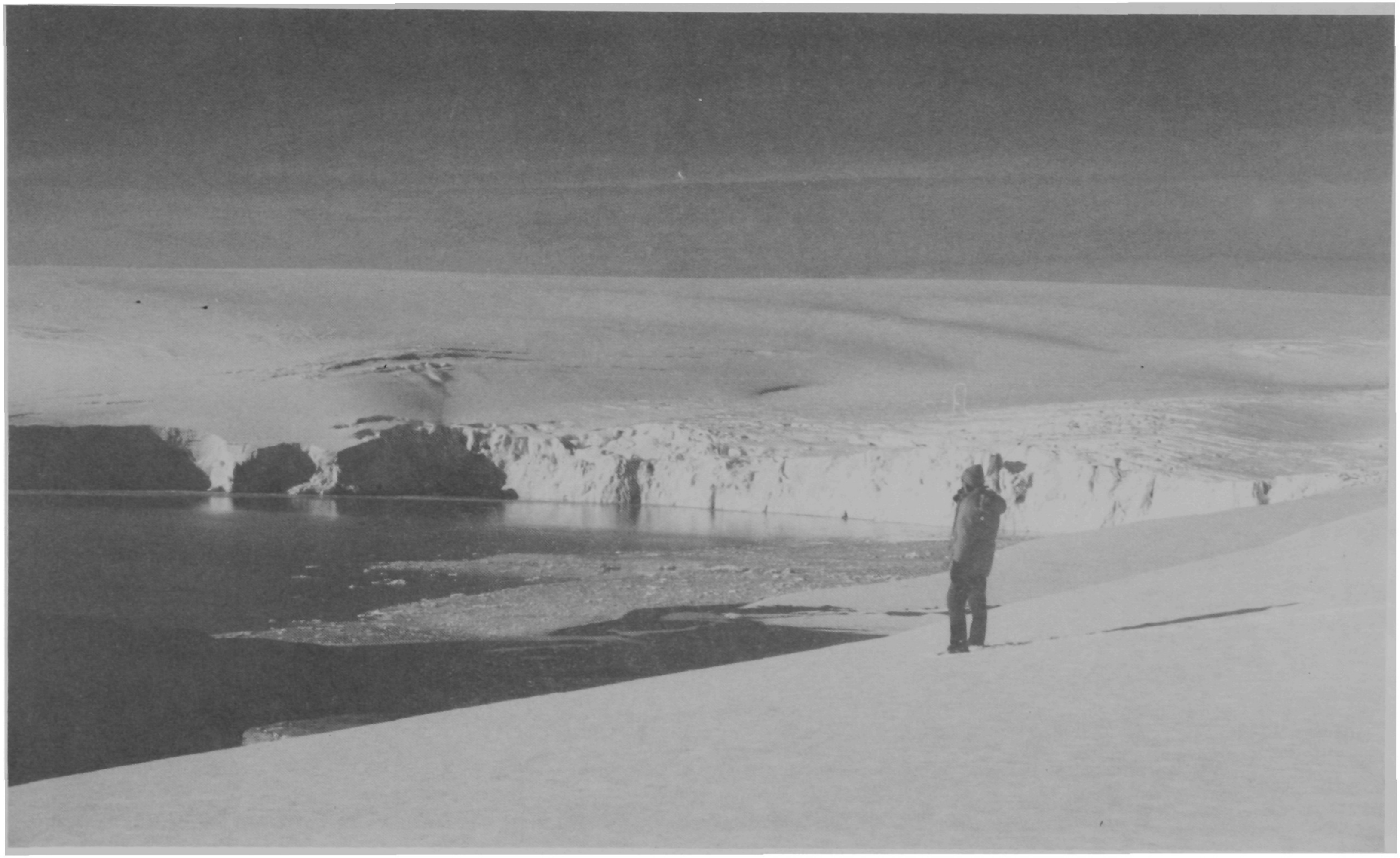

Fig. 6. Ice calving from central ice cap into Potter Cove, King George Island.

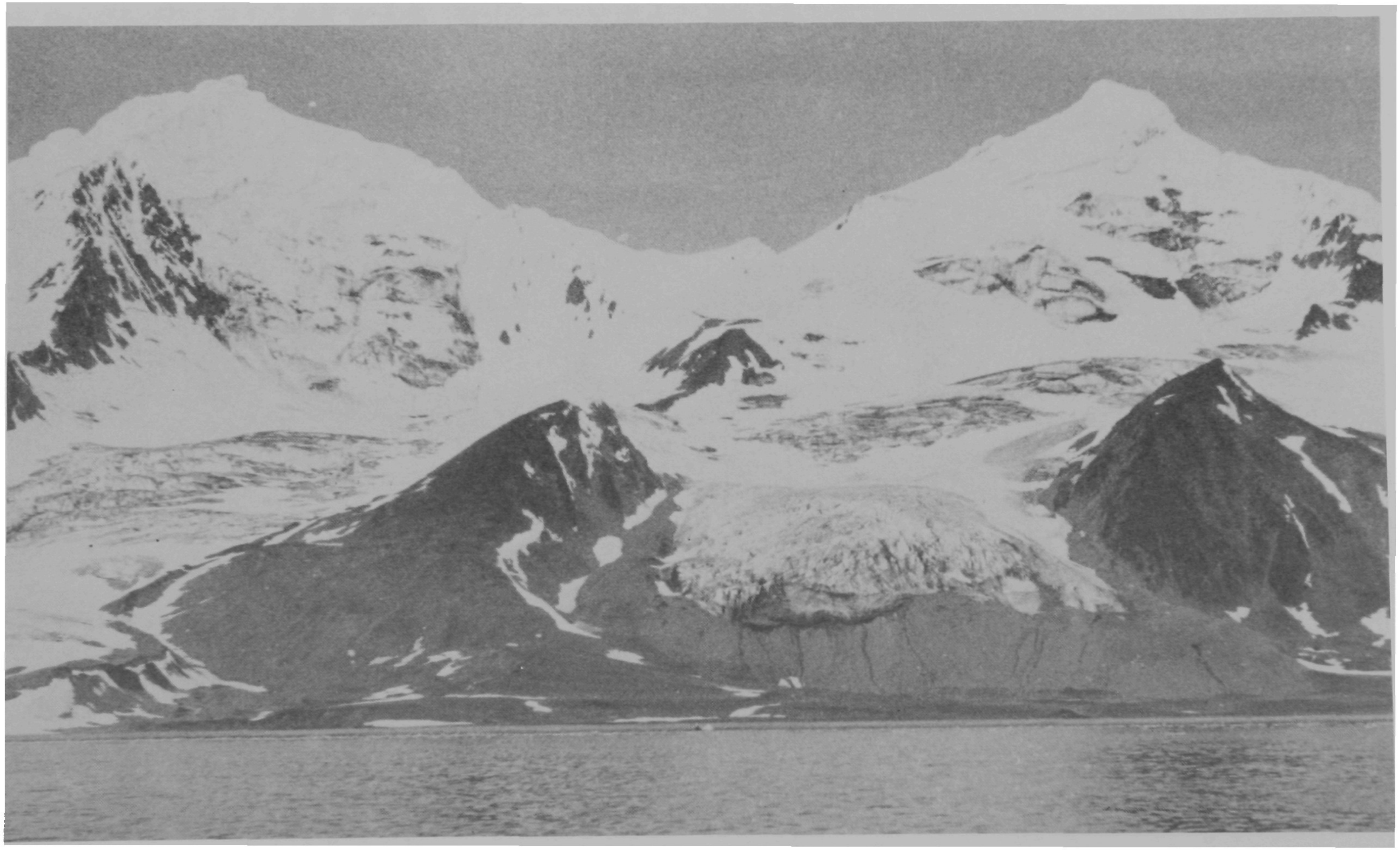

Fig. 7. Cirque and valley outlet glaciers terminating on land about 50 m above present sea-level. View facing east, at False Bay, Livingston Island.

due to calving into the bay. During 1957-58 the net budget showed a mean loss equivalent to only 5 cm of water, which indicates a condition near equilibrium (Robin and Adie, 1964). The mass balance of the Rotch Ice Dome and Glacier G-1 (Deception Island) during the period 1968-73 were also near equilibrium or slightly negative (Orheim, 1972).

The present near-equilibrium to slightly negative condition of all the glaciers studied appears typical of the islands, and from geologic evidence revealed at the ice margins of these and other glaciers, it was concluded that no detectable major advance had occurred within about the past two centuries. There was only intermittent retreat and thinning which is probably in response to the global warming trend that occurred between about 1870 and 1940 (Mitchell, 1961; 1963; Orheim, 1972).

A minor advance (dated during this study) indicated by push moraines at the terminus of several small glaciers occurred shortly before this 70-year retreat. This slight advance is also indicated by a series of moraines below cirque glaciers at False Bay, Livingston Island, and ice-covered moraines near Stranger Point, King George Island. Crests of the well developed ice-cored moraines stood about 8-10 m above the ice terminus, indicating a recent slight lowering of the ice cap margins.

DESCRIPTION OF THE STUDY AREA

Byers Peninsula

Byers Peninsula, Livingston Island is the largest ice-free area (66 km^2) in the South Shetland Islands (Fig. 8). The predominant rocks are basaltic agglomerates and augite andesites; these subsequently were eroded by glacier activity and marine planation.

The central portion of Byers Peninsula consists of an elevated erosional platform of subdued relief (± 20 m) about 40 km^2 in area. The mean altitude of this platform is about 85 m; it reaches a maximum elevation of about 100 m in the geographic center near Chester Cone. This high region is covered with numerous volcanic plugs that extend above its surface as much as 192 m (Hobbs, 1968) in the vicinity of Start Point (Fig. 9).

Byers Peninsula is separated from Rotch Ice Dome and the island ice cap which is to the east, by an arcuate band of multiple crested end moraines (Fig. 10).

The periphery of the 85 m platform on the remaining three sides consists of a step-like series of sub-areal and marine erosional platforms and surfaces followed by a complex sequence of raised beaches gradually extending to sea level.

Toward the margin of the central platform, wide shallow valleys, emanating in a radial pattern from the Chester Cone area, vary from 5-20 m deep. These valleys become steep-sided "V" cut-channels where they reach the platform edge. The periphery itself is a prominent cliff trending approximately parallel to the present coastline.

This cliff-line marks the edge of the 85 m platform and drops at an angle of 35^o to 42^o to the erosional surfaces and wave-cut platforms below. At an altitude of approximately 20 m, this steep profile flattens abruptly to a nearly horizontal bedrock terrace, into which a series of modern and raised marine beaches have been incised.

Along South Beaches, between Vietor Rock and Elephant Point, this series of sandy and pebbly raised beaches is about 500-1,000 m wide (Fig. 11). Similar beach widths occur along the western coastline, but on the north side of Robbery Beaches the raised beach sequence is no more than 100 m wide. To the northwest along the coastline the profile becomes much steeper and is almost vertical between Essex Point and Richards Cove.

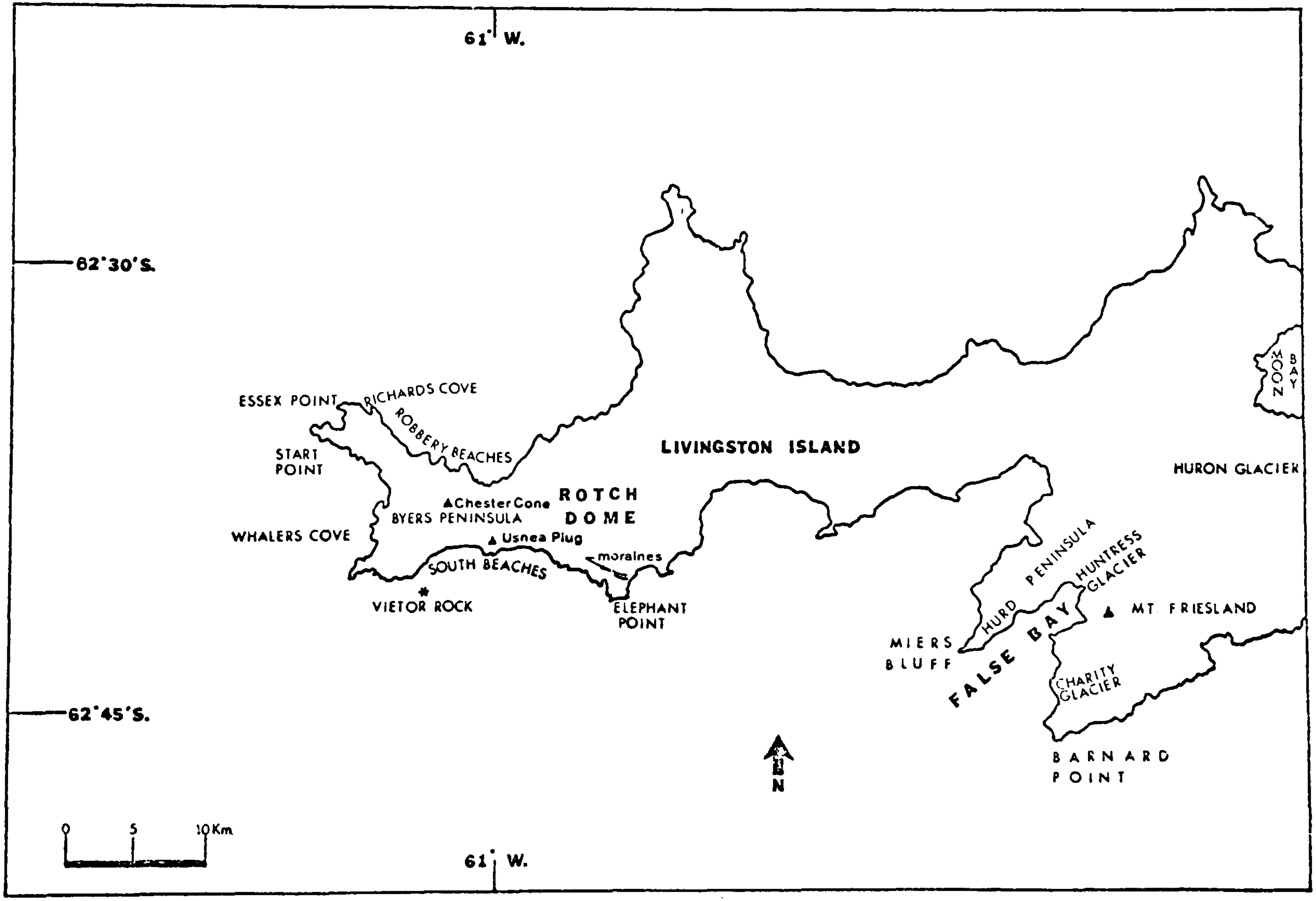

Fig. 8. Index map of Livingston Island, Antarctica.

Figu. 9. Panorama of Byers Peninsula looking westward from Rotch Ice Dome.

Fig. 10. Arcuate, crested end moraines separating the western margin of the Rotch Ice Dome from Byers Peninsula.

Fig. 11. Raised beach series along South Beaches between Vietor Rock and Usnea Plug. Maximum width of beach below 20 m elevation was 1100 m.

The contrast between the north and south coasts is believed to be due to the effects of wave action. The submarine profile is much steeper along the northwest coast of Livingston Island, reaching 124 m one mile north of Start Point and it is also this coast that faces the direction of the most prevalent summer winds. According to Davies (1964), these islands lie in the Southern Hemisphere storm belt, in a high energy storm-wave environment where cliffing and the mechanical formation of shore platforms is at a maximum. Sea ice seldom extends to the north-west of the island chain and marine action is prevalent throughout the year, whereas the southeastern coasts are protected by fast ice for about 6 to 8 months each year.

The submarine profile to the south of Livingston Island is more gentle (18 m in one mile along south beaches), and it is suggested that the shallow bottom restricts beach erosion in two ways by restricting the size or thickness of drifting ice reaching the beaches, and by forcing the waves to crest at a distance from the beach, which partially dissipates their energy on the offshore bottom. Consequently, the most completely preserved raised beach sequences are formed along south-facing coastlines and in protected embayments.

False Bay

False Bay (15 km^2) is the most spectacular region of Livingston Island (Fig. 12). It is characterized by high ice-covered peaks and glaciers flowing from the mountains to the sea. On the western side of the bay, the island ice cap extends across a wide plateau, Hurd Peninsula, which flows between mountain peaks along its margin eventually calving into the bay.

The most prominent topographic feature of False Bay is the horned peaks of the Mt. Friesland massif. These peaks rise abruptly to an altitude of 1,600 m to the northeast. Hurd Peninsula (185 m) with its numerous mountain peaks (averaging 350 m) flank the northwestern side of the bay.

According to Hobbs (1968), False Bay is a fault-controlled indentation presumably resulting from the Andean Orogeny. A ridge underlain by the Mt. Friesland massif, on the upthrown side of the fault, trends east-northeast from Barnard Point in the southwest to Renier Point in the northeast, a distance of 34 km. This ridge averages about 750 m in altitude, except in the vicinity of Mt. Friesland. The massif is composed of tonalite (Andean Intrusive Suite) and minor hornblende schist (False Bay Schist), whereas the southwestern mountains of Miers Bluff and Hurd Peninsula, on the opposite side of the fault, consist of greywacke-shale flysch-type deposits (Miers Bluff Group).

Fig. 12. View of False Bay looking NE from open water. Charity Glacier is in the right foreground.

The central part of the fault trench separating the two mountain ridges reaches an elevation of about 550 m and forms a divide transverse to the long axis of the bay that is occupied by two glaciers. The Huron Glacier flows eastward into Moon Bay, whereas the Huntress Glacier (8 km x 3.2 km) flows along the fault trace into the headwaters of False Bay (Fig. 13).

Charity Glacier originates on the southwest slope of Mt. Friesland and flows southwestward between two horned peaks into False Bay (Fig. 14). This glacier is about 8 km long, and nearly 2 km wide at its terminus. Multiple-crested lateral moraines and protalus ramparts flank the southern margin.

Although Charity Glacier is actively calving into the bay, the base rests on solid ground about 1.8 m above present mean tide. The terminus is an ice cliff about 20 m high (Fig. 15). The vertical face and high grounding line are partially the result of wave erosion during severe storms.

The snow line in mid-January of 1973 was slightly less than 100 m, which was about the same elevation measured on the Huntress Glacier. The low altitude of the snow lines is probably due to katabatic winds that do not affect the smaller glaciers.

Valley outlet glaciers drain ice from the central ice cap across Hurd Peninsula. The upper limits of these glaciers are formed along the perimeter of the peninsula, and they have remarkably steep gradients. These glaciers are fed by ice flowing through cols from the 185 m elevation of the peninsula, are heavily crevassed, and then resemble ice falls (Fig. 16). Although the main source is from the glaciers above, the upper end is above the snow line and some accumulation is due to direct precipitation. All of these glaciers reach the bay so major net loss is through calving.

Numerous small glaciers flow from cirques toward the bay from both mountain ranges (Fig. 17). Several of these cirques no longer contain glaciers or they are occupied by decaying stationary ice, and nearly all cirque glaciers terminate in the highlands at least 50-75 m above sea level. Figure 18 is typical of several small glaciers located near Miers Bluff. The presence of cirque glaciers peripheral to Hurd Peninsula is indicative of former and more active glaciation, since these features are produced only at times of reduced ice flow across the peninsula. During periods of ice advance across the plateau, these glaciers must rapidly increase in size.

Well preserved multiple crested end moraines are developed at several elevations below many of the cirque glaciers (Fig. 17). Some are closely associated with raised beaches. This relationship has provided a means

Fig. 13. Huntress Glacier calving into headwaters of False Bay. Mt. Friesland is the high mountain peak to the right of the glacier.

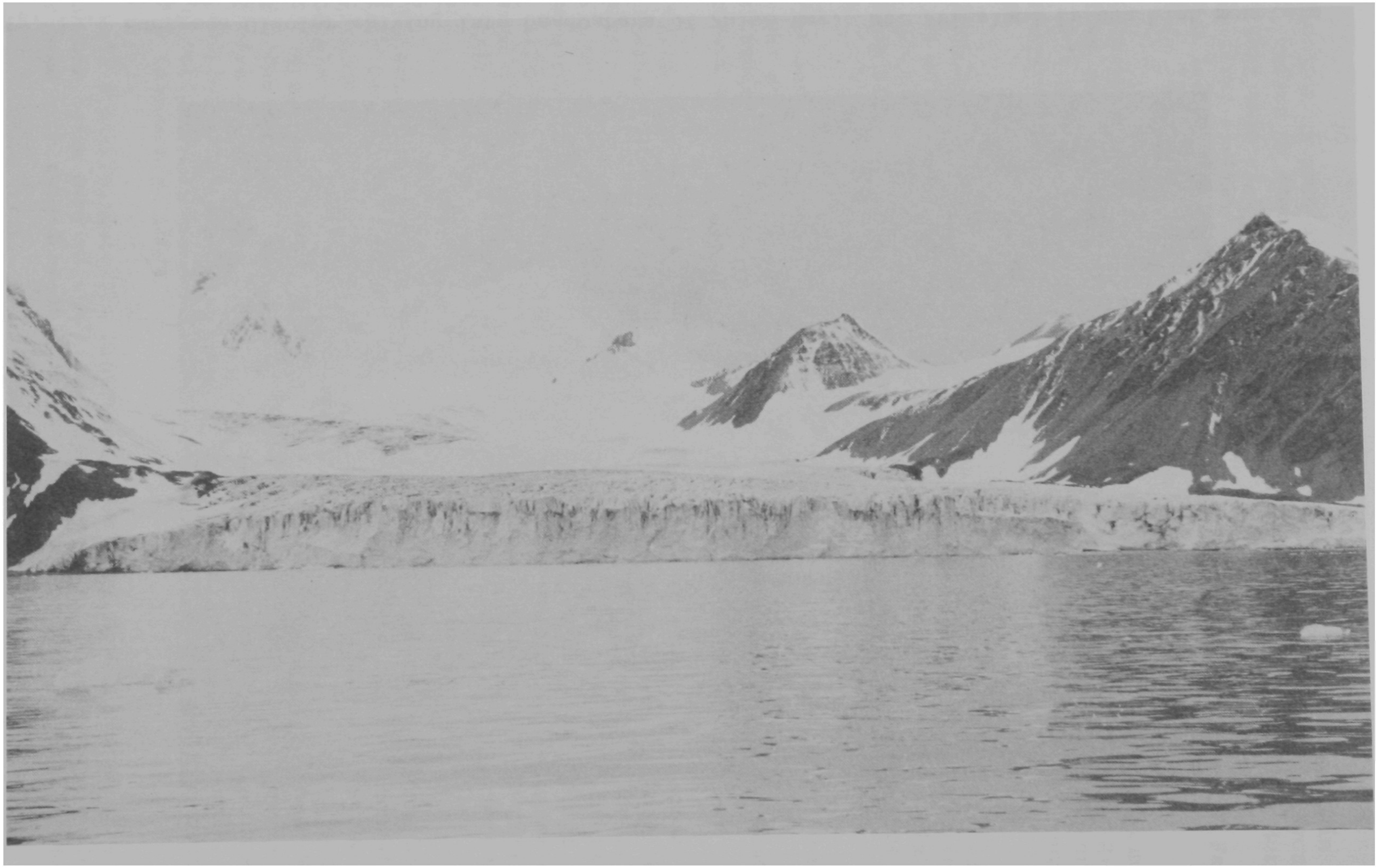

Fig. 14. Charity Glacier calving into False Bay, Livingston Island.

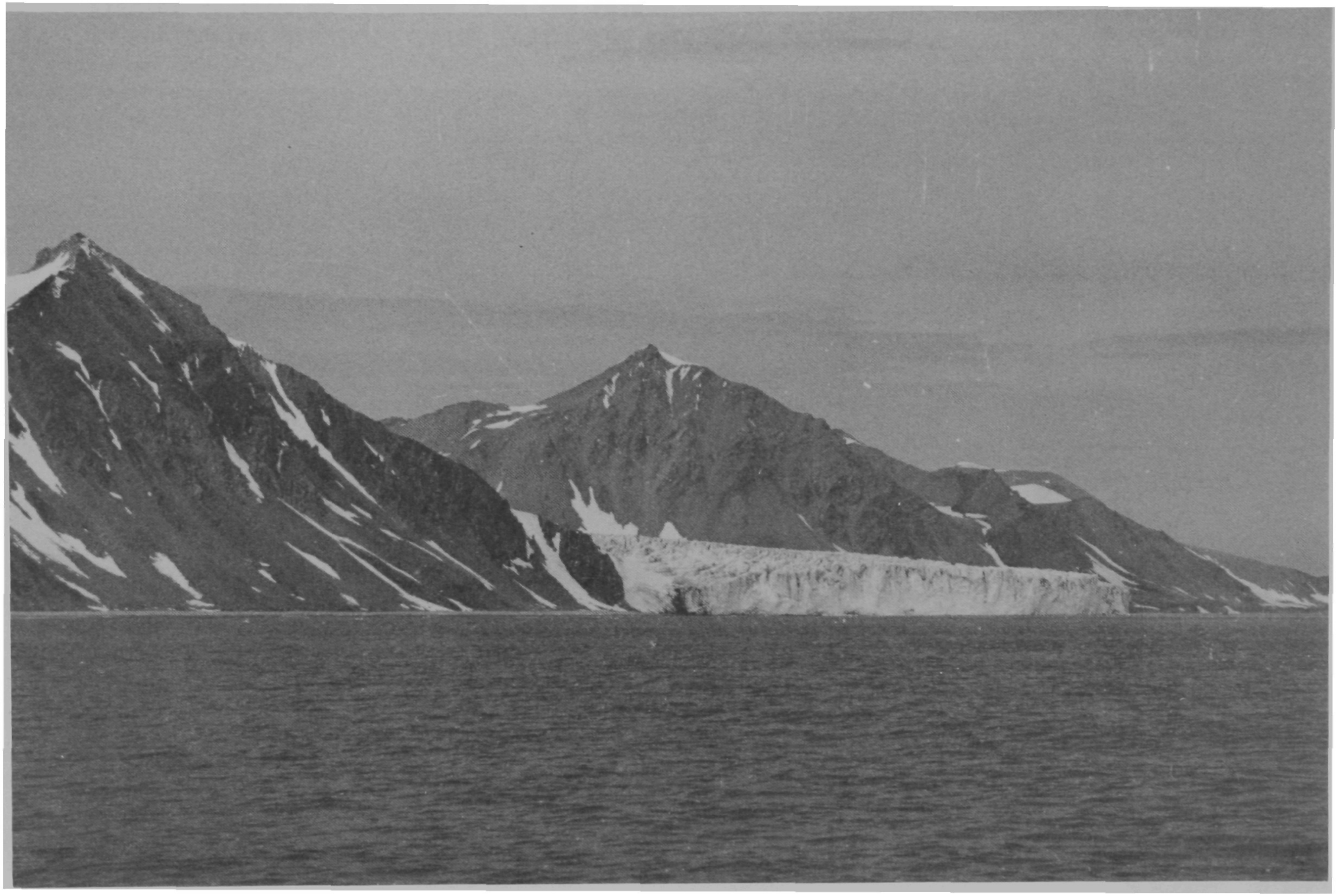

Fig. 15. Vertical ice cliff at terminus of Charity Glacier. The base of the glacier is residing on beach materials 1.8 m above sea level.

Figure 16. Valley outlet glacier calving into False Bay, Livingston Island. The source of this glacier is from ice flowing from the island ice cap across Hurd Peninsula and through the col.

Fig. 17. Cirque glacier flowing east near Miers Bluff. The snow line altitute is 103 m. Ice is presently flowing to this glacier from Hurd Peninsula through the col at the glaciers headwall.

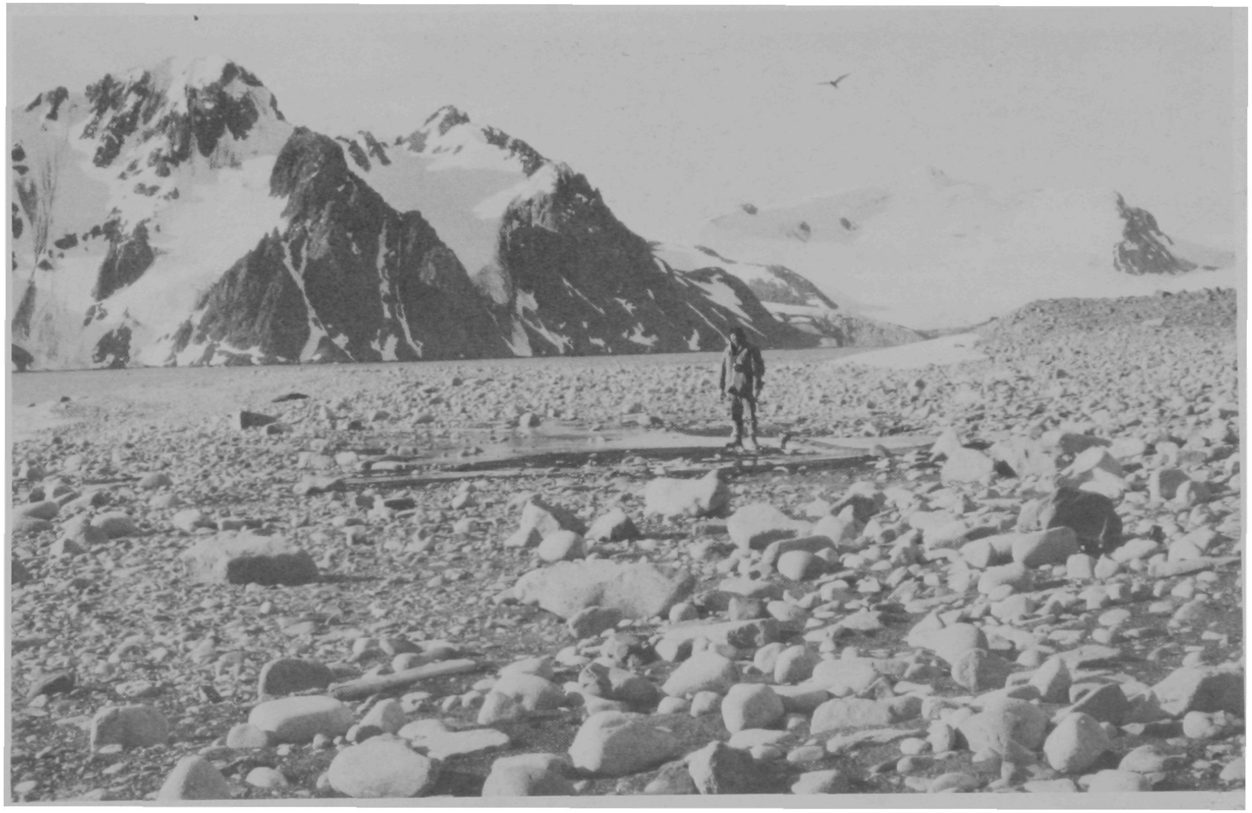

Fig. 18. Cirque glaciers near Miers Bluff, Livingston Island. Foreground shows cobbles and boulders in raised beaches.

for determining the sequence of more recent glacial fluctuations. These moraines represent the latest record of subtle ice fluctuations.

Beaches developed on the eastern and western margins of False Bay differ markedly. On the western flank, the modern beach is narrow and has a shoreline gradient similar to that of South Beach, Byers Peninsula. The modern and raised beaches on the eastern flank, however, are steep and at many places reach sea level at angles exceeding 30^o.

The eastern shoreline is composed of extremely well rounded tonalite and schist cobbles and boulders ranging in size from five to more than 30 cm in diameter. Sorting of beach clasts produced diameters gradually increasing southward toward open water. The contrast in east and west beaches is a result of both the geology and the local environment. Beaches on the west are in an area protected from storms that approach from the southwest. Storm beaches on this side of the bay, marked by the farthest in-land occurrences of recent wave-deposited materials, were about 8 m wide transverse to the coastline at an elevation of 0.8 m.

The eastern side of False Bay, especially near Barnard Point, directly faces the storm winds. Here the storm beach is about 1.8 m high with a horizontal distance varying from 17-43 m. During a storm that occurred in January, 1973, wave action was intense and hurled drift wood over the storm beach crest as far as 10 m. Wave force exerted against the beach boulders was sufficient to momentarily dislodge them causing a deep rattling sound as they settled back into place. The source of beach materials in both locations is a combination of talus and till.

Raised beaches are well developed along the entire coastline of False Bay. In many locations these features are overlain by, or incised into till.

King George Island

King George Island (Fig. 19) is nearly covered by ice. Except for a few nunataks in the interior of the island, the most extensive ice-free areas border Maxwell Bay and are Fildes Peninsula (60 km^2), Barton Peninsula (15 km^2), Ardley Island (5 km^2), and a narrow plateau between Potter Cove and Start Point (15 km^2). Keller Peninsula (10 km^2) and other small ice-free areas (less than 5 km^2) border Admiralty Bay to the east of Maxwell Bay.

Maxwell Bay

Maxwell Bay is a wide inlet opening southeastward into Bransfield Strait. It is flanked to the south and west by Nelson Island, and it is connected with the waters of Drake Strait through the narrow aperture of

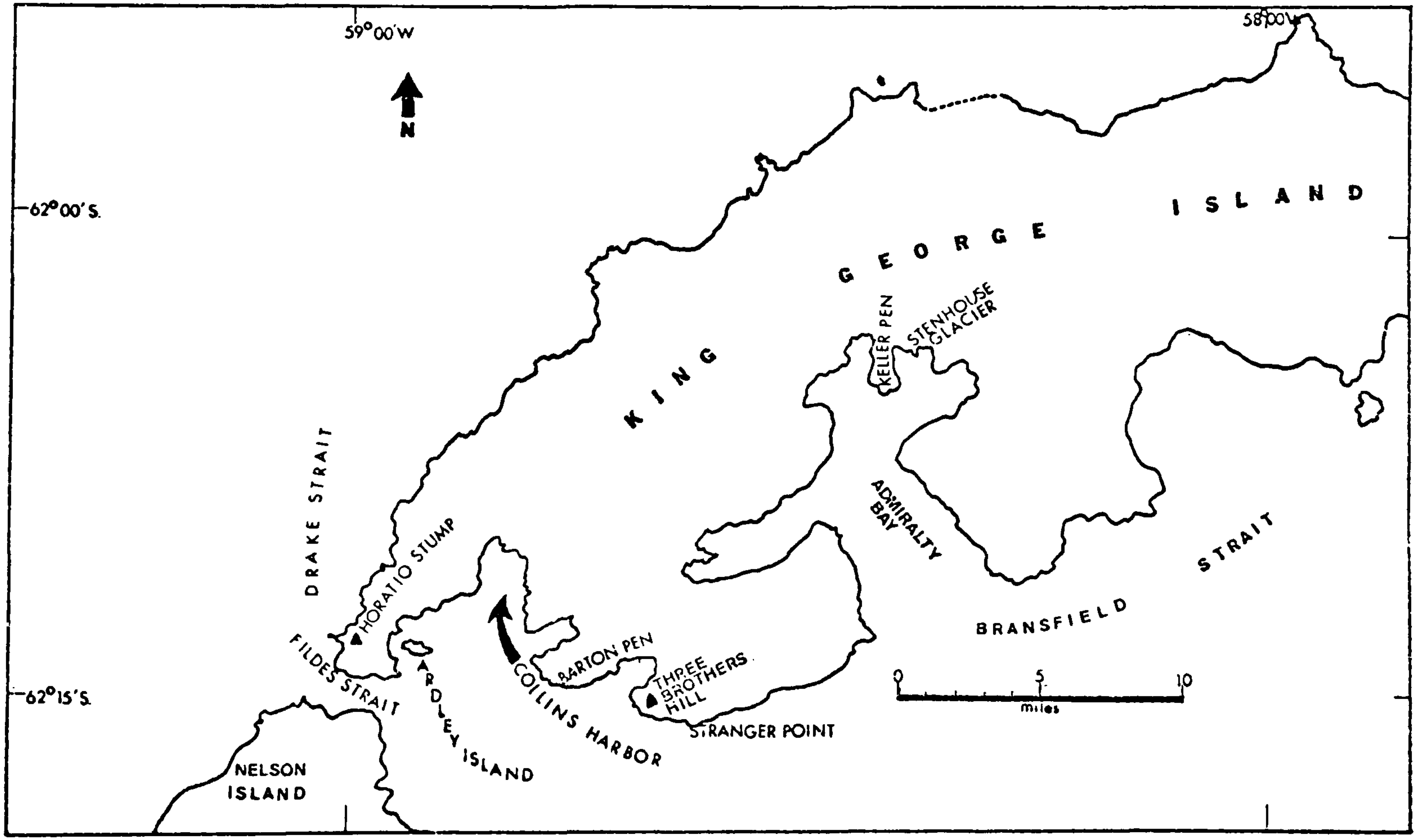

Fig. 19. Index map of King George Island.

Fildes Strait. The five ice-free areas mentioned above are separated by ice calving into the sea from the central ice cap.

The highest topographic feature near the bay is Noel Hill (295 m altitude, Fig. 20) on Barton Peninsula. The greater part of the coastal zone is not more than 155 m high.

A large submarine trough exists in Maxwell Bay and is shown on Admiralty Navigation Chart no. 1774. East of Ardley Island there is a steep drop from 177 m to 408 m at the head of the trough and a depth of 484 m is recorded just 2 km to the south. Near the tip of Nelson Island there is a steep drop at the trough edge from 44 m to 539 m in a distance of less than 3 km. This trough is deeply incised into the submerged offshore shelf, and it is more than 730 m at its mouth on the north slope of the Bransfield Strait (John, 1972).

The depths and general configuration of this trough were confirmed during this study with the aid of recording sonar equipment aboard R/V Hero. The width of the trough increases toward the south, and the flanks, although steep, were observed to be smooth and curved (convex downward). Although it is not possible to determine the genesis of this feature based on bottom profile alone, the non-parallel walls (widening toward the south) and definite "U"-shaped cross-profile tend to favor a glacial origin over the hypothesis of a rift valley bounded by parallel faults as proposed by Griffiths and others (1964). However, Maxwell Bay may have been initiated as a structural valley and later modified by flowing ice. The present shape and depth of this trough suggests that Maxwell Bay is a glacially eroded channel formed by ice flowing southeast across Fildes Peninsula into a pre-existing embayment.

Fildes Peninsula

Fildes Peninsula resembles Byers Peninsula, though the relief is more pronounced. The peninsula is about 8 km long, and nearly 3 km wide near the center (Fig. 21).

The Jurassic volcanic rocks of Fildes Peninsula consist of a lower series of folded andesites, contact volcanic breccias and agglomerates separated by a disconformity from an upper series of highly-altered pyroclastic rocks. Local faulting has exposed the lower series including several volcanic plugs of andesitic composition on the western half of the peninsula (Barton, 1965).

The dominant landscape features are extensive erosion surfaces and ancient marine clifflines and platforms (Fig. 22). The highest of the flat platforms are Horatio Stump at an altitude of 158 m and Flat Top Peninsula at an altitude of 155 m (Fig. 23). Both of these features are

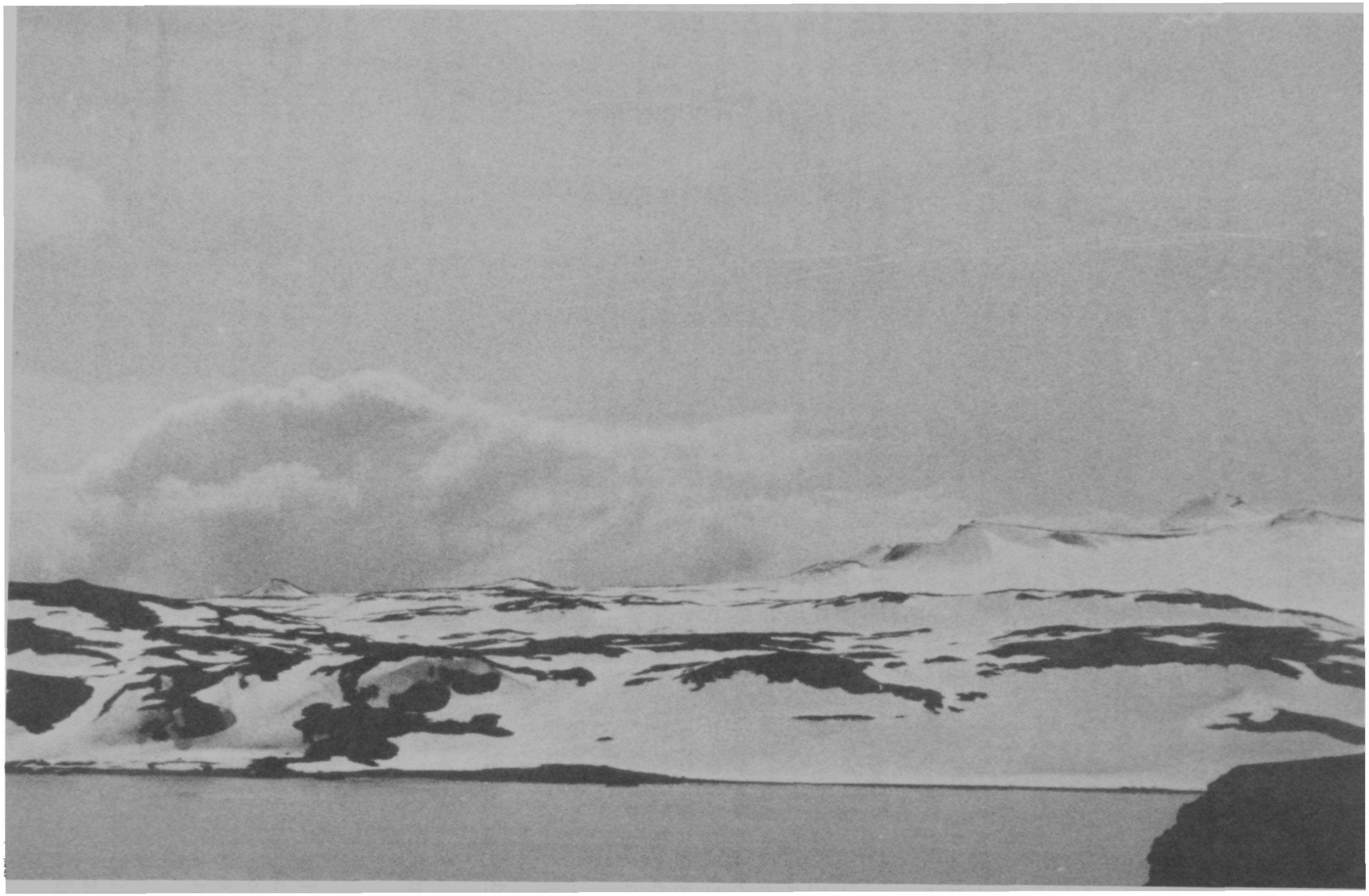

Fig. 20. Southern flank of Barton Peninsula. High peak to right is Noel Hill (altitude 295 m).

Fig. 21. Pronounced relief of Fildes Peninsula. Maxwell Bay looking northwest toward Ardley Island.

Fig. 22. Dominant landscape features of Fildes Peninsula. Photograph facing southwest from the summit of the local ice dome.

Fig. 23. Flat Top Peninsula northwest of Fildes Peninsula. Flat upper surface occurs at an altitude of 155 m and was formed by marine planation.

underlain by andesitic volcanic plugs. The perfectly planar upper surfaces of the plugs were suggested by Barton (1965) and others to be the result of marine erosion; however, no other platforms at this elevation were discovered at Maxwell Bay.

Beaches below an altitude of about 11 m are only a few tens of meters wide along the southern coast, except in two protected areas near Suffield Point north of Ardley Island. On the north side of the peninsula, these lower beaches are even narrower and are either poorly preserved or locally absent.

Above the lower beaches the slopes become almost vertical up to an altitude of 38-52 m. At this altitude is a platform that flanks the southern and western portion of the coast (Fig. 24). This platform is about 1 km wide and nearly 8 km long and is cut across the bedrock structure. The platform slopes toward the sea at an angle of about 1^{o}-1.5^{o}. A narrower platform at about 40 m is developed along the north of the peninsula. The outer margin of this platform generally terminates as a vertical cliff extending to sea level. Flat Top Peninsula rises vertically from the sea adjacent to the northern coastline (Fig. 25).

Inland from the 38-52 m plateau, other erosion surfaces are etched into the terrain which, except for the volcanic plugs, terminates abruptly at an altitide of about 105-115 m. The somewhat planar surfaces suggest that a broad plateau once existed at this altitude that was subsequently dissected, leaving only isolated remnants of its former surface.

A broad central depression extends across the peninsula just northeast of Ardley Island, separating the highlands to the southwest from the northeast (Fig. 26). The width of this depression is about 1-1.5 km, narrowing in the central portion, and it slopes to the southeast. Base level was presumed to be the surface of the 40 m platform on the northwestern side of the peninsula and the floor could be traced to present sea level to the southeast.

Fildes Peninsula is dissected by a complex series of anastomosing dry channels showing a marked preferential alignment across the peninsula (Fig. 26). The trend of the larger of these channels is approximately from north-northwest to south-southeast, although some variation was observed from the southeast to the west of the peninsula.

The large channels are aligned parallel to cols in the highlands and are truncated at a series of raised beaches and marine platforms above an altitude of about 20 m. Several of the well developed channels slope from the highlands at gentle gradients of 2^{o}-3^{o} and terminate at the edge of the 38-52 m platform.

Fig. 24. 38-52 m marine platform flanking southwestern coast of Fildes Peninsula. Narrow beaches are developed at base of this cliff. Photograph facing southwest near Suffield Point.

Fig. 25. Northwestern coastline of Fildes Peninsula. View looking southwest from summit of local ice dome.

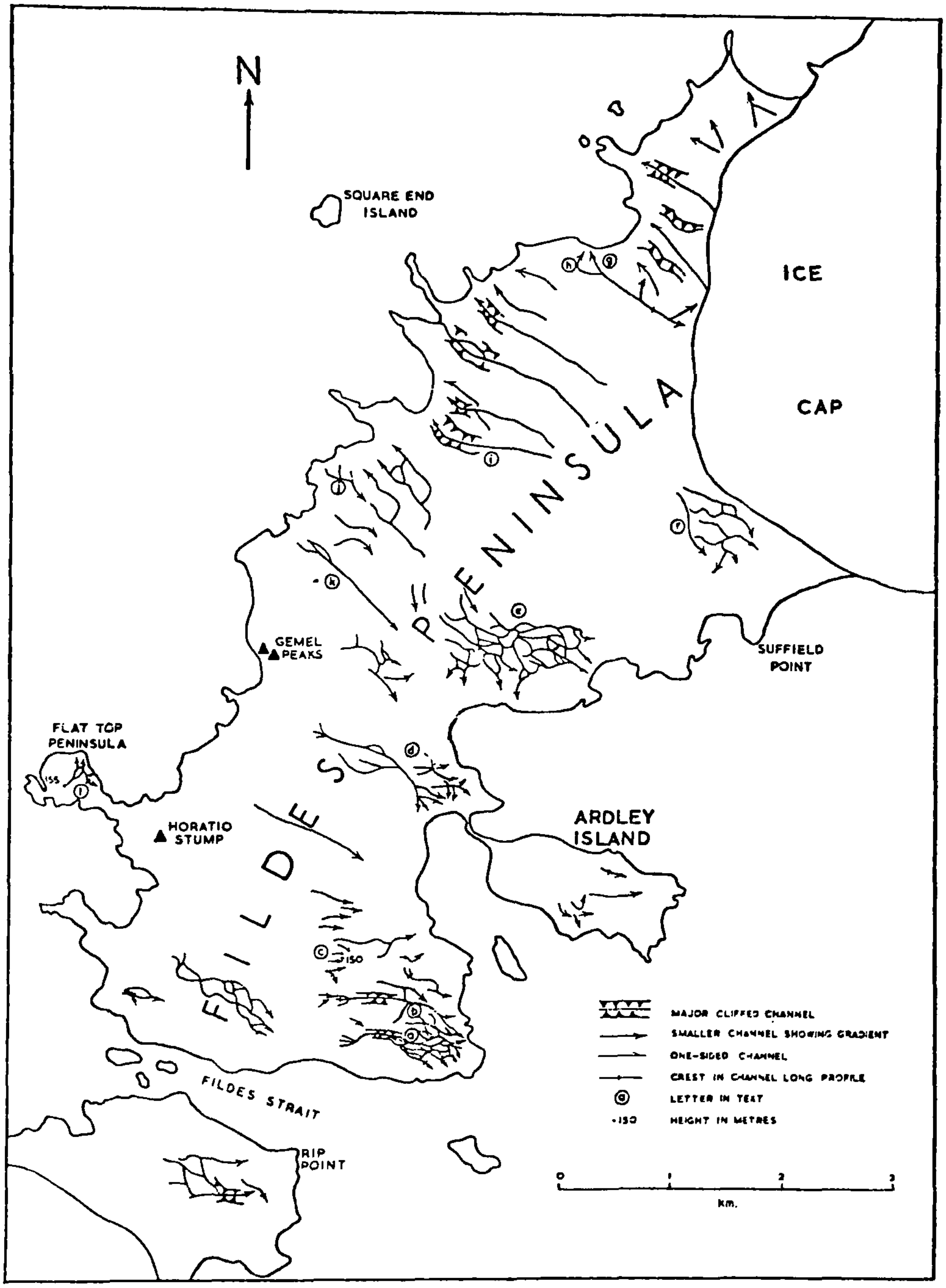

Fig. 26. The pattern of meltwater channels on Fildes Peninsula, reflecting a transverse movement of meltwater from northwest to southeast. Each anastomosing pattern in the east is related to a col breaching the upland axis of the peninsula. (After John and Sugden, 1971).

There is a marked contrast between the straight channels of the northwest side of the peninsula and the anastomosing pattern of the southeast side (Fig. 26). These channels, some of which are more than 70 m deep and several hundred meters wide (opposite Ardley Island) cannot be satisfactorily related to the small amounts of meltwater flowing in other intermittent channels today.

John (1972), and John and Sugden (1971) have investigated these channels in more detail and conclude that they were probably formed by meltwaters flowing from an ice cap that covered most of the South Shetland Islands during a period of maximum glaciation. Although the melting of a smaller ice cap centered over Fildes Peninsula could produce similar but smaller features, other evidence, discussed later (pp. 113-120) favors John and Sugden's hypothesis.

Ice encroaches the eastern margin of Fildes Peninsula where it is separated from the 38-52 m platform by a series of end moraines fringing a small ice dome. The ice dome is about 5 km in diameter and attains an altitude of 280 m (by Paulin altimeter). To the southeast the dome is presently calving into Collins Harbor, and terminates on land to the southwest and northwest. On the northern and northeastern sides the surface profile falls about 100 m and then rises up to the central ice cap. The profile suggests that it may be a residual of a more extensive ice cap previously covering all or part of Fildes Peninsula.

Barton Peninsula

This peninsula, bordering Maxwell Bay, consists of the most extensive single outcrop of Jurassic rocks on the island, and is composed of almost 300 m of metasomatized andesites, agglomerates, and thin tuffs. Noel Hill, which is the highest point on Barton Peninsula at an altitude of 295 m, is formed of intruded granodiorite (Barton, 1965).

A remarkably well developed and continuous series of raised beaches, moraines, and ancient marine platforms occurs on the flanks of the peninsula, and extend from present sea level to as high as 275 m.

Other Ice-Free Areas

Raised beaches, erosional platforms, and moraines are well preserved along the eastern margin of Maxwell Bay between Potter Cove and Stranger Point.

Admiralty Bay (Fig. 19) is an elongated fjord approximately 16 km by 4 km with a deep "U"-shaped channel attaining a depth of 545 m before it drops off into the depths of Bransfield Strait (Barton, 1965). Keller Peninsula lies at the northern head of the bay and is a long thin 2 km by 5 km streamlined arete that disappears under the Stenhouse Glacier at an altitude of about 350 m (Fig. 27). Raised beaches and marine platforms are well preserved along its southern margin, and a series of end moraines from cirque glaciers are interrelated with several of the marine erosional features. Above Keller Peninsula the central ice cap attains its highest altitude of about 600 m. The Stenhouse Glacier flows from the central ice cap to the south on both sides of Keller Peninsula (Fig. 28).

Fig. 27. View of headwaters of Admiralty Bay and western shore of Keller Peninsula (lower left).

Fig. 28. Stenhouse Glacier flowing around a nuntak on the east shore of Keller Peninsula.

HISTORY OF GLACIATIONS

The intensity and sequence of previous glaciations are reflected in the development of several characteristic landforms and their interrelationships. These landforms can be broadly grouped according to their processes of formation: (1) glacially produced erosional and depositional features; (2) platforms produced by marine planation; and (3) deposition of raised beaches. A distinction between surfaces produced by marine planation and raised beaches is made on the basis of the erosional nature of the former in contrast with the depositional and erosional aspects of the latter.

The Earliest Phase of Glaciation

Evidence for an ice cover that was previously more extensive than today is found on all of the ice-free peninsulas in the form of ice-molded and ice-scoured surfaces that are aligned transverse to the long axes of both Byers and Fildes Peninsula.

The movement of ice across Byers Peninsula from the north is well demonstrated by the ice-sculptured stoss and lee topography developed on volcanic plugs of the central (85 m) platform (Fig. 29). A scour channel about 100 m wide and 20-25 m deep is incised into the top of Usnea Plug (133 m) at Byers Peninsula (Fig. 30), and conforms with the general trend of the stoss and lee topography. Pockets in this channel and other portions of the plug above the altitude of about 98 m are plastered with coarse gravels. Striations preserved above this channel are aligned approximately N 20° W.

Landforms comparable to those on Byers Peninsula are even more abundant on Fildes Peninsula. On the 105 m surfaces small volcanic knobs of more resistant rock 2-20 m above the surface near Horatio Stump have been molded into rock drumlins. An examination of more than a dozen of these features noted the general trend of N 80° W to N 70° W and indicates ice flow from the northwest. Similar features with the same trend occur at Barton Peninsula and at Three Brothers Hill, an elongated volcanic plug rising 148 m above Potter Cove. At Fildes Peninsula the rock drumlins are on the northwestern coast, and could only have been formed by ice approaching from off-shore.

The most spectacular features of the South Shetland Islands that indicate former directions of ice movement are the submarine troughs. At King George Island, the troughs of Maxwell Bay and Admiralty Bay are aligned roughly parallel, indicating ice flow toward the southeast. Similar submarine troughs are present north of the island. One 12 km north cuts through a submarine platform. The depth of this trough is 530 m and became deeper toward the south with the same trend as those south of the island (D. Sugden, personal communication).

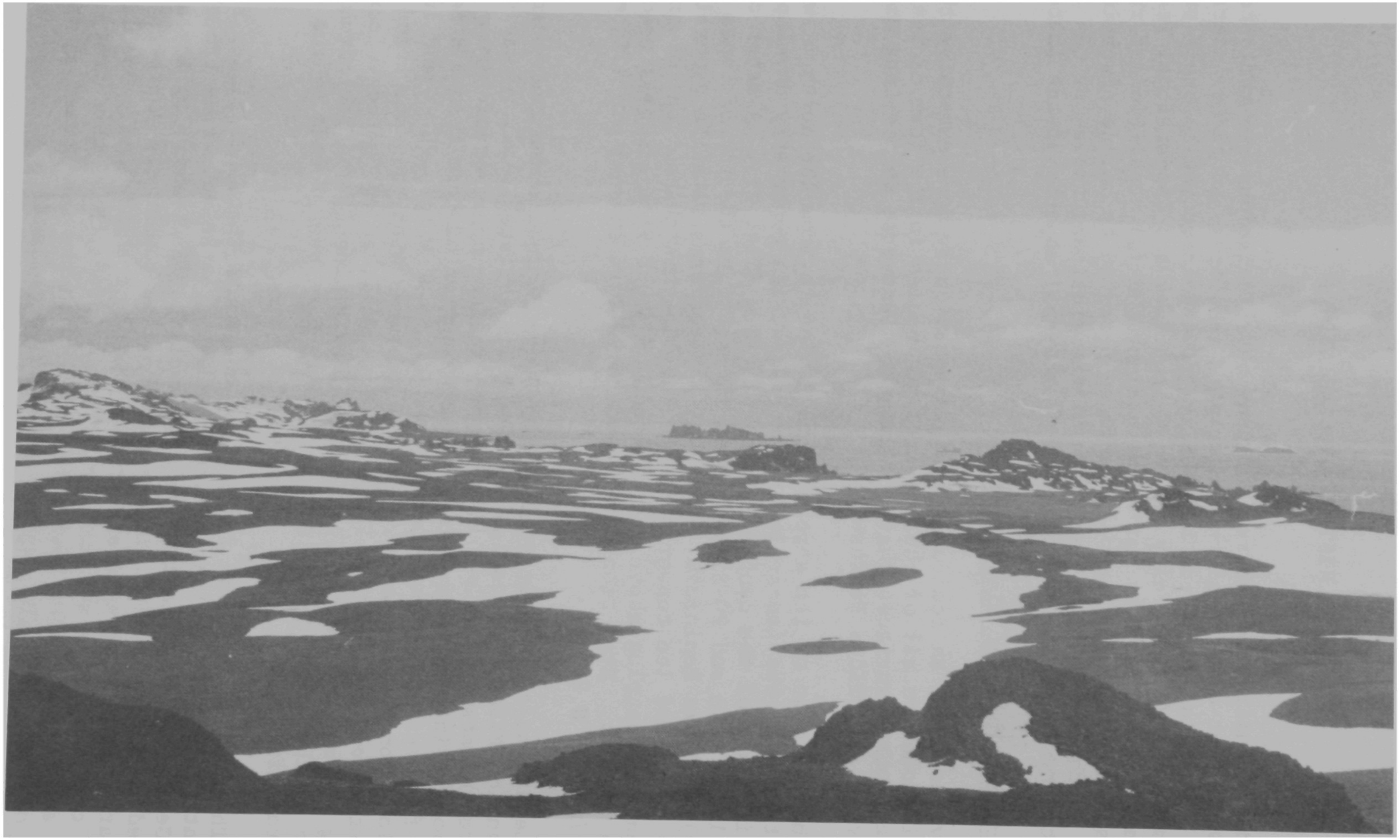

Fig. 29. Stoss and lee topography developed on northeastern coast of Livingston Island. View toward Start Point from Rotch Ice Dome.

Fig. 30. Base of ice-scoured channel developed across top of Usnea Plug. Elevation of channel base is 20 m below altitude of marine platform developed on top of the plug at 133 m.

The bathymetric map (Fig. 31) shows seven major troughs located along the south side of the island chain. Five of these are nearly parallel, with the remaining two southwest of Greenwich Island, forming a radial pattern that converges to the north of the islands. All exhibit about the same maximum depth and reach the Bransfield Strait at about the same distance offshore. In addition, ice molded and sculptured features are parallel to these troughs, revealing the direction of ice flow on both sides as well as across the islands.

These observations strongly suggest that all of the troughs were ice-eroded by a large ice cap that previously existed to the north and covered most of the islands. The axis of the cap was probably centered over the wide shallow submarine platform trending roughly parallel to the island chain (Fig. 31).

The Ice Cap Associated with the Earliest Stage of Glaciation

A reconstruction of an ice cap symmetrical with respect to the 200 fathom (370 m) isobath would completely encompass the islands with the possible exception of a few mountain peaks protruding as nunataks. The dimensions would have been approximately 70 km at its widest point and more than 240 km long. The geometric axis would also be located north of most of the islands except where it would cross Byers Peninsula (Fig. 32). Selection of the 370 m isobath was based on the average maximum depths of the glacial troughs where they terminate near the Bransfield Trough, but this choice should be considered somewhat arbitrary. Such an ice cap may have extended much farther with an ice shelf that may possibly have reached across the Bransfield Strait to the Antarctic Peninsula. A similar estimate by John and Sugden (1971) suggested tha grounding line to be shallower, at about 100 fathoms. Although the reconstruction of such an ice cap is speculative, it does account well for all of the evidence previously described.

A rough approximation of the thickness of the ice cap can be made from its lateral ice limits (area within the 200 fathom isobath). The profile can be fitted approximately to a parabola with the equation $h = Ax^{\frac{1}{2}}$, in which h is the height or ice thickness above the terminus, x is the map distance from the margin to the ice cap axis, and A is a coefficient which varies from glacier to glacier (Mathews, 1974). Hollin (1972) and Nye (1952), using this formula with a value of $A = 4.7\ m^{\frac{1}{2}}$, found that it fit very well to the present profile of the Antarctic ice sheet near Mirnyy and to portions of Greenland. Using this same value, the reconstructed ice cap was on the order of 1,500 m thick at a point on the axis midway between King George Island and Livingston Island. Even an approximate determination of ice thickness such as this provides some insight when discussing the magnitude of isostatic adjustments and the formation of marine planation surfaces and raised beaches. Other

Fig. 31. Bathymetric map of the South Shetland Islands, Antarctica. Note position of 200 fathom isobath. From Ashcroft, 1972.

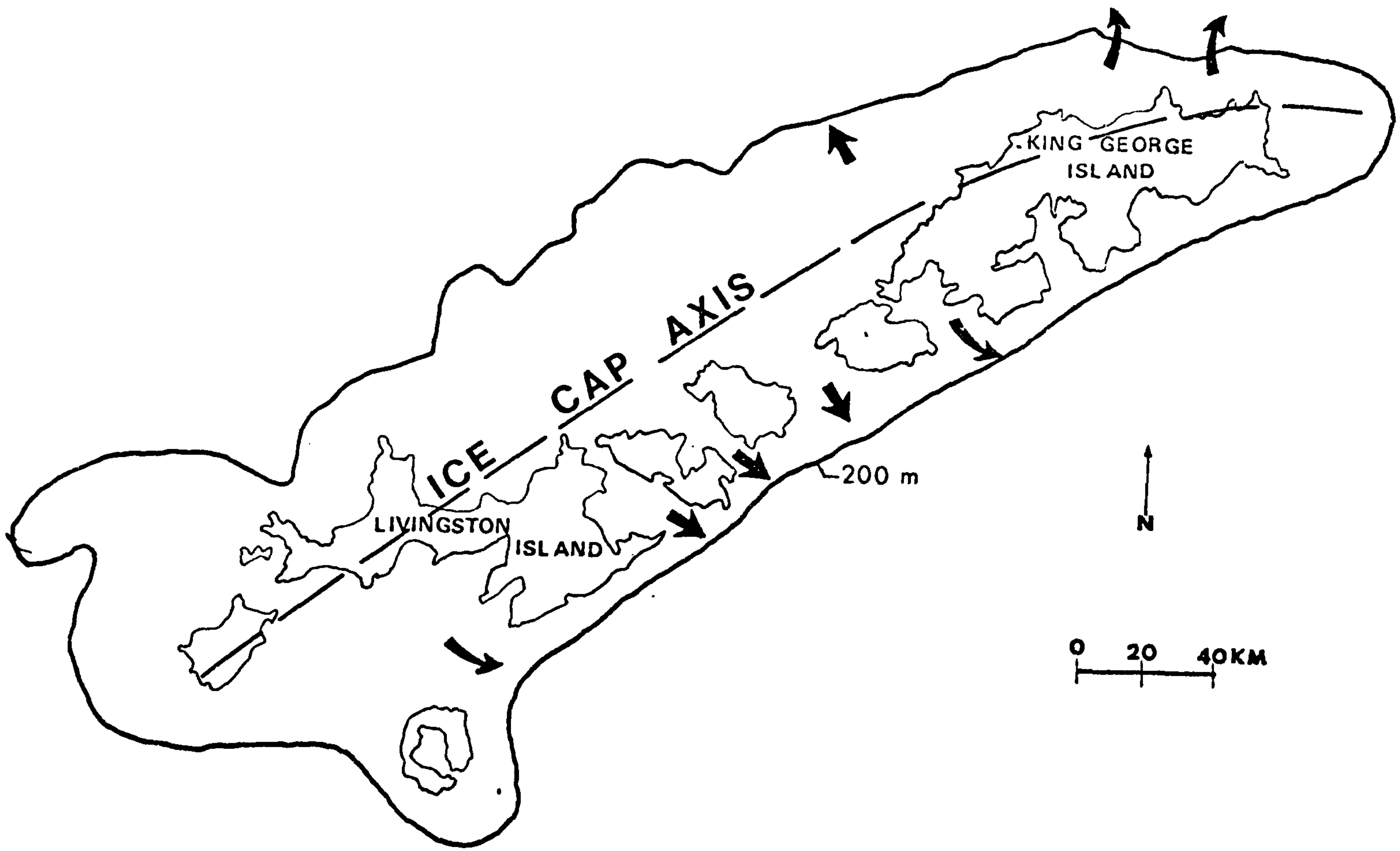

Fig. 32. Diagram showing margins and axis of major ice cap covering islands during early phase of glaciation (Illinoian?). Arrows show directions of ice flow in submarine troughs.

morphologic and stratigraphic evidence (pp. 95-111) indicates that this ice cap does represent the earliest and most intense phase of glaciation found in the islands.

During this phase of maximum glaciation, the weight of the expanded ice cap must have produced a considerable isostatic depression of the islands. Presuming that this ice cover persisted long enough to reach an adjusted state, an estimate of the magnitude of the depression would be about one third of the ice column thickness which is about 300 ± 50 m (Weertman, 1964).

Warm Interval Following Maximum Glaciation

Following this depression, a warm interval (interglacial?) may have occurred, causing rapid but interrupted ablation (?) of most of the previous ice-cover. Evidence of this wastage is reflected by the development of the meltwater channels on Fildes and Byers Peninsula (John and Sugden, 1971) and the erosion of surfaces formed by marine planation and raised beaches.

Several of these platforms and beaches occur at remarkably high altitudes. On Barton Peninsula marine terraces are cut across bedrock as high as 275 m near Noel Hill (Fig. 33). Other marine platforms and beaches are etched into the structure of this peninsula at altitudes of 228 m, 198 m, and 132 m. At False Bay, the highest raised beach surfaces are marked by wave-rounded cobbles resting on extensive horizontal but narrow surfaces at 155 m and 137 m. These beaches must have been formed at sea level and at a time of large-scale isostatic depression during standstills in the thinning of the ice cap. This mode of formation seems more likely than tectonic uplift because of the present day near-horizontal character of all the platforms and raised beaches and their occurrence at approximately the same altitudes over a wide geographic range. Another explanation for the high features may be that Late Tertiary to early Pleistocene sea levels were much higher than they are today, but no other evidence of interglacial sea levels as high as 275-300 m have been reported. Possibly, a combination of all these considerations is responsible.

Subsequent Expansion of the Ice Cover

Many of these raised beaches and marine platforms have been overridden by ice since their formation. Evidence consists of erratic fans of striated beach cobbles deposited over the beaches and marine surfaces. Many of the ice-free areas are overlain by till and erratic blocks.

Two moraines and a till between Potter Cove and Stranger Point provide evidence of local ice advance (Fig. 34). To the southwest of these recently developed ice-cored moraines till overlies the ice-free

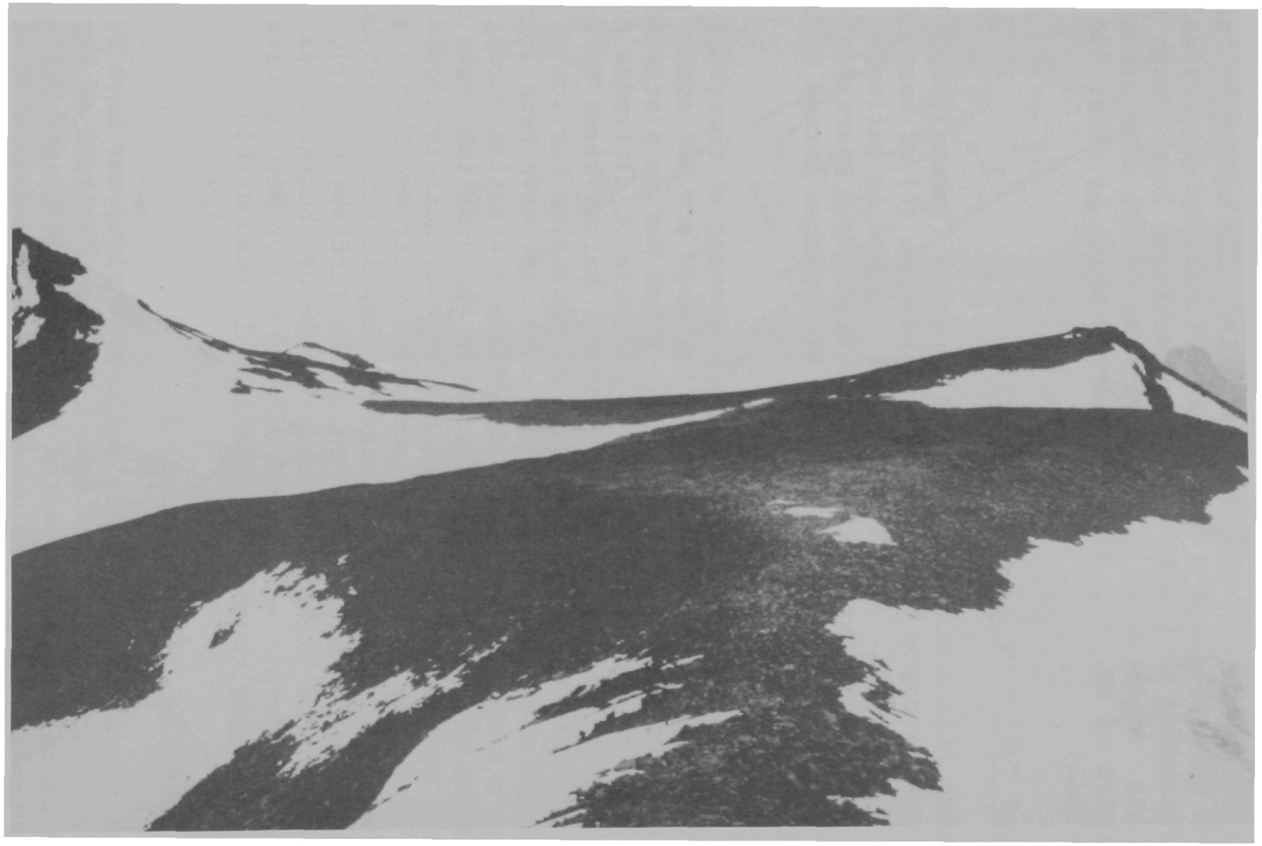

Fig. 33. Marine terrace at 275 m on Noel Hill. View facing southeast toward Barton Peninsula, King George Island. The slightly higher elevation of the forward slope is due to resistance of the Jurassic dikes striking parallel to the present coast.

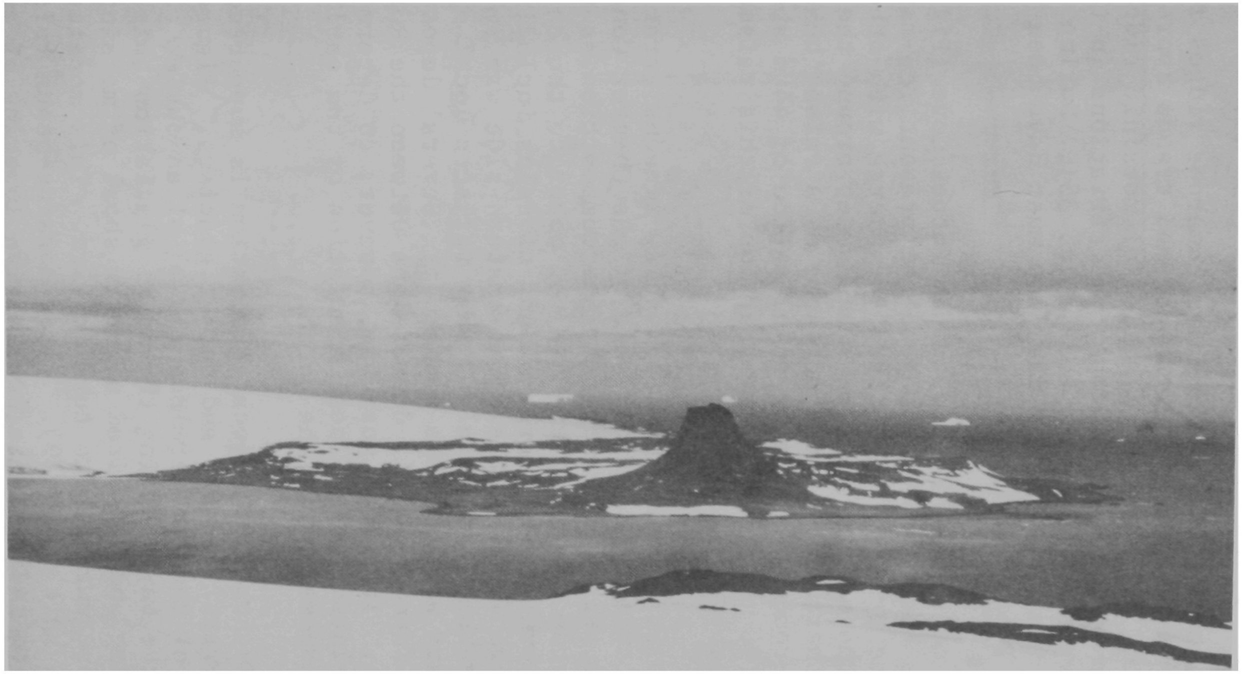

Fig. 34. Moraines to west of ice cap between Potter Cove and Stranger Point. The first moraine belt below the ice cap is ice-cored. View looking toward the southwest from Barton Peninsula, King George Island.

surface at an altitude of 55 m. This surface, presumed to be a bedrock terrace, extends to within about 500 m of the coastline and terminates as a bedrock controlled cliff. Below this cliffline, a series of raised beaches extend to sea level.

The upper till-covered surface exhibits numerous ridges formed by resistant andesite that dips to the northeast and trends approximately parallel to the present ice margin. A series of morainic ridges is formed in conjunction with these outcrops, and striations in the outcrops indicate that ice movement was to the west (Fig. 35). During the earlier phase of glaciation, the direction of ice flow must have been to the southeast toward the Bransfield Strait.

In the vicinity of the outlet glacier at Potter Cove (Fig. 36), lateral moraines have been developed beyond the present ice margins and can be traced to Three Brothers Hill where they merge with other morainic ridges derived from the east. These moraines sweep around the volcanic plug burying the northern and eastern portions of a raised beach. This raised beach occurs around the plug at an elevation of 44 m above the surrounding surface (98 m). The western portion of this raised beach appears to be undisturbed (Fig. 37).

On the central platform of Byers Peninsula, igneous erratics were found resting on volcanic agglomerates west of the Chester Cone and Usnea Plug (Fig. 8). These erratics are of the same composition as the plugs, are more rounded towards the west, and did not occur to the east of the plugs. Chester Cone exhibited a large amount of talus including a few erratics on its western flank, whereas the eastern side was smoothed and well swept of most weathered materials. This reflects local expansion of Rotch Ice Dome westward across Byers Peninsula. Several deposits of rounded gravels were found in small depressions between the Rotch Ice Dome and Chester Cone. It is not possible, however, to determine whether these gravels were related to the local glaciation or the earlier phase associated with ice movement from the north.

At False Bay evidence of the local glaciation is supported by the moraines formed by several cirques and outlet glaciers. Figure 38 shows the present position of the ice terminus (50 m) of an outlet glacier on the eastern side of the bay. During the local glaciation this glacier advanced into False Bay and deposited a narrow shoal of morainic debris, which forced near-shore currents to turn bayward. This moraine presently appears as an arcuate spit (Fig. 39). Clear moraine-beach relationships were found at this site indicating a progressive lowering of sea level from either local-isostatic and/or eustatic causes, which resulted in the formation of a series of beach ridges (Fig. 39). The arcuate depressions formed behind the beaches represent the former positions of ice masses stranded during glacier retreat (Fig. 39). A Late Neoglacial moraine

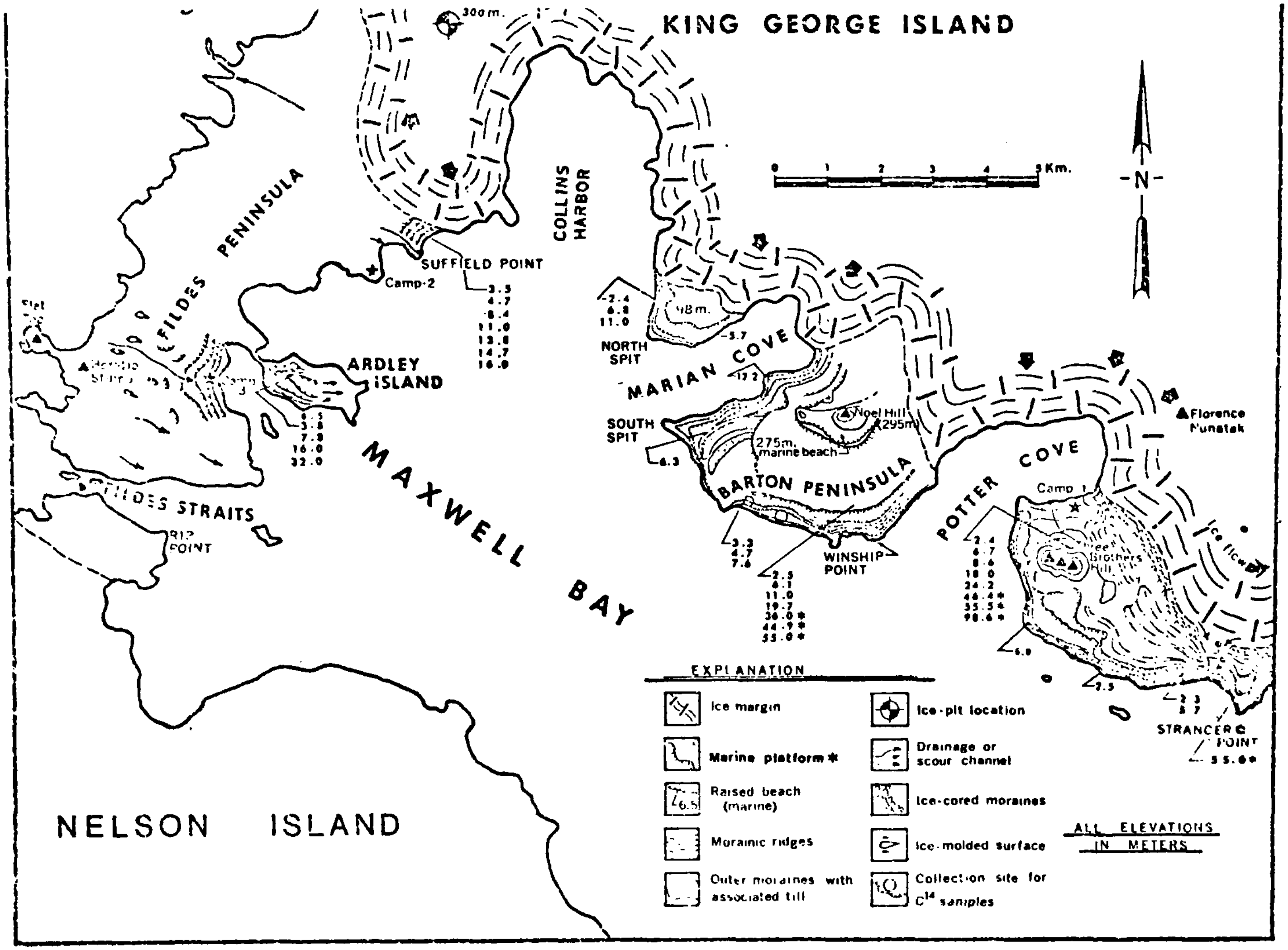

Fig. 35. Till and moraines between Potter Cove and Stranger Point, King George Island.

Fig. 36. Lateral moraines developed beyond present ice margin of Potter Cove outlet glacier. Ridges are contrasted against snow. View toward southeast, from boat in Potter Cove, King George Island.

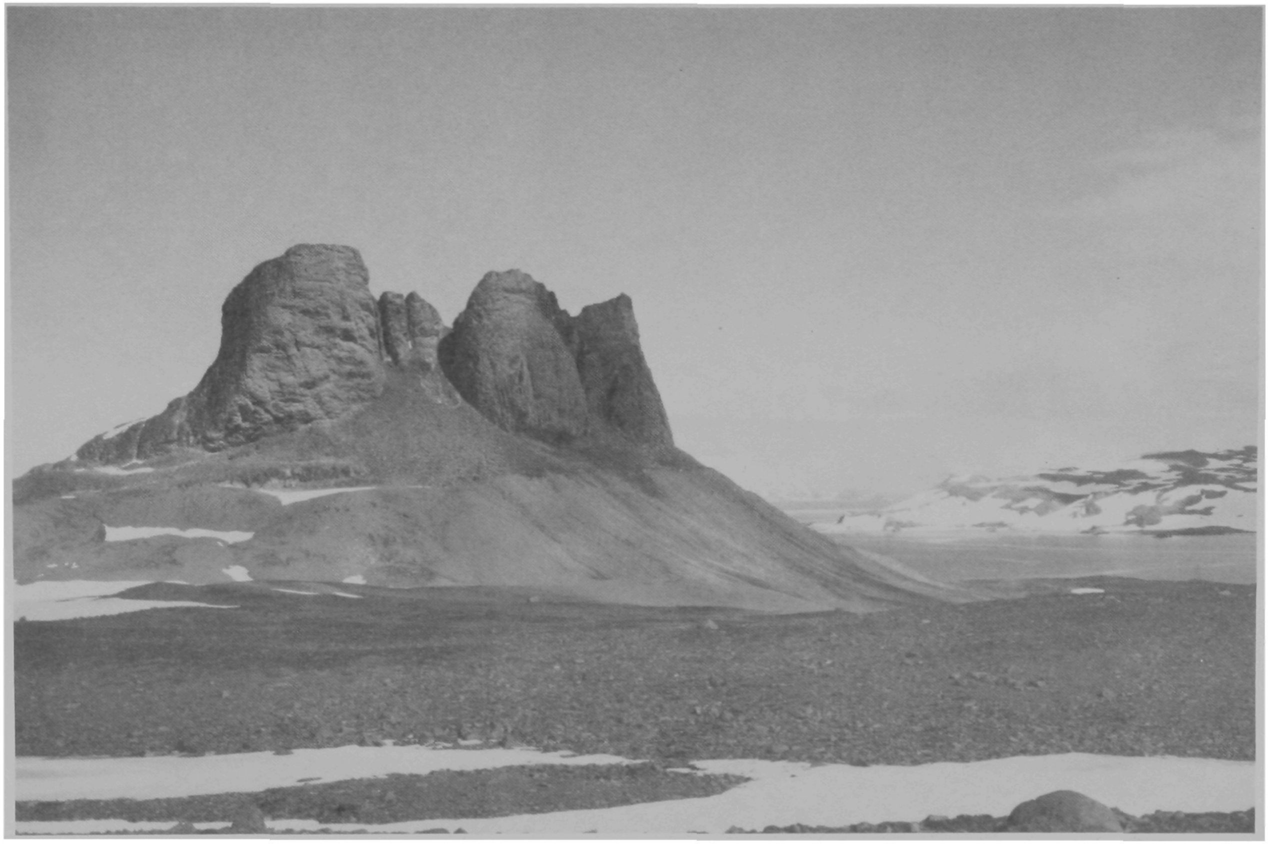

Fig. 37. Moraines and till deposited on eastern and northern flanks of Three Brothers Hill. View facing toward the west.

Fig. 38. Terminal moraines west of outlet glacier draining ice from several cirques on eastern side of False Bay, Livingston Island.

Fig. 39. Arcuate spit formed of moraine from the local glaciation. A series of 16 beaches are formed on the moraine in a horizontal distance of only 103 meters, False Bay, Livingston Island.

was formed contemporaneously with, or possibly just prior to a 6.5 m beach into which the moraines grade in a transitional manner. Beaches at this site occurring above this altitude (6.5 m) have all been overridden by the local ice advance. Similar moraine-beach relationships were recognized to the south of Charity Glacier at Potter Cove and Marian Cove and on the south side of Keller Peninsula. In these cases the highest raised beach formed within the moraines is about 6.5 m. From this evidence it can be concluded that the 6.5 m beach was being deposited at about the same time the recession of the late Neoglacial Advance began.

Recent Ice Advances on Livingston and King George Islands

Two recent and very minor advances occurring in late Neoglacial times after the local glaciation is suggested by the crested ice-cored moraines at Maxwell Bay, push moraines to the southeast of Rotch Dome, and ice-cored moraines deposited over the local glaciation moraines at False Bay.

Push moraines, below the outlet glacier shown in Figure 38, were deposited over the recessional moraines formed during retreat of the local glaciation. These push moraines are ice-cored and their fresh unleached character suggests that they are late Neoglacial.

The moraine-beach relationship shown in Figure 40 further demonstrates their recent appearance. The 6.5 m beach grades into moraines associated with the first of these two advances. Below 6.5 m another prominent undisturbed raised beach was developed on the older moraine at an elevation of 3.5-5 m. The recent moraines were deposited over older moraine and beaches developed at 6.5 and 3.5-5 m, but before or contemporaneously with the formation of a series of raised beaches at 2.5-3 m that grade into the recent moraines. These 2.5-3 m raised beaches are continuous and undisturbed along the coastal margin elsewhere at False Bay.

Two smaller moraines of fresh character are developed south of the Rotch Dome near Elephant Point (Fig. 41). These moraines, one of which is lichen encrusted, are similar in appearance to the recent moraines described at False Bay and are believed to represent the same minor advance. The ice-cored moraines just beyond the ice cap margin at Maxwell Bay and those near Elephant Point and at False Bay were formed during the same recent minor advance.

In summary, there is excellent geomorphologic evidence of at least two phases of glaciation followed by two relatively recent and minor late Neoglacial ice advances.

During the earliest phase the islands were covered by a large ice cap (70 km by 240 km) trending parallel to the islands and possibly extending as shelf ice to the adjacent Antarctic Peninsula. This phase

Fig. 40. Moraine-beach relationship formed by "recent advance", False Bay, Livingston Island.

Fig. 41. Neoglacial moraines developed at terminus of ice cap above Elephant Point, Livingston Island. View facing the south-southeast, Livingston Island.

of glaciation was probably Illinoian or earlier and was followed by a non-glacial interval (interglacial?). During this interval, sea level was high enough to submerge most of the islands and produce marine platforms and beaches now raised as high as 275 meters. At this time the ice cover must have been reduced more that that of today or it could have completely disappeared since only a small portion of the islands remained above sea level. The fairly rapid disintegration of the ice cap during this warm interval is supported by the development of meltwater drainage patterns across high surfaces of Fildes and Byers Peninsulas. Raised beaches and marine platforms developed during standstills in the isostatic readjustment, perhaps indicating cooling trends during the warmer interval.

Local glaciation (Wisconsin) following the non-glacial interval ensued. Island ice caps expanded and deposited locally derived till and erratics over the ice-free peninsulas and many of the raised beaches and marine platforms. How long this condition prevailed is not known, but it was followed by ice retreat to about its present position.

Two minor late Neoglacial advances after the phase of local glaciation occurred fairly recently as evidenced by fresh moraines at Maxwell Bay, False Bay, and Elephant Point.

The 6.5 m beach was formed contemporaneously with or slightly after the deposition of the first series of moraines (late Neoglacial) at False Bay and Maxwell Bay. A similar relationship has been shown to exist between the most recent minor advance (late Neoglacial) and the deposition of the 2.5- 3 m raised beaches.

RAISED MARINE FEATURES

The relationship between raised marine features, those preserved at the glacier margins, reflects the fluctuations of the glaciers as they advanced or withdrew from a position covering most of the islands.

Occurrence

Raised marine features occur at many altitudes between present sea level and 275 meters. Most of these features are near sea level and they become fewer and less well preserved with increasing altitude.

Elevations of raised marine features were measured at Livingston Island and King George Island. The surveys were started at sea level, and extended to the highest identifiable marine surface in the area. All surfaces were examined for composition and *in situ* organic remains suitable for radiocarbon dating. Crustose lichen thalli were measured for growth rate determinations where encountered.

The typical criteria used in identifying raised marine features were: (1) A nearby horizontal surface typically sloping gently seaward. Many of the higher benches observed (above 50 m) truncated the local structure. (2) Abundant well-rounded pebbles, cobbles, and boulders on or underlying these surfaces. Striated materials were considered to be remnants from older marine surfaces derived from above and not characteristic of local marine action. (3) Marine organisms deposited within or on top of the surface. These consist of whale bones and in a few cases seaweed in the sediments. Seal and penguin bones were not considered as evidence of shore activity because many living animals were observed as far as 3 km inland and at elevations exceeding 100 m. Small marine shells were also considered as non-diagnostic, especially in nesting areas.

A summary of identified raised marine features is presented by locality and elevation in Appendix A. All elevations are above mean half-tide and represent the mean elevation of the features unless otherwise noted.

The most prominent raised marine features are listed in Table 2. Some liberty has been taken in generalizing these altitudes for the convenience of discussion.

Description of Prominent Raised Marine Features

1.8 m Beach. The 1.8 m beach is a prominent and continuous feature observed throughout the islands. Driftwood, flotsam, marine vegetation, and in one place an alligator carved of wood, deposited across the forward slope of this beach clearly distinguished it as today's modern storm beach

Table 2. Prominent Raised Marine Features

Altitude in meters	Description
1.8	Modern storm beach.
2.5 - 3	Raised beach.
3.5 - 5	Raised beach.
5.6 - 6.5	Raised beach.
11.1 - 17.5	Raised beach.
18.5 - 20.5	Raised beaches and marine platform.
30 - 33	Marine platform, surface or raised beach.
38 - 55	Extensive marine platforms encompassing approximately 38% (≈ 60 km^2) of the total ice-free areas (160 m^2) investigated.
85 - 100	Extensive marine platform encompassing approximately 25% (40 km^2) of the total ice-free areas investigated.
132	Raised beaches, marine surfaces.
155	Marine platforms on volcanic plugs.
189	Marine platform, raised beaches.
228	Raised beach.

(Fig. 42). The elevation of this beach along the open coastline is between 1.7-2.2 m, but in protected embayments it is much lower. North of Ardley Island this beach lies at 0.5 m. It appears to be accumulating rapidly and a narrow tombolo between Ardley Island and Fildes Peninsula is visible at low tide (Fig. 43). Composition of this beach varies between sand and gravel on the south beach to well-rounded cobbles and boulders at Maxwell Bay and False Bay. Outlet glaciers at both Livingston Island and King George Island appear to be grounded on this beach.

2.5-3 m Raised Beach. The 2.5-3 m raised beach is nearly as continuous as the modern storm beach. The elevation of this beach varies only slightly between the islands, with the highest elevation occurring on the north end of Ardley Island. At this site the surface of the beach is nearly horizontal (3.2 to 4.2 m), and the forward slope (3.2 m) is truncated by a steep cliff inclined at about 25^{o} to 30^{o} (Fig. 44); the beach here is 50-75 m wide and shows evidence of intermittent drainage (Fig. 45). Elsewhere the width of this beach varies from about 300 m at South Spit, Barton Peninsula (Fig. 46) to no more than 10 to 20 m along Byers Peninsula.

The 2.5-3 m beach is the highest raised beach observed in the islands that was not overridden by moraine. At Maxwell and False Bays this beach cuts or grades into recent fresh moraine produced during a recent ice advance. Figure 47 further demonstrates the development of this beach on moraine that extends nearly to the toe of a small outlet glacier west of Miers Bluff. Since this beach formed contemporaneously with or slightly after deposition of the recent moraines, radiocarbon ages obtained from this beach provide a limiting age of the recent ice advance, which is 265 ^{14}C years BP.

The 6 m Raised Beach. The 6 m raised beach is a prominent feature at nearly all of the field sites investigated. It is continuous, appears as a beach ridge or an extensive terrace, and occurs at a remarkably constant elevation. This beach is continuous around Byers Peninsula. Along South Beaches, Byers Peninsula the 6 m beach occurs as a beach ridge with a slightly inclined profile (Fig. 48). The beach ridge slopes seaward and the forward edge occurs at elevations between 4.7 to 5.9 m. Behind the foreslope is a slight bench that rises up to an average elevation of about 6 m. The rear of the beach is commonly 1-2 m higher. The small bench developed on the foreslope is only a locally continuous feature probably produced as an "ice pushed ridge" common to beaches investigated at Marguerite Bay by Nichols (1947; 1953; 1964). The entire beach surface at Byers Peninsula is veneered with a well-rounded cobble pavement (Fig. 49). Beneath this pavement, water-laid sands and gravels are interbedded with highly oxidized seaweed.

The 6 m beach is nearly as continuous at Maxwell Bay near Winship Point. The rear of the beach frequently terminates against a bedrock cliff at elevations of 6.8 to 7.7 meters.

Fig. 42. The rucksack marks the foreslope of the 1.8 m modern storm beach developed along the coastline of South Beaches, Byers Peninsula.

Fig. 43. Modern storm beach occurring at 0.5 m forms a tombolo between Ardley Island and Fildes Peninsula at low tide. Photograph facing toward the southeast.

Fig. 44. The steep forward slope of a raised beach occurring between 3.2-4.2 m along the northern shore of Ardley Island.

Fig. 45. Surface of the 3.2-4.2 m raised beach at Ardley Island. An intermittent stream can be seen incised into the forward beach surface. The 6.4-7.2 m beach rises abruptly to the right.

Fig. 46. The 2.5-3 m raised beach at South Spit, Barton Peninsula. This beach is about 300 m wide and grades into the modern beaches which are presently forming a spit that extends into Marian Cove.

Fig. 47. The 2.5-3 m raised beach developed on recent fresh moraine at the toe of an outlet glacier west of Miers Bluff.

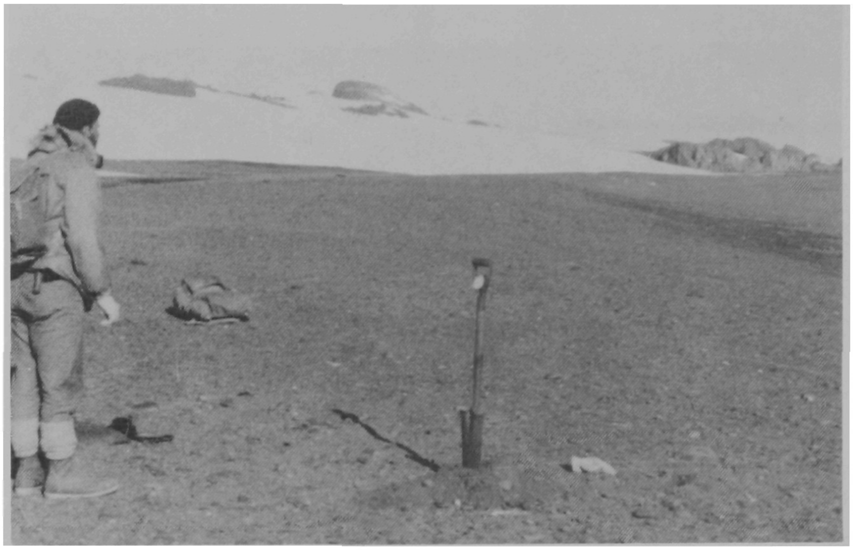

Fig. 48. Surface of the 6 m raised beach formed along South Beaches, Byers Peninsula. This beach is a nearly continuous feature around Byers Peninsula.

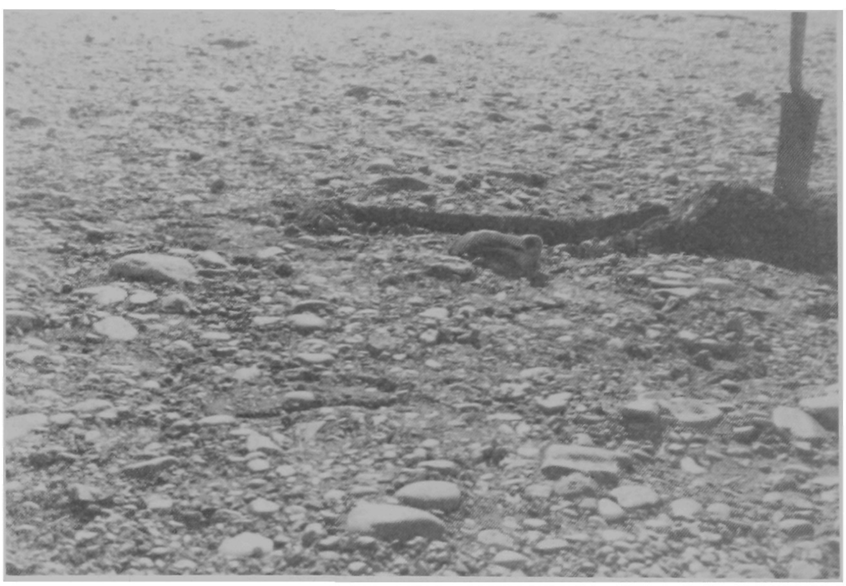

Fig. 49. Cobble and boulder pavement on surface of the 6 m raised beach along South Beaches, Byers Peninsula, Livingston Island.

The 6 m beach is the highest beach with a fresh appearance, and is also the highest beach in which whale bone is common.

At False Bay and Potter Cove the 6 m beach grades transitionally into, or developed upon, older ground and terminal moraines below glacier outlets. The beach developed in conjunction with the moraine is partially lichen encrusted, somewhat frost shattered, and consists of well-rounded cobbles and boulders. Recent moraines have been deposited below cirque and outlet glaciers that overlie the 6 m moraine-beach sequence. These moraines represent the most recent minor advance, are ice-cored in many locations, and consist of fresh angular debris cemented in a clayey matrix (Fig. 50). The 6 m beach is believed to have formed contemporaneously with or slightly after a late Neoglacial phase of ice advance.

<u>11-17 m Raised Beach</u>. This raised beach is deposited on a bedrock platform south of Usnea Plug and at several other locations at South Beaches. The surface slopes gently seaward and the forward edge (11 m) appears to be bedrock controlled.

South of Usnea Plug this surface is developed above all of the lower beaches and terminates abruptly within a few meters of the coastline between two sea stacks. At the forward edge the slope drops at about 30^{o} to numerous other sea stacks at present sea level. Thin remnants of the other beach levels are developed on this forward slope. This platform is several hundred meters wide and the elevation is probably controlled by dikes radiating from Usnea Plug.

To the east and west of Usnea Plug along South Beaches the 11-17 m platform is discontinuous. The beach deposits resting on this platform are more deeply weathered than the surface occurring below it. Frost shattered beach cobbles are common but not abundant and lichens appear more established. Patterned ground dominates the more horizontal surfaces (Fig. 51). Although this beach occurs at South Beaches, it was noticeably absent or poorly developed elsewhere. One explanation might be that it is equivalent to the 18.5 to 20.5 m beaches elsewhere, but it occurs slightly lower on Byers Peninsula due to differential isostatic adjustment or minor tectonic influences.

<u>18.5-20.5 m Platforms and Beaches</u>. This beach is a prominent feature of both islands. It is wide and can be found on most ice-free areas of Maxwell Bay and Keller Peninsula (Fig. 52). This is the highest fresh surface occurring in the islands. Above this altitude surfaces and platforms are covered with till and gelifluction materials.

At False Bay this beach is extremely well developed at a nearly constant altitude. Here the beach is best preserved in coves on the western side of the bay. It is nearly horizontal to the west of Huntress Glacier at the campsite shown in Figure 53. At this location

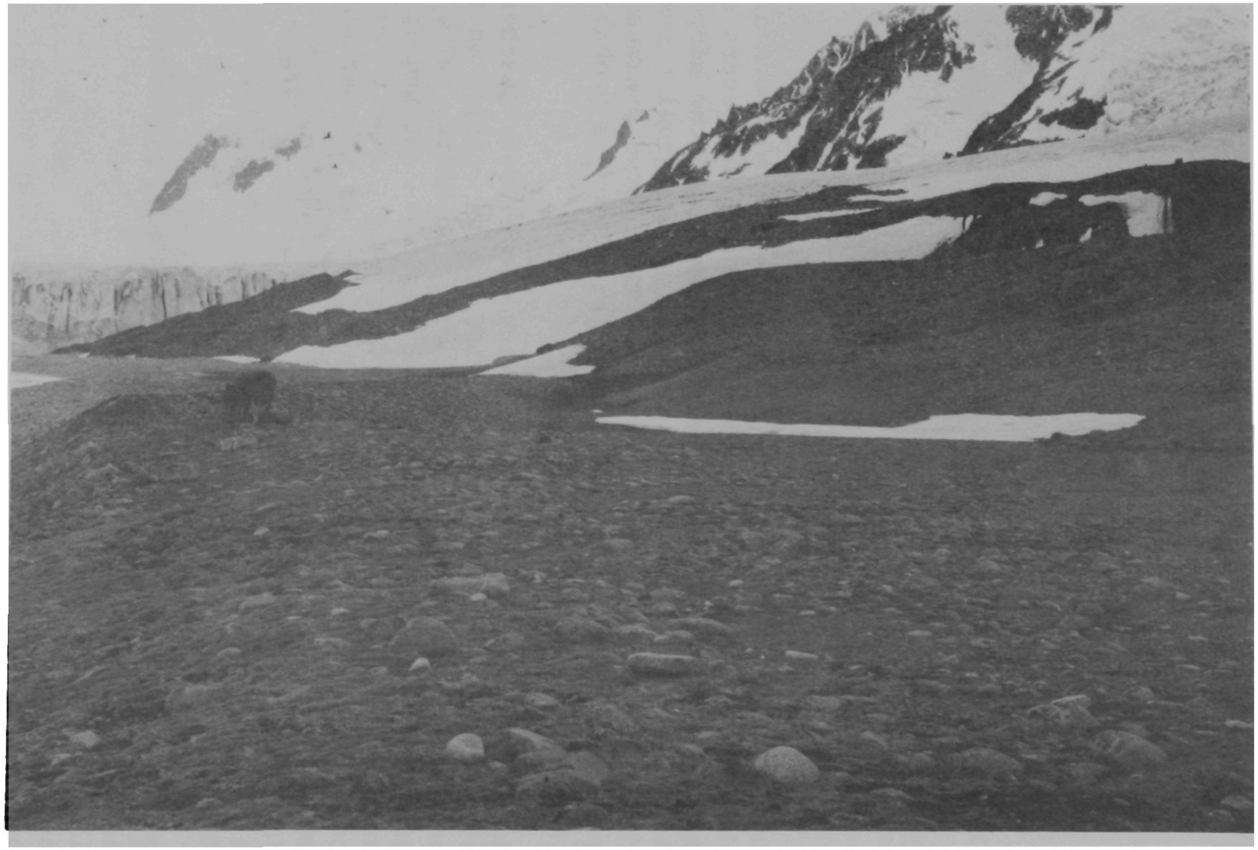

Fig. 50. Ice-cored Neoglacial moraines deposited above Wisconsin (?) moraine. Eastern False Bay, Livingston Island.

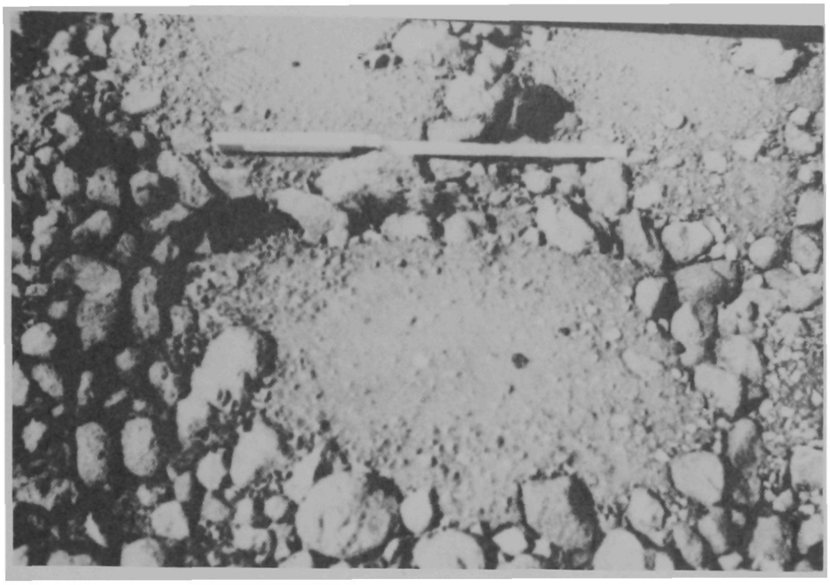

Fig. 51. Patterned ground occurring on the rear slope of the 11-17 m raised beach along Byers Peninsula. The stone net is approximately 30 cm in diameter.

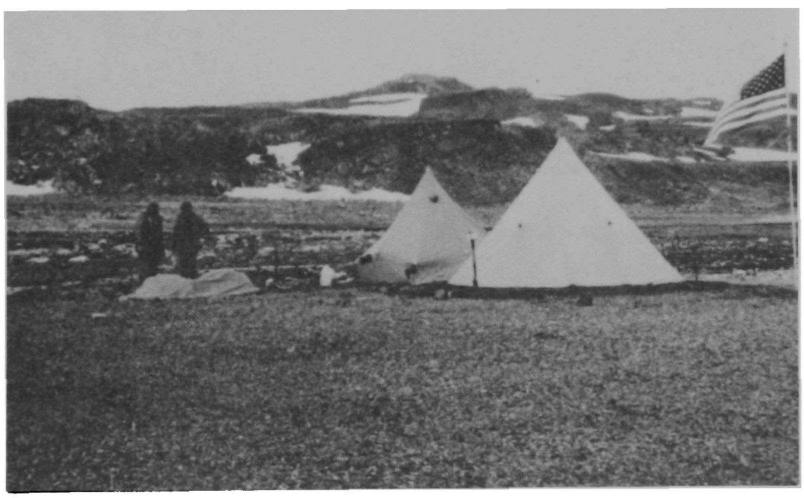

Fig. 52. The 18.5-20.5 m raised beach developed behind camp-site at Fildes Peninsula. The tents are pitched on the 6 m raised beach surface.

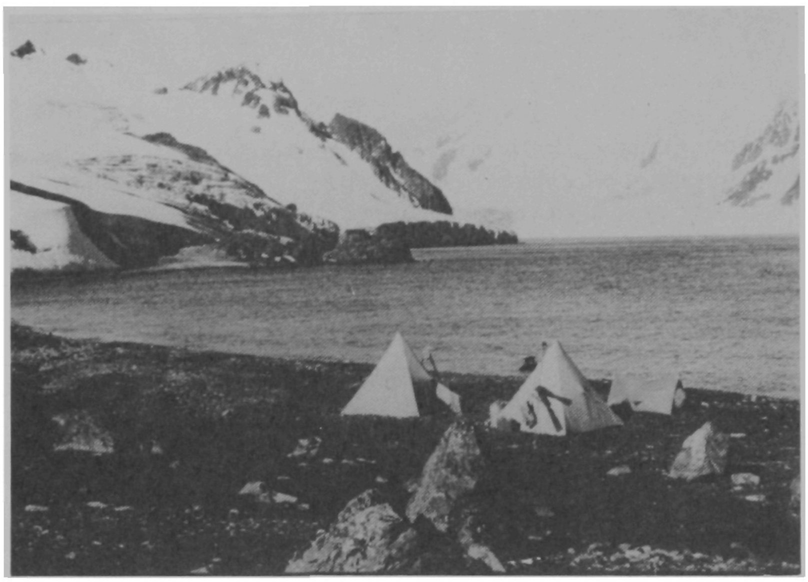

Fig. 53. The 19 m raised beach on the western flank of False Bay. View looking northeast toward Huntress Glacier, Flase Bay, Livingston Island.

the beach is about 100 meters wide and the back slope is covered with a thin layer of solifluction debris. The rear of the beach terminates at a bedrock cliff. Near Miers Bluff this beach is deposited on a wide platform extending about 500 m from the coast, it slopes seaward at about 1^o-2^o, and the center is cut by a drainage channel about 10 m wide and 3 m deep (Fig. 54). The platform increases gradually in elevation from the forward slope and terminates below a series of moraines deposited at the toe of a cirque glacier shown in Figure 17. On the eastern side of False Bay, this beach is deposited on bedrock surfaces below cirques and outlets. It has been overridden by moraines of both the recent advance (neoglacial) and the local glaciation (Wisconsin).

Above this elevation on both islands marine features are discontinuous and poorly preserved. The 18.5-20.5 m beach was the largest raised beach of fresh composition encountered.

At Fildes Peninsula the 18.5-20.5 m beach, as well as those below it, is developed within the mouths of meltwater channels occurring near sea level, but all marine features above this elevation are cut by the channels. This implies that the 18.5 to 20.5 m and lower beaches post-date both the major phase of glaciation involving extensive ice cover over most of the islands and also the warmer interval of meltwater channel development.

Raised Beaches above 20 m. The upper beaches are discontinuous features rarely occurring at the same elevation. These beaches are not nearly as fresh as the ones below 20 m. The beaches above 20 m are heavily weathered, and frost shattering increases steadily with elevation. Many of them have been overridden by ice and are covered by till and fans. This debris was derived from remnant beaches elsewhere, and include water-rounded striated cobbles and boulders, which give the impression of *in situ* beach deposits (Fig. 55). They are not extensive surfaces and probably represent short-term standstills of sea-level during wasting of the ice cap following the period of maximum glaciation. Several raised beaches on Barton Peninsula are unusually high. These beaches occur at elevations between 89 and 275 m.

A prominent marine platform on Barton Peninsula and North Spit (across Marian Cove) at 98 m is covered with beach cobbles (Fig. 56). Narrow and discontinuous frost-shattered beaches appear at 132 m and 189 m; and at 228 m a raised beach occurs above a small cirque. A 275 m marine beach is well developed west of Noel Hill (Fig. 57). The beach deposits consist of well-rounded cobbles beneath a heavily weathered surface (Fig. 58).

The locations and elevations of the features surveyed are given in Figures 35, 59 and 60.

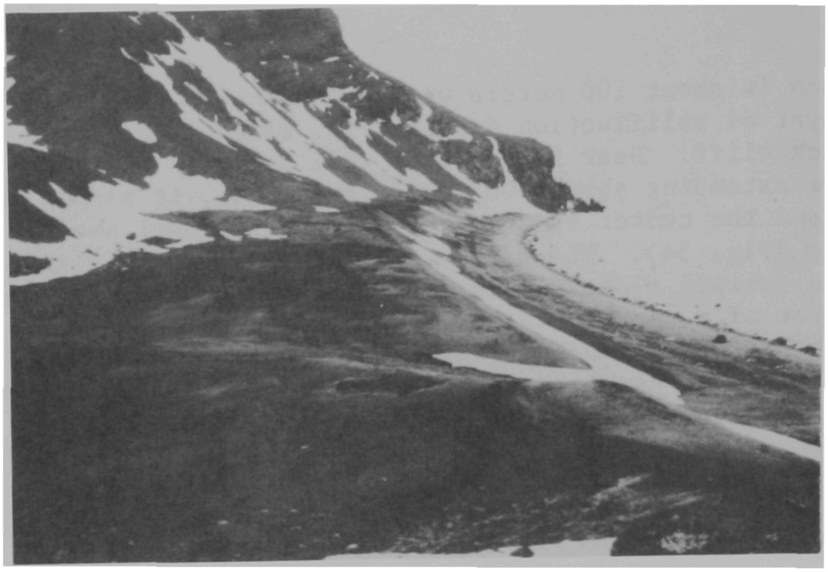

Fig. 54. The 18.5-20.5 m raised beach in cove near Miers Bluff, False Bay.

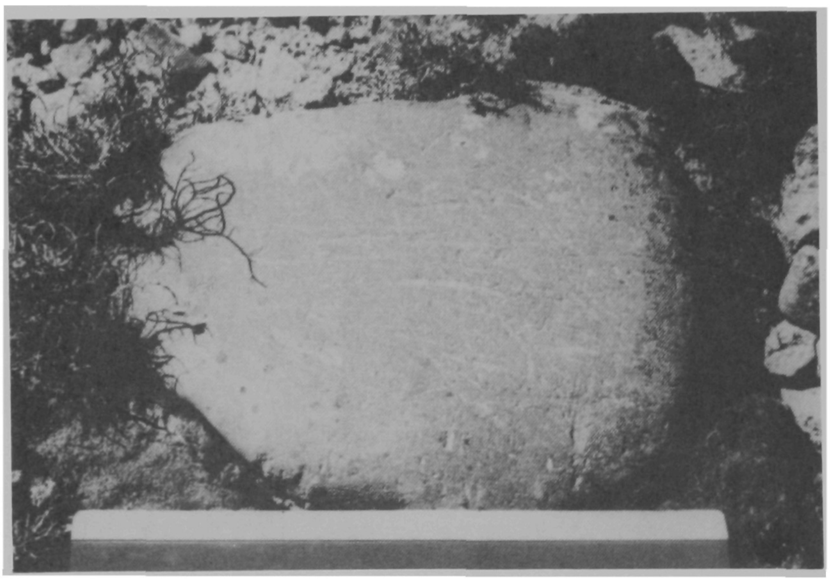

Fig. 55. Striated beach boulder in erratic fan deposited on the 189 m raised beach at Barton Peninsula. This boulder is a remnant from a beach derived elsewhere.

Fig. 56. The 89 m marine platform and raised beaches at North Spit, Marian Cove. The ice dome east of Fildes Peninsula can be seen above the platform. View looking north from Barton Peninsula.

Fig. 57. The 275 m marine platform with raised beach at Barton Peninsula, King George Island. This is the highest marine feature identified in the South Shetland Islands.

Fig. 58. Frost-shattered appearance of the 275 m beach on Barton Peninsula. Well rounded beach cobbles appear under the weathered covering. View looking west from Noel Hill, King George Island.

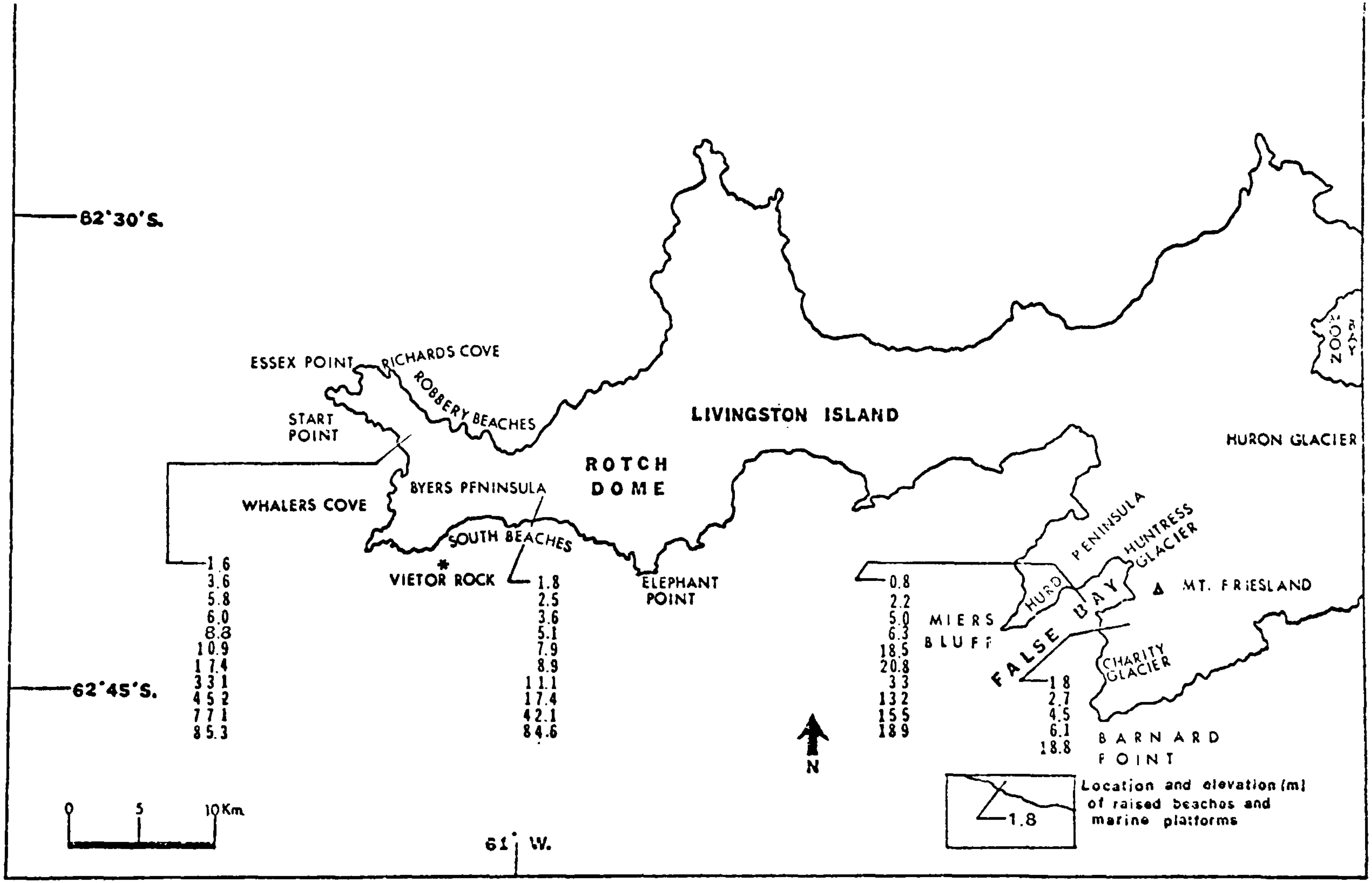

Fig. 59. Location and elevation of raised beaches and marine platforms surveyed on Livingston Island.

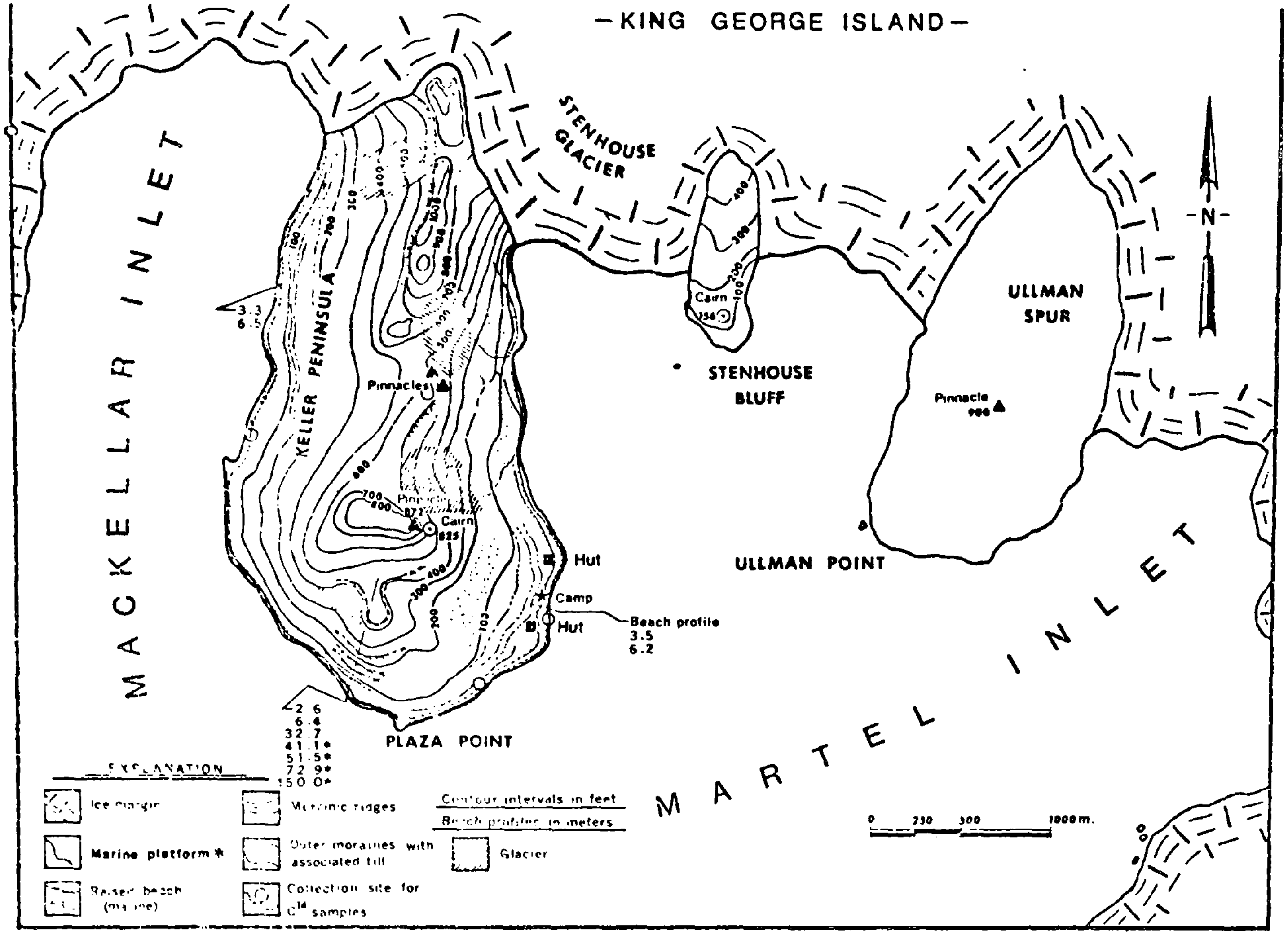

Fig. 60. Raised beaches and marine platforms surveyed on Keller Peninsula, Admiralty Bay, King George Island.

Development of Raised Beaches

The development of raised beaches is influenced by several factors: (1) the composition of the surface from which beach materials are derived; (2) the intensity of marine action (wave size) and drifting ice; and (3) the length of time sea level remained at a constant elevation. The platforms and beaches described are interpreted as developing during standstills over a long period of fluctuating sea levels. It is assumed that the most extensive beaches represent the longest standstills. Smaller features probably represent standstills of shorter duration, but could be remnants of more extensive features subsequently partly destroyed by erosion. Unfortunately beaches occurring at the same elevations may not necessarily have formed at the same time.

Additional information other than the elevation of a beach is needed to determine the sequence in which these marine features were produced.

It has been demonstrated in the preceeding section, through stratigraphic evidence, that since the last phase of major glaciation these raised beaches and platforms apparently were formed at progressively lower altitudes. Because of this, it is considered that the highest features are the oldest. It is also concluded that the high altitudes of the features are the result of local isostatic adjustments and eustatic variations. Tectonic influences, although they do not appear to be a significant factor, are unknown.

Relationship of Raised Beaches to Phases of Glaciation

The more prominent raised beaches occur at several distinct altitudes over a wide geographic range, and appear to represent large-scale events. The raised beach at 2.5-3 m was formed during or slightly after the time of deposition of ice-cored moraines from a recent and minor period of ice advance. The 6 m beach appears to have formed contemporaneously with or slightly after a period of local glaciation, and the 18.5-20.5 m beach apparently closely followed the major period of glaciation and the wastage of the ice cap during a period of climatic warming (Sangamon interglacial?).

The stratigraphic relationship shown between the beaches and moraines demonstrates their usefulness as time-stratigraphic horizons. Radiocarbon ages of materials from these beaches provide a partial chronology of earlier glaciation.

DATING THE PERIODS OF ICE ADVANCE

Radiocarbon Ages of the Raised Beaches

Whale bone for radiocarbon dating was collected *in situ* from several of the raised beaches at Livingston and King George Islands. These bones were abundant near sea-level but became increasingly more difficult to find with elevation. An exhaustive search revealed no bone on raised beaches above 6 m (Fig. 61). The whale bones normally occur in the fore-slope of the beach below the crest (Fig. 62). This position was assumed to represent median tide or even slightly lower. The floating carcasses did not lodge at the upper levels of wave action as does driftwood, but drift ashore where they become grounded slightly below high tide and were subsequently buried. During the burial process the skeletons may have been broken apart. Some fragments may have become imbedded in sediment at the original grounding site whereas others might have moved out into deeper water or been pushed or carried farther inland by ice rafting or wave action.

Where whale bones are abundant, care was taken to select specimens from nearly complete animals, thus avoiding the possibilities of drifted or reworked fragments.

Marine shells were not abundant within the beaches but occurred scattered on the surface. These shells were not considered representative of the time of beach deposition.

In addition, several recent specimens of whale and seal bones were collected for determining the apparent radiocarbon age of Antarctic sea waters.

Occurrence

Not all of the beaches at or below 6 m contain whale bone. Beaches with the most bones occur on coastlines adjacent to deep water or in deep water embayments and coves. The locations of collection sites and specimen numbers are shown diagrammatically on Figure 63. Table 3 indicates the composition of the specimen and the raised beach in which it was collected.

Radiocarbon Dating of the Bone Specimens

Bone material (total carbonate complex) is considered a reliable material for dating of Holocene and older events (Krueger, 1965). All of the specimens collected were partially exposed on the beach surfaces, so that contamination due to dissolved younger or older carbon in surface run-off and/or atmospheric carbon dioxide may be a possible source of

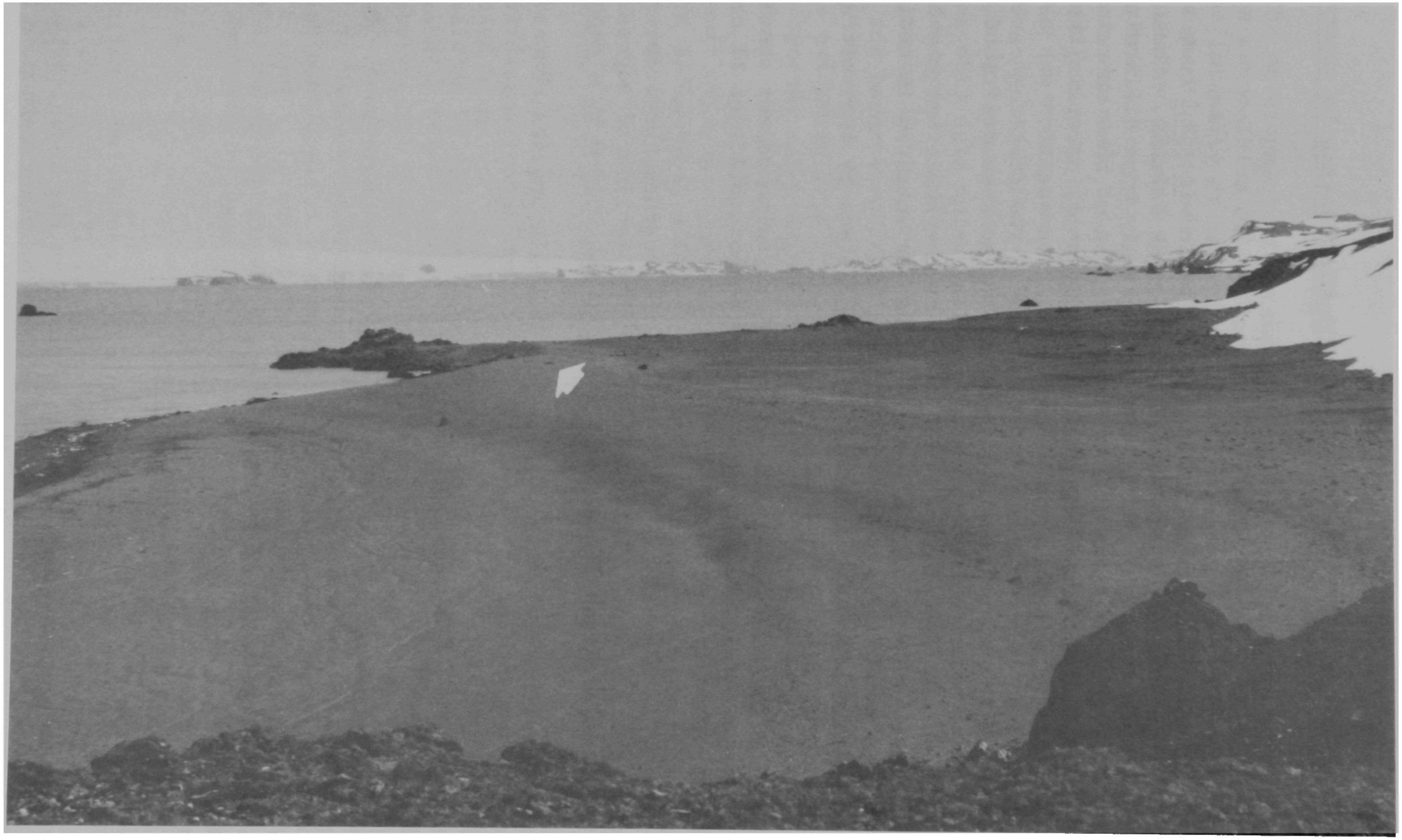

Fig. 61. A nearly complete whale bone carcass partially exposed on surface of 6 m beach near Three Brothers Hill, Maxwell Bay. This was the collection site for specimen MB-3.

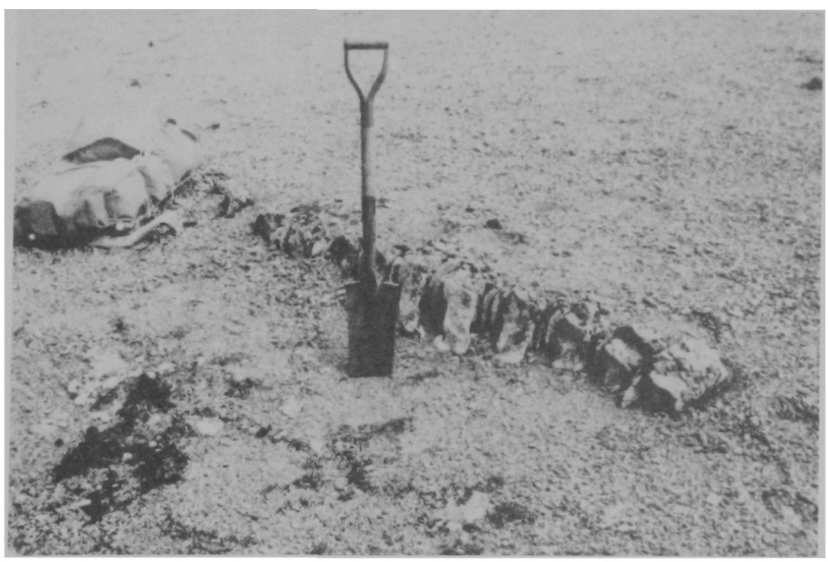

Fig. 62. Whale vertebrae discovered in foreslope of 3 m beach along South Beaches, Byers Peninsula.

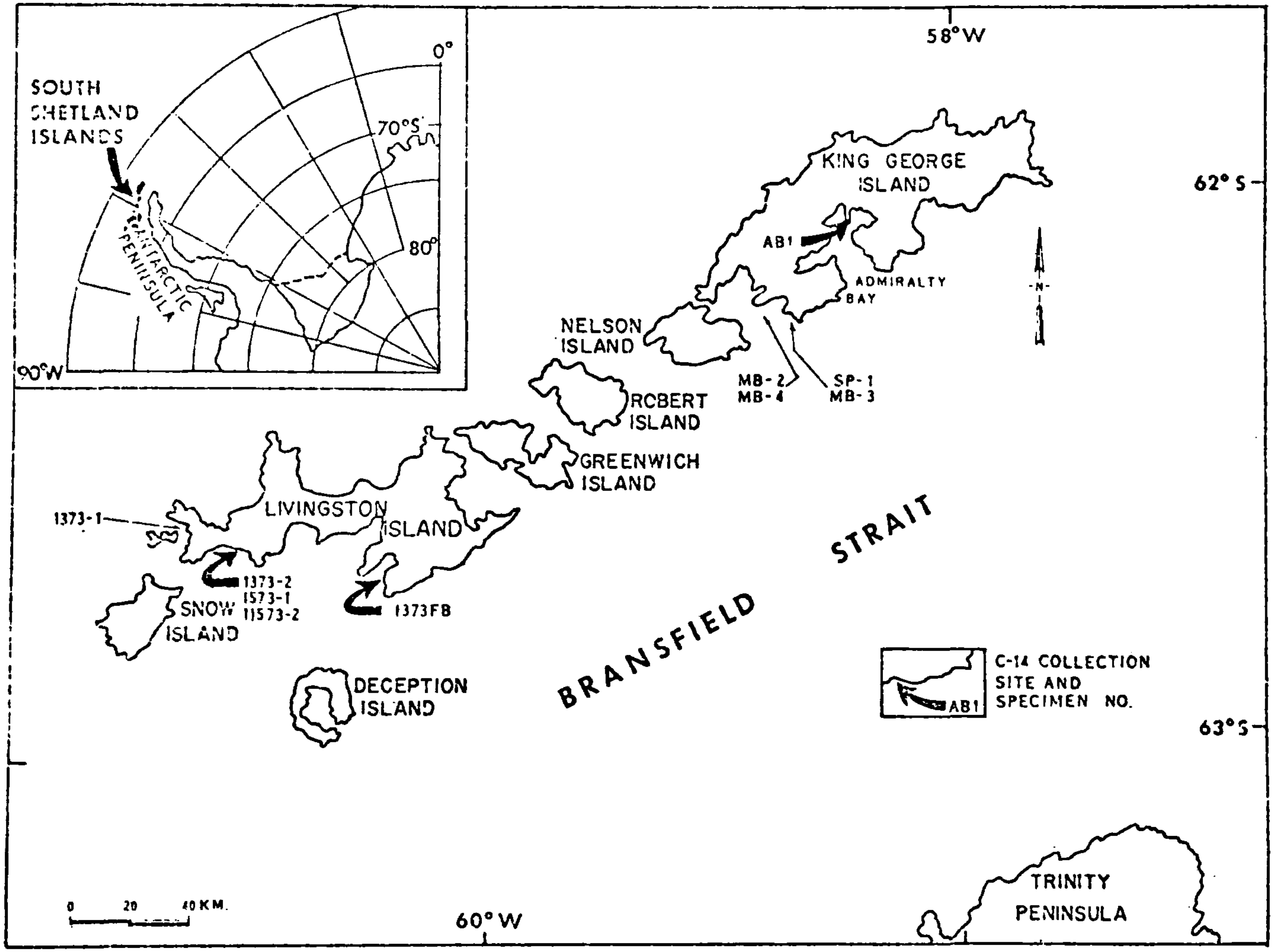

Fig. 63. Radiocarbon specimen collection sites in the South Shetland Islands.

TABLE 3. Radiocarbon Specimens Collected

Specimen Number	Specimen Composition	Altitude (meters)	Feature in which specimen occurred
115732	Whale vertebrae	4.5	Foreslope of 3.5-5 m raised beach.
15731	Whale vertebrae	7.6	Rear of 6 m raised beach
13731	Whale vertebrae	1.8	Completely exposed on rear of storm beach.
13732	Whale ear bones	1.8	Above ice-pushed ridge on storm beach
1373FB	Elephant seal skull, intact with flesh	1.8	Modern storm beach.
AB-1	Whale ear bones from slaughtered whale	1.8	Modern storm beach
SP-1	Whale vertebrae	2.1	In foreslope of 2.5-3 m raised beach
MB-2	Whale vertebrae	5.2	Foreslope below 6 m raised beach
MB-3	Whale vertebrae	6	Top of 6 m raised beach.
MB-4	Whale ear bone	2	Foreslope of 2.5-3 m raised beach

error in the age determinations. The carbon content of bone is quite low and it is contained in a very porous structure, so it is highly susceptible to contamination of this nature. Bone is composed of calcium-phosphate, calcium-carbonate, and collagen (bone protein). The inorganic constituents are supported by a network of collagen fibrils that divide the specimen into two fractions. The collagen (organic fraction) consists of tightly bound carbon that is considered to be almost totally resistant to replacement by carbonates dissolved in percolating waters and atmospheric carbon dioxide (Olson and Broecker, 1961), which commonly contaminate the inorganic fraction. For this reason, only the collagen fractions of the specimens were dated.

Present-day seawater and living marine organisms assume an apparent radiocarbon age due to the circulation of carbon in nature. As Broecker (1963) has pointed out considerable caution must be employed in the interpretation of these radiocarbon dates because of the "very old" ^{14}C ages that can be attributed to two principal factors: (1) Variations of the apparent age of the ocean water resulting from the circulation of water near the surface with older radiocarbon of deeper bottom waters (where the mixing rate is much slower), and (2) the influx of infinitely-old dead radiocarbon (exceeding 50,000 years) to the marine waters by the melting and calving of Antarctic glacier ice.

Radiocarbon deficiencies resulting from these two factors may yield apparent ages from about 200 years to more than 2500 years in excess of their true ages, depending on the history of the relevant water masses (Mangerud and Gulliksen, 1975). The error in true age of an organic specimen as a function of the percentage of contamination with "infinitely-old" carbon shows that if only 10% of the sample consists of "infinitely-old" material, the apparent ^{14}C age will be 850 years too high (Olsson, 1974). Errors of this magnitude can be critical for samples that vary, in reality, from about 200 years to several thousand years in age. Since the ^{14}C ages of intermixed bottom waters and glacier ice may vary from "infinitely-old" to slightly older than the age of the living marine organisms, the actual amount of the ^{14}C deficiency does not readily lend itself to theoretical prediction. Therefore, a correction factor for the age of the marine waters, in which the dated animals lived, must be extimated from data acquired through empirical observation of these variations. Without a reasonably accurate estimate, the uncorrected ^{14}C dates are of little significance in establishing an absolute chronology.

Previous field investigations in the South Shetland Islands by John and Sugden (1971); Sugden and John (1973); and Schytt (1972) resulted in the availability of several ^{14}C dates; however, only two dates of recently dead seaweed and a seal carcass (bone material used for date) were directly related to a determination of the age of Antarctic marine water. These dates fell between 420 years ± 100 and 2512 years ± 50 before the present (1950). A more definite ^{14}C age determination of the waters was not possible considering the wide variation between these reported limiting ages. Olson and Broecker's (1961) estimate of the age of Antarctic waters suggested a "built in" age of about 600 years, which was based on radiocarbon analyzed from the Atlantic Ocean of both hemispheres, but this estimate was not actually substantiated for Antarctic waters.

Faced with the paucity of data, a generally applied correction of about minus 500 to minus 600 years for absolute age determinations agreed fairly well with Olson and Broecker's estimate and Schytt's seal carcass date from Livingston Island.

In an attempt to establish a more precise magnitude of the ^{14}C deficiency in these waters, an empirical method was used. It involved the radiocarbon ages of recently dead organic remains collected from the present day intertidal zone and adjacent beaches of Byers Peninsula, Maxwell Bay, and Keller Peninsula. Whale and seal remains were collected from the recent beaches and were used for this determination (Table 4).

Description of Specimens

Specimen 1373FB, from Livingston Island, consisted of a fleshy seal skull removed from a partially-decomposed juvenile elephant seal that had recently died and was discovered on the beach slightly below the high-tide mark (Fig. 64). From the fresh condition of the carcass, the approximate time since death was estimated to be not more than about 1-5 years. Specimen 13732 was collected from a partially decomposed whale carcass that had drifted ashore and subsequently grounded at low tide. This sample consisted of both ear-bones which were removed from the skull. The time since death for the specimen was estimated to be not more than about 10 years. Specimen AB-1 was collected from Admiralty Bay, King George Island, and consisted of ear bones from a hump-backed whale. This specimen was taken from skeletal remains discarded on the beach after flensing by whalers. Axe and saw marks clearly visible on the vertebrae of the remains tended to substantiate this conclusion. Hump-backed whaling commenced in these waters about 1900 and by 1915 these whales had become rare in Antarctic waters. Pelagic whalers (factory ships) were initiated in the Antarctic about 1910 and facilitated the recovery of the entire whale carcass, which was totally consumed in the oil-rendering process. An approximate time of death of this whale should fall between 1900-1910 and was estimated at 1905. This conclusion has been substantiated by Sir Vivian Fuchs (personal communication).

It is very difficult to render pure collagen, and since it is the amount and nature of the remaining contaminants that determine the quality of the date, it is important to state the method used for cleaning and extracting the collagen (Olsson, 1974). The partially decomposed nature of specimen 1373FB required the removal of the carrion in the field. This was accomplished by boiling the specimen in a dilute solution of sodium hydroxide for about one hour, followed by the removal of the more stubborn flesh with dental instruments (Fig. 64). After cleaning, the specimen was air dried and sealed in aluminum foil as were the other specimens.

TABLE 4

Radiocarbon Measurements of Modern Marine-specimens Collected from the South Shetland Islands, Antarctica

Specimen number	Lab.ref. no.*	Specimen composition	Locality	Lat. S.	Long. W.	Date collected	Time of death in years BP	Weight of collagen in grams	Apparent ^{14}C age in years BP**
13732	DIC-372	Whale bone	Livingston Island	62^{o} 39'	61^{o} 00'	1-3-73	2-10	2.0328	840 ± 75
1373FB	DIC-370	Seal skull	Livingston Island	62^{o} 42'	60^{o} 24'	1-13-73	2-7	2.4399	970 ± 50
AB-1	DIC-367	Whale bone	King George Island	62^{o} 05'	58^{o}-23'	2-13-74	70	2.4357	1000 ± 45

* Age determinations by DICAR Corporation, Case Western Reserve University, Cleveland, Ohio

** Apparent age in years before present established by international convention to be in years before 1950 A.D. Ages calculated for Libby half-life of 5730 years; specific activity of 1950 modern standard = 7.543 c/mg^{-1}.

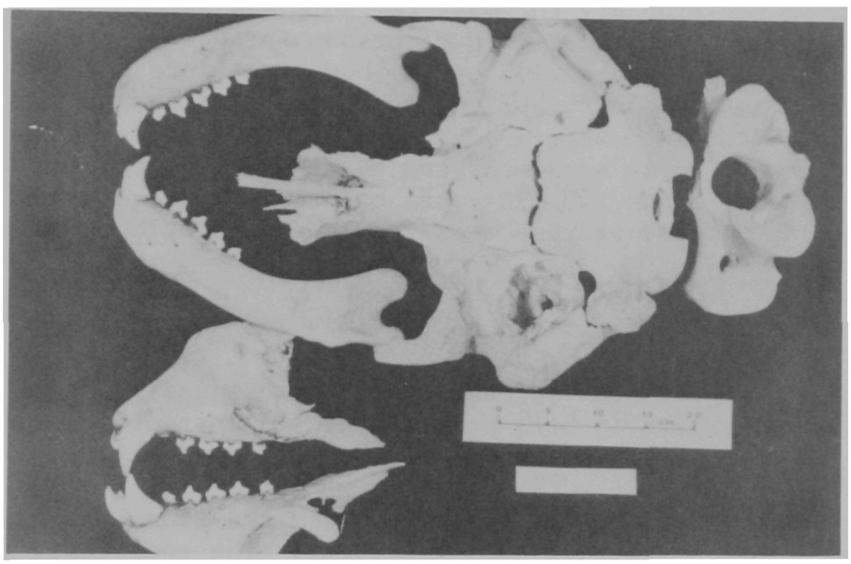

Fig. 64. Elephant seal skull from False Bay (1373FB) after carrion was removed. The radiocarbon age of this specimen was 970 ± 50 years BP.

Additional laboratory cleansing was required before the collagen fraction was isolated. This cleansing consisted of removing other organic compounds, which are frequently a source of contamination, with repeated baths of very dilute hydrochloric acid and cold sodium hydroxide. The outer portion of the bone material of each specimen was removed physically by cleaning ultrasonically and grinding with a dental drill under a 90X microscope (Stehli, personal communication). The collagen was isolated by dissolving the inorganic fraction in hot hydrochloric acid and decanting the solution. The collagen residue was then converted to benzene and the specific activity of the ^{14}C counted. Table 5 lists the radiocarbon ages of the specimens.

Because the carbon cycle of specimen AB-1 terminated about 1905, an additional 70 years must be subtracted from its apparent ^{14}C age. This specimen has probably the most reliable age because its life cycle terminated before industrial or nuclear bomb-produced ^{14}C would have influenced its carbon ingestion cycle; however, since the apparent age of this specimen was about the average value, this sample was not weighted above the others. The dates appear to be in broad agreement, and assuming that the dates of these specimens are equally valid, the non-weighted average is 936 or about 940 ^{14}C years before present. This value should be subtracted from radiocarbon ages from the Antarctic to approximate absolute age.

Ages of the 6 m and 2.5-3 m Beaches

A summary of the radiocarbon dates is presented in Table 5. Radiocarbon dates are given in both uncorrected and corrected (-940 years) values.

The contemporary samples collected from the storm beaches are fairly consistent in age except for specimen 13731. The remarkably old age of this specimen suggests that it may have been originally deposited at a higher elevation. Only a few scattered bones are located at the site and this explanation seems the most reasonable, but the possibility of laboratory error remains.

The dates from specimens MB-2 and MB-3 places the formation of the 6 m beach and the related phase of local glaciation about 420-500 years before present. However, specimen 15731 is in disagreement by about 1000 years. The explanation might lie in the fact that this specimen was collected at the rear of the 6 m beach at one of its highest elevations (7.6 m) and may be related to the period of formation of the higher beach level developed before the 6 m beach. Several radiocarbon dates from the 6 m beach by Sugden and John (1973) favor this conclusion, and they support the younger age. Whale bone sample Birm-224 (1390 ± 140 BP) was collected at an altitude of 6-7 m on Barton Peninsula. An additional radiocarbon date (Birm-17) of 1430 ± 470 years BP was

TABLE 5. Radiocarbon Dates from the South Shetland Islands

Specimen Number	Lab. Ref. Number	Raised Beach	Uncorrected ^{14}C age Years BP***	Corrected ^{14}C Age BP (-940 years)
115732	I-7869*	3.5-5	1025 ± 80	85 ± 80
15731	I-7870	6	2530 ± 85	1590 ± 85
13731	I-7872	1.8	4905 ± 100	3965 ± 100
13732	DIC-372**	1.8	840 ± 75	----
1373FB	DIC-370	1.8	970 ± 50	30 ± 50
AB-1	DIC-367	1.8	1000 ± 45	60 ± 50
SP-1	DIC-368	2.5-3	1200 ± 110	260 ± 110
MB-2	DIC-373	6	1440 ± 55	500 ± 55
MB-3	DIC-371	6	1360 ± 165	420 ± 65
MB-4	DIC-369	2.5-3	1210 ± 55	270 ± 55

* Teledyne Radioisotopes, Inc.
** Dicar Corp., Case Western Reserve University
*** Radiocarbon years before present as of 1950 A.D.

reported for seaweed buried between inclined gravels within this beach, at the same location (Sugden, personal communication). The similarity of these four dates, two of which were determined in a different laboratory, suggest that they are fairly reliable. Based on this evidence, formation of the 6 m beach occurred about 500 radiocarbon years ago and it is clearly late Neoglacial.

Radiocarbon dates from specimens SP-1 and MB-4 date the deposition of the 2.5-3 m beach and the major ice advance that occurred contemporaneously with it at approximately 265 years before present.

The late Neoglacial ages suggested for both of these ice advances account for the fresh appearance of the raised beaches at or below 6 m and the ice-cored moraines associated with the 2.5-3 m beach. An independent age was also determined for this recent advance by lichenometry.

Some insight as to the age of glacial events occurring before the 6 m beach is revealed by two additional radiocarbon dates. According to Sugden (personal communication), marine mollusc fragments (Birm-48A) were deposited in marine sediments (3.5 m) 9760 ± 230 years BP during a period when the Potter Cove outlet glacier (Fig. 6) was sufficiently withdrawn not to have affected marine deposition of the southern shore. Above this beach specimen the marine deposits coarsen upwards, possibly indicating advancing ice, and they are overlain by a sandy till about 1.5 m above Birm-48A. A radiocarbon date of 7683 ± 86 years was obtained from sea weed occurring at the interface between marine deposits and till. These dates suggest that the Potter Cove outlet glacier was withdrawn inside the present position (presently about 800 m behind the site) as early as about 9000 to 7000 years ago or by late Wisconsin time. As suggested by the marine deposits found up to an elevation of about 5 m, relative sea level was also higher.

Lichenometric Ages

The climate of Antarctica, except in the northern part of the peninsula, imposes severe limitations on the growth of land plants. Only two flowering plants, bryophites and lichens, have flourished under these limitations (Dodge, 1973). However, in the maritime Antarctic somewhat milder conditions prevail and lichen colonization is extensive. Although lichenometry has been used extensively as a technique for dating geomorphologic phenomena associated with ice retreat in the Northern Hemisphere (Andrews and Webber, 1970), it has not been used thus in the Antarctic due to a lack of colonized substrata of known age.

Crustose lichens were observed on moraines of the recent ice advance near Elephant Point, Livingston Island (Fig. 41). They were also observed on related ice-cored moraines on the southern margin of Charity Glacier and on a fresh moraine deposited about 20 m below the cirque glacier shown in Figure 17.

Lichens were identified on these and other features at Livingston Island by Lindsay (1971). Five abundant lichens identified by Lindsay were: (1) Rhizocarpon geographicum, (2) Umbilicaria Antarctica, (3) Caloplaca elegans, (4) Usnea antarctica, and (5) Caloplaca cf cinericola. The first three of these are crustose and were observed on the substrates of all the recent moraines. The thalli diameters of single round Rhizocarpon geographicum specimens (Fig. 65) were measured using a millimeter scale placed directly over the thallus, and the largest diameter of eight readings was recorded. A similar set of measurements was made on the walls of a sealers' hut located less than 500 m from the recent moraines near Elephant Point. This hut was reported to have been built by American sealers between about 1821 and about 1825 (Sir Vivian Fuchs, personal communication). The seal population was completely depleted during this short period.

Maximum thalli diameters for Rhizocarpon on recent moraines at False Bay were 36 mm, and on the Elephant Point moraines 35 mm. Two size distributions were found at the sealers'hut. On the inner and outer walls of the stone hut the maximum thallus diameter was 54 mm. This diameter was measured from the four largest thalli at random positions, inside as well as outside the hut.

The maximum thallus iameter from 18 other specimens found only on the outer walls, was 21 mm. It is believed that the 21 mm diameter represents maximum lichen growth established after the hut was built, while the larger thalli were established on the substrate before the hut was constructed. A growth rate curve based on the 21 mm maximum growth after the hut construction date of 1821 is presented in Figure 66. If this growth curve is valid, the ages of the moraines can be determined by plotting maximum thalli diameters against time (Beschel, 1961; 1973). This plot assumes that growth was linear, and that establishment time for both the substrates was the same.

The lichenometric ages for the recent advance are correspondingly 264 years for the False Bay moraines and 257 years (about 1720 A.D.) the moraines near Elephant Point.

These ages agree very well with the radiocarbon dates associated with this advance. In addition, they are not subject to the problems associated with ^{14}C in seawater, and they tend to substantiate the -940 year ^{14}C correction factor previously described. Considering the many variables associated with these two dating methods, the remarkably close agreement (within a few years) should not be misconstrued to represent a measurement of the precision of the techniques.

A growth rate of about 13.5 mm per 100 years. for Rhizocarpon geographicum on Livingston Island is broadly similar to the growth rate (16 mm per 100 years) reported by Lindsay (1973) for Signy Island, South

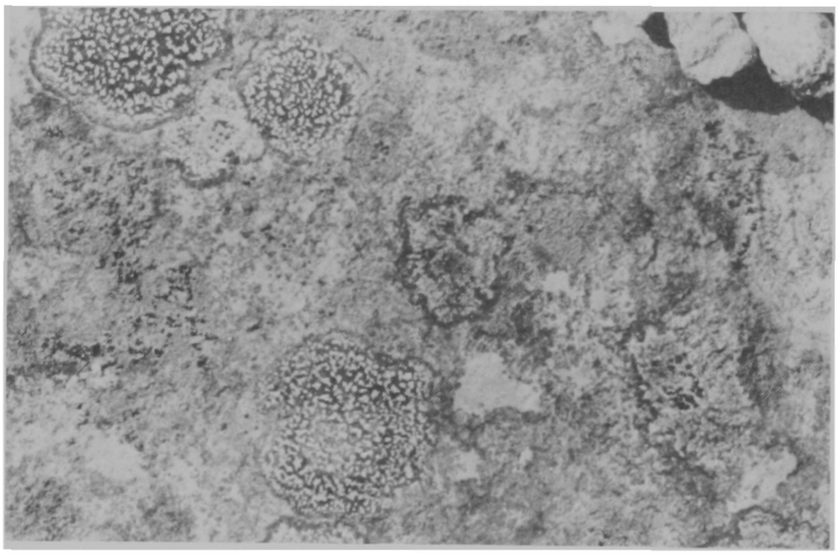

Fig. 65. Rhizocarpon geographicum thalli on boulder in recent moraine near Elephant Point, Livingston Island.

GROWTH RATE DIAGRAM FOR RHIZOCARPON GEOGRAPHICUM ON LIVINGSTON ISLAND.

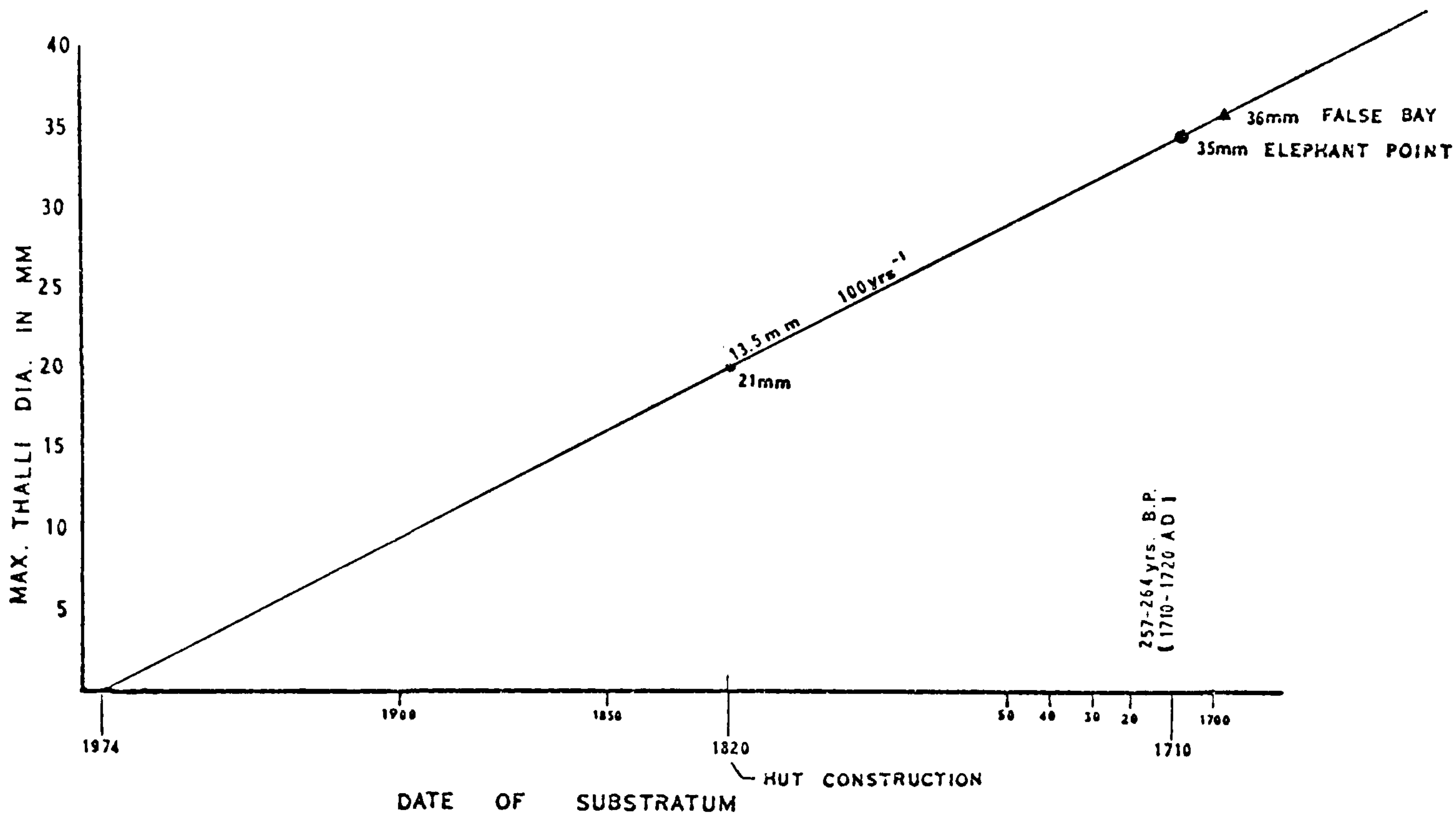

Fig. 66. Linchenometric ages of Neoglacial moraines at False Bay and near Elephant Point, Livingston Island.

Orkney Islands. These islands are only about 500 km distant and at nearly the same latitude with similar climates. A similar set of recent moraines occurring on Signy Island was dated at 1740 A.D. (Lindsay, personal communication).

Discussion of the Dates

The deposition of beaches at sea levels from 3 to 6 m higher than at present within the past 500 years is puzzling. A eustatic fluctuation of this magnitude is not supported by studies elsewhere. Interpreted in terms of isostatic recovery, the uplift rate for the 2.5 to 3 m beach is of the order of about 0.01 m $year^{-1}$ which is approximately the same for the 500 year old 6 m beach. This uplift rate is only about twice that presently occurring at Home Bay, Baffin Island, related to deglaciation at 9000 years BP (Andrews, 1970). It is believed that local isostatic adjustments are responsible for these relative fluctuations in sea level, although the influence of eustatic sea level changes, and peripheral bulge from the Antarctic Peninsula (Hollin, 1970) cannot be completely eliminated from consideration.

The formation of the raised beaches apparently coincides with deglaciation following earlier and more extensive glaciation. It is reasonable to conclude that their elevations are primarily related to isostatic rebound from glacial unloading, but are also a function of eustatic changes.

A fairly rapid deglaciation followed the major glaciation (Illinoian or earlier late-Pleistocene?) and isostatic uplift must have been initially rapid. From the evidence of the 275 m beach, it can be assumed that little ice remained on the islands at this time and isostatic recovery during deglaciation must have been greatly accelerated as compared to that of the present day.

Evidence of a fairly rapid uplift rate after deglaciation of the main phase is reflected by the older beaches above 45 m. These beaches are poorly developed and heavily weathered, and the vertical distance between them is much greater than that of the more recent beaches. The paucity of beaches above this elevation and their small size (aside from prolonged exposure to weathering processes) indicates that there were few standstills in sea level of long duration.

The 19 m beach was probably formed during a marine transgression toward the end of the Wisconsin stage, but it was also influenced by continued isostatic adjustment.

The smaller differences in elevation between the beaches occurring below 19 m suggest that isostatic rebound had decelerated considerably by these times, perhaps due to approaching equilibrium or in response to the build-up of ice to about the extent at which it is found today.

The well developed and continuous beaches formed at 6 m and at 2.5 to 3 m are statigraphically associated with late Neoglacial ice advances occurring within about the last 500 years, and follow the first two periods of deglaciation that probably occurred after the Wisconsin and Illinoian glaciations. The late Neoglacial ice advances may have been sufficient to slow, halt, or even change the direction and velocity of isostatic uplift temporarily.

GLACIAL HISTORY

The absolute dates presented in the last chapter suggest a chronology for recent ice fluctuations, but a more complete history of glaciation can be reconstructed from the relationships between the marine features and other distinctive landforms.

History of Glaciations

The main uplift of the South Shetland Islands probably occurred in Late Cretaceous to Early Tertiary time as a result of the Andean Orogeny, which was accompanied by intrusion and faulting (Ashcroft, 1972). Volcanic activity was renewed toward the end of the Oligocene, producing many sediments and volcanics that were deposited in a shallow submarine environment. During Oligocene-Miocene times a vegetative cover flourished in a temperate environment (Hobbs, 1968). The climate had become sufficiently cooler by Pliocene or Pleistocene times for the establishment of permanent ice caps (Adie, 1962; Barton, 1964; 1965). The broad surfaces and platforms were developed above 52 m to about 155 m on the peninsulas including the 100 m submarine platform to the north of the islands. These were formed during standstills at a time when the islands first emerged from the sea and prior to the onset of glaciation.

The Illinoian (?) Stage

When glaciation commenced in the South Shetland Islands is uncertain. According to Adie (1964) and Barton (1964), it may have begun as early as Late Pliocene, bu the well preserved nature of the beaches and platforms now at high elevations suggests that they could not be much older than Illinoian. The initial stage probably began with island ice caps which subsequently expanded to form a major ice cap (270 km by 70 km) that covered the islands with ice that was 1200 m to 1500 m thick. This ice cap probably represents the maximum extent of glaciation occurring on the islands, for it destroyed the evidence of previous glacial activity. The dominant direction of ice movement and submarine trough development suggests that the center of this ice cap was above the broad submarine platform to the north of the islands. The number of oscillations or the duration of this major glaciation is not known but it was followed by a warmer non-glacial period (Sangamon interglacial?).

The Sangamon Interglacial

The non-glacial interval was initiated by a period of climatic warming that caused dissolution of the central ice cap. Meltwater channels were developed across Fildes and Byers Peninsulas. These channels were formed by large volumes of glacial meltwater, indicating melting during a warmer climate, probably during the Sangamon Interglacial.

The major phase of glaciation (Illinoian?) and late glacial meltwaters were followed by a non-glacial interval during part of which sea level was high enough to submerge most of the islands.

Evidence of this submergence exists in the form of raised beaches deposited as high as 275 m (Noel Hill). These beaches are very well preserved in places; they are composed of well-rounded pebbles which are commonly found banked or resting against surfaces cut into the surrounding bedrock in protected areas. Little ice could have existed on the surrounding highlands at the time of deposition of the 275 m beach.

Raised beaches become progressively more weathered (frost-shattered) with elevation and in places were obscured by till and striated beach cobble fans deposited on them. This material originated from still older beaches at higher altitudes. The freshness of the beaches suggests they belong to late Pleistocene (Riss-Illinoian).

The high altitudes at which these raised beaches occur can be explained adequately by isostatic uplift and eustatic sea level rise following the rapid unloading of the central ice cap, but may have been influenced to some degree by tectonic activity. If the non-glacial interval did represent a true interglacial period (San amon Interglacial?) then a eustatic rise in sea level aided in the formation of the high beaches.

The Wisconsin Stage

A second stage of glaciation followed the non-glacial interval. This advance is indicated by the glacial deposits overlying the raised beaches above 19 m and on the ice-free peninsulas. A veneer of till containing erratics and striated, faceted cobbles from earlier beaches is found over part of Byers Peninsula and most of Fildes Peninsula including all of the meltwater channels observed. The direction of ice movement indicated by some of the erratics and erratic fans suggests that ice approached from the east along both the peninsulas, which was transverse to the direction of flow during the earlier ice sheet phase of glaciation. The small ice dome to the east of Fildes Peninsula may be a remnant of the formerly more extensive ice cap which overrode the peninsula to the west of the Wisconsin Stage.

Erratics west of Chester Cone on Byers Peninsula (Fig. 8) bear evidence of a local expansion of the Rotch Ice Dome. At False Bay, till of this glaciation formed spits extending below sea level, and expansion of the island ice cap at this time deposited till on the 185 m surface of Hurd Peninsula. Lateral moraines of the Potter Cove outlet glacier merged with those of the central ice cap between Potter Cove and Stranger Point and partially obscured a raised beach formed around Three Brothers Hill at 93 m.

This phase of glaciation consisted of (local) expansion of island ice caps nearly to the island's present shores. The inability of the ice to remove all traces of the raised beaches or to have modified the preexisting ice-molded features oriented at 90° to its movements suggests that this glaciation was less intense and moved in a perpendicular direction to the earlier glaciation. An indication of sea level during this period is noted by the occurrence of till, solifluction, and striated erratic fans on top of raised beaches above about 45-55 m.

Following the Wisconsin (?) phase of local-island glaciation the ice margins retreated to about the position in which they are found today. Evidence of this retreat is shown by several moraine-beach relationships. Below the elevation of about 45 m, raised beaches occur more frequently. The surfaces of these beaches show no signs of overriding by glacial debris, but they become slightly more frost-shattered with altitude. These beaches were produced by uplift as the local ice caps withdrew. The retreat was probably gradual and meltwater was minimal since no drainage pattern or glacio-fluvial deposits were found related to the withdrawal.

A prominent and continuous raised beach deposited at about 19 m near the present margins of the ice indicated that the ice caps had withdrawn to about their present position before the formation of this beach.

Some indication of the age of this withdrawal is reflected by the stratigraphy and radiocarbon dates obtained from Potter Cove. Retreat of the outlet glacier to several kilometers behind its lateral and terminal moraines during this glaciation occurred. The approximate 9000 year BP age of the mollusc shells found in marine sediments (coarsening upwards) suggests that at that time the ice was well behind the sample site and was possibly starting to re-advance. This advance occurred some time after about 6800 BP as evidenced by the radiocarbon date from seaweed at the till-marine deposits interface. Since the retreat of the ice to about its present position at the end of this glaciation (late Wisconsin?), it appears to have been stationary with the exception of the late-Neoglacial minor advances until recent times.

Late Neoglacial Chronology

Evidence of two late Neoglacial ice advances consists of two distinct moraines associated with the 6 m and 2.5 to 3 m beaches. The radiocarbon dates and lichenometric ages have shown that late Neoglacial advances occurred about 500 years ago and about 265 years ago. Glaciological studies conducted by Orheim (1972) in the South Shetland Islands indicate that the present mass balance is near equilibrium or possibly slightly negative. Some evidence of a gradual thinning of the ice margins is revealed by the crested ice-cored moraines surrounding the present ice caps at Potter Cove and Byers Peninsula. A possible explanation is the effect of the slight climatic warming period before 1940.

Significance of the Data

A tentative sequence of glacial events was reconstructed from this data. This sequence is summarized in Table 6. The upper part of this sequence is adequately dated by radiocarbon and lichenometric determination, while the lower part appears compatible with other evidence from the Antarctic Peninsula and Patagonia.

Regional Correlation of Glaciations

Little data are presently available that would allow the major stage of glaciation to be dated. The inferences that can be drawn directly from the South Shetland Islands are that it was the earliest and most extensive glaciation(s) of which evidence is preserved today. The preservation of the marine platforms and raised beaches at high elevations suggests that the last time the major ice cap existed was in late Pleistocene time. A tentative correlation is Illinoian or several thousand years earlier (?), but definitely not early Pleistocene. The early Pleistocene-Pliocene glaciations of East Antarctica may pre-date the emergence of the South Shetland Islands above sea level. If an early Pleistocene record of glaciation did exist on the islands, it was probably destroyed by this Late Pleistocene ice cap. The separation of the two glaciations by a warmer interstadial or interglacial indicates dissolution by climatic warming. Evidence of climatic warming in West Antarctica during the Sangamon Interglacial has been discussed by Mercer (1968a).

Lake sediments in Central Antarctica indicate that summer temperatures were 7^{o} to $10^{o}C$ warmer than they are today sometime during the late Pleistocene. According to Mercer (1968a), a temperature rise of this magnitude would have caused a portion of the West Antarctic Ice Sheet to disintegrate raising the sea-level by about 4-6 m. Uranium and thorium isotope dates indicate that this melting occurred about 120,000 years ago at the end of the Sangamon Interglacial (Mercer, 1968a). Temperatures then fell again, and the Wisconsin Stage of the West Antarctic Ice Sheet was established. This ice sheet has survived to the present day. A Sangamon warm period is also supported in the glaciological record of the Byrd ice core (Epstein and others, 1970). The Sangamon warming period tentatively correlates with the non-glacial phase on the South Shetland Islands. If so, the main glaciation is late Pleistocene and possibly Illinoian. The subsequent local phase of glaciation, by the ^{14}C date, (9000-6800 years BP) is Wisconsin in age, and this glaciation may correlate with Mayewski's (1973) Amundsen Glaciation. The radiocarbon dates in Potter Cove suggest that partial deglaciation had occurred by about 9000 ^{14}C years ago. This is in agreement with evidence of warming since 15,000 years BP from the Byrd

Table 6. Tentative Glacial History

Period and Epoch			Age	Suggested Events	Climate Indicated	Sea level from the Present
QUATERNARY	Recent	Late Neoglacial	To Present	Gradual thinning of ice caps	Warmer	Lowering with Fluctuat-ions
			265 yrs BP	Minor re-advance ≈265 yrs BP Deposition of 2.5-3 m beach.	Cooler	
				Retreat of ice	Warmer	
			500 yrs. BP	Local re-advance ≈ 500 yrs.BP Deposition of 6 m beach.	Cooler	Halt(?)
			7000-9000 yrs. BP	Formation of ≈8.5-20.5 m raised beach.	Warming	Standstill or trans-gression.
				De-glaciation, ice withdrawl to about present position	Warmer(?)	≈45-55 m
	Pleistocene	Late	Wisconsin	Local glaciation, expansion of island ice caps	Warmer	Lowering
			Sangamon (?)	Non-glacial interval beaches formed up to 275 m	Cooler Warmer	up to 275 m
				Deglaciation, rapid melting, meltwater channels.	Warmer	Higher
			Illinoian or Earlier	Major phase of glaciation(s) (270 km by 70 km)	Glacial	-100 m (?)
				Ice caps forming.	Glacial Colder	Lower
		Early		No record.	Glacial?	
TERTIARY	Plio.			Development of moraine surfaces and platforms above 55 m	Cooler	±100 m 300 m Fluctuat-ing.
	Mio.			Vegetative cover		
	Oli.			Falling and volcanic activity.	Temperate or warmer (?)	Numerous fluctuat-ions.
	Eoc.			Andean Orogeny		

ice core (Johnsen and others, 1972), and correlates well with Mercer's (1968b, 1970) work on Patagonian glacier variations. The warming trend in Patagonia appeared to be around 11,000 years BP or somewhat earlier than the 9000 years BP in the Northern Hemisphere. These results suggest that the periods of glaciation in the South Shetland Islands correspond in time with similar events in West Antarctica and South America.

Calkin (1964) noted evidence of two distinct phases of glaciation that occurred in the McMurdo Sound region. The west-east troughs of Victoria Land were cut by major outlet glaciers flowing from the main Antarctic ice sheet during the earlier major glaciation. Less extensive glaciation occurred later and was responsible for a succession of moraines deposited in the troughs. Calkin's interpretation of the sequence of events in McMurdo Sound is compatible with the South Shetland Islands evidence. The record since late Pleistocene glaciation in the islands also demonstrates a broadly synchronous relationship with the last major Northern Hemisphere glaciation.

Correlation of Marine Platforms

The Antarctic Peninsula and fringing islands have been described by Adie (1964), Bibby (1965), Dewar (1967), King (1964), and Linton (1963; 1964). The highest elevation of a suspected marine feature was noted at 2,440 m on Alexander Island by King (1964). According to the others, residuals and platforms occur at various altitudes between King's high plateau and several hundred meters, but no obvious correlations with those of the South Shetland Islands were apparent. This may be due in part to the lack of investigation, or there may be no necessary correspondence between one island and another in the whole chain.

Correlation of Raised Beaches

Numerous raised beaches have been described elsewhere in the Antarctic Peninsula. Bibby (1965) described beaches up to 24 m on James Ross Island and Nichols (1947; 1953) recorded more than 20 well developed raised beaches extending as high as 33.6 m at Marguerite Bay. John and Sugden (1971) noted several beaches in the Marguerite Bay area (Fig. 1) that were similar in all appearances to those of the South Shetland Islands. These beaches occurred at 6-7 m, 5-7.5 m and 18 m. A similar weathering contrast existed above the 18 m beach as did those described above 20 m on the South Shetland Islands. The correlations of beaches between these two areas suggest a similar pattern of deglaciation and isostatic response for the Antarctic Peninsula.

Several marine terraces and beaches were radiocarbon dated elsewhere in Antarctica. Cameron and Goldthwait (1961) reported a date of 6,040 ± 250 years BP for algae in a lake on a 23 m terrace in the Windmill Islands. Nichols (1964) suggested a maximum age of 7000 years BP for beaches in the McMurdo Sound area. Black and Berg (1964) calculated a general age of deglaciation occurring 10,000 years ago.

This date was acquired from growth rates estimated for sand wedge polygons. Auer (1956; 1958; 1960) estimated a general initiation of post glacial conditions at 9000 radiocarbon years BP for Tierra del Fuego-Patagonia. A similar conclusion was reached by Mercer (1965) after dating recent moraines in Patagonia. These dates are similar to the tentative chronology suggested for the South Shetland Islands.

Significance of the Neoglacial Advances

The only re-advances for which there are absolute ages are the two re-advances following Wisconsin ice retreat. These events are dated at about 500 radiocarbon years BP (6 m beach) and about 265 years ago (2.5-3 m beach). There is no evidence to show that the South Shetland Islands glaciers had been further advanced at any time since the Late Wisconsin deglaciation. Therefore, these two re-advances represent the maximum Late Neoglacial or Little Ice Age ice positions. It has been suggested that Antarctic glaciations and climatic trends may be out of phase with those of other portions of the Southern Hemisphere and the Northern Hemisphere (Wilson 1964; John and Sugden, 1971). It has been tentatively demonstrated that here the Wisconsin and Sangamon Ages are approximately synchronous to those that occurred in both hemispheres. A similar correlation of the Late Neoglacial ice advance is possible.

Late Neoglacial Correlations

Porter (1974) noted that corrected carbon dates, historical records, and lichen and tree ring ages indicated that a major episode of glacier extension culminated 300 years ago. This recent episode (Late Neoglacial) was a global phenomenon well documented in nearly all glaciated regions and first called Little Ice Age by Matthes in the Sierra Nevada.

Neoglacial events in the Malaspina, Lituya Bay, and Glacier Bay districts of the St. Elias Mountains, Alaska, have been studied in detail. Goldthwait (1966) suggests the very end of the "little ice age" at Glacier Bay occurred about 1700 A.D.. Two neoglacial advances for the Malaspina Glacier in the same region were given by Plafker and Miller (1957). Radiocarbon date I-439 indicated an advance at 560 ± 75 years ago. Sharp (1958) indicated a younger advance of slightly less than 300 years BP (L-238) for wood overrun on the same glacier. Subsequent to the advance stagnation occurred. Some questions as to the regional scope of neoglaciation in this area have been suggested by Porter and Denton (1967). A major neoglacial advance culminated in Norway about 1740 A.D.. Unfortunately, few dates of neoglacial advance are available from the Southern Hemisphere. Dates from Patagonia indicate re-advance as early as 1300 A.D. (Mercer, 1970), but Lindsay (1973) indicated neoglacial advances dated at 1880 A.D. and 1740 A.D. in the South Orkney Islands.

The dates of these neoglacial advances appear to roughly correlate with those of other areas of the Southern Hemisphere, the northwestern United States, and Norway.

Conclusion

The tentative glacial history reconstructed for the South Shetland Islands demonstrates at least two distinct ages of glaciation separated by a warmer climate interval that is interpreted as the Sangamon Interglacial. Radiocarbon dates and lichenometric ages suggest that two late neoglacial advances occurred at approximately 1475 A.D. and 1720 A.D.. The ice margins have thinned gradually since the neoglacial fluctuations probably in response to the secular warming trend that commenced recently and extended until about 1940.

Both the long-term and short-term glacial fluctuations in the South Shetland Islands appear to be broadly synchronous with world-wide climatic trends.

Appendix A: Raised marine features in the South Shetland Islands

Location	Altitude (meters)	Description
LIVINGSTON ISLAND		
Byers Peninsula		
South Beaches	1.8-2.1	Modern storm beach.
	2.5-2.7	Raised beach, veneered with gravel
	3.6-5.1	Raised beach, forward slope marked by pumice.
	5.6-6.1	Raised beach, wide, continuous.
	8.9-9.2	Raised beach, dissected by intermittent drainage.
	11.1-17.4	Raised beach, well developed below Usnea Plug and supported by bedrock platform. Rear of beach frequently covered by perennial snow, many erratics, patterned with fines in center where beach is wide. Rear of beach covered with crystalline erratics, patterned ground.
	42.1-46.2	Narrow marine surface, no beach deposits.
	84.6	Top of central platform.
	99.8	To base of Chester Cone.
	133.2	Horizontal marine surface on top of Usnea Plug.
Start Point	1.3-1.7	Storm beach in cove across from Rugged Island.
	3.5-4.7	Raised beach, veneered with locally derived cobbles.
	5.6-6.3	Raised beach, continuous, 50-200 m wide. Rear of beach grades into solifluction lobes.
	8.7-8.9	Discontinuous, narrow, raised beach.
	10.6-17.4	Raised beach, extensive, grades into steep bedrock cliff at rear.
	29.4-33.1	Marine platform, slopes seaward, arcuate, rear is steep cliff.
	44.4-46.9	Marine surface, narrow, 2-5 m wide, arcuate.
	77.1	Marine surface, narrow and arcuate, considerable solifluction.
	82.5-85.3	Surface of central platform.

Appendix A (continued)

Location	Altitude (meters)	Description
FALSE BAY		
Miers Bluff	0.8-1.8	Modern storm beach, 3-5 m wide.
	2.2	Raised beach, marine rounded cobbles.
	5.0-6.3	Raised beach, well-rounded cobbles, rear terminates or grades into bedrock or till cliffline.
	18.5-20.8	Marine platform, 500-700 m wide, dissected in center by intermittent stream, rear terminates at series of moraines deposited below cirque glaciers, till-covered.
	33(?)	Planed at about 33 m on till.
	132	Narrow raised beach overridden by talus, reduced cobbles present.
	155	Raised beach, narrow but continuous, beach cobbles overridden by solifluction and till.
	189	Marine platform of Hurd Peninsula, extensively overlain by till. Disappears under ice cap to the north.
North of Charity Glacier (E. side of bay)	1.8-2.2	Modern storm beach
	2.5-3.1	Raised beach. Continuous; grades into fresh moraine below several cirques.
	3.4-5.1	Raised beach overlain by fresh moraine below cirques, fairly continuous.
	6.1-6.4	Raised beach developed along coast, overlain by fresh moraine but grades transitionally into older moraines.
	7.4-7.9	Raised beach, narrow, discontinuous.
	11.4-11.5	Raised beach, deposited on lip of a more prominent beach extending between 11-18 meters.
	11-18	Raised beach, extensive, rear terminated below low bedrock lip.
	18.5-20.8	Raised beach, 75 m wide, rear terminates below steep bedrock sea cliff.

Appendix A (continued)

Location	Altitude (meters)	Description
E. False Bay (cont'd)	33.2	Marine surface, very narrow, poorly preserved.
KING GEORGE ISLAND <u>Maxwell Bay</u>		
Potter Cove	1.0-1.8	Modern storm beach
	2.5	Raised beach, narrow, composed of rounded boulders about 3-5 m wide, continuous.
	3.4-3.7	Raised beach, developed on moraine near outlet glacier.
	6.1-6.5	Raised beach, fairly continuous, developed on older moraine but disappears under fresh debris at margin of outlet glacier.
	8.8	Raised beach, boulders and cobbles.
	19.3	Marine platform, till-covered, wide below Three Brothers Hill (50-100 m), slight depression filled with solifluction debris in center.
	24.4	Surface narrow, till-covered with striated rounded cobble erratics.
	32.1-35.6	Marine platform, narrow, overridden by moraine in some places.
	48.6	Marine surface, narrow cut into bedrock cliff.
	55.6	Marine platform, appears to be old erosion surface beneath moraine, continuous to south.
	72.5	Marine platform cut into ground moraine.
	98.8	Raised beach, rounded cobbles on west side of Three Brothers Hill; this beach partially obscured by moraines to east side of hill.
Stranger Point	1.6-2.0	Modern storm beach, wide along point.
	2.3-3.6	Raised beach, continuous, cut across weathered moraines near point.
	5.9-6.1	Raised beach, continuous, highest occurrence of <u>in situ</u> whale bones, slopes seaward, rear terminates at bedrock cliff in many areas.

Appendix A (continued)

Location	Altitude (meters)	Description
Stranger Point (cont'd)	11-18	Raised beach developed in protected areas, dissected by streams, surface of scattered and weathered cobbles, solifluction lobes at rear.
	52.9-53.3	Marine platform above Stranger Point, 500 m wide depression in center with drainage to southeast.
	71.1	Marine surface, narrow, cut into cliff rising above Stranger Point.
	93.8-100.3	Bedrock surface outcropping beneath moraine, highest surface at Stranger Point, about 15 m above margin of ice cap.
Winship Point	2.3	Raised beach, cobbles and boulders, fresh sea stacks developed immediately offshore.
	3	Raised beach, continuous.
	6.1	Raised beach, continuous, highest whale bones, slopes slightly seaward.
	7.7	Raised beach, narrow, discontinuous.
	11.2	Raised beach, extensive, more weathered surface than lower beaches, patches of perennial snow cover. Rear under this snow cover.
	18.4-19.8	Extensive raised beach, highly weathered surface, solifluction encroaching rear.
	30.8	Marine surface, narrow bench 1-3 m wide.
	45	Marine surface, irregular surface covered with erratics and solifluction from cliff line at rear of surface.
Barton Peninsula	0.9	Modern storm beach.
	2.0	Raised beach of fresh gravel and cobbles.
	2.5-3.5	Raised beach, continuous.
	5	Raised beach, fairly continuous.
	6.1	Raised beach, rounded cobbles, grades into and cuts moraines formed by outlet glacier in Marian Cove.
	7.9	Raised beach, barely visible between moraine deposits.
	11.4	Raised beach, located between moraine deposits.

Appendix A (continued)

Location	Altitude (meters)	Description
Barton Peninsula (cont'd)	28.2	Raised beach, discontinuous.
	79.9	Raised beach, cut into old heavily weathered moraines (?).
	98	Marine platform, extensive at Barton Peninsula and North Spit.
	128	Marine surface, cut into bedrock cliff.
	132	Marine surface, apparently cut into bedrock.
	148	Raised beach, well formed cobbles.
	228	Raised beach, discontinuous, found mostly covered by talus, marine rounded cobbles, visible only in protected portions of cliffline.
	270-280	Raised beach, deposited on extensive erosion surface, forward edge higher due to presence of dike, behind dike surface heavily frost-shattered, faint pattern of unsorted polygons, underneath frost-shattered material found rounded beach cobbles, cobbles well preserved at rear of beach in protected areas below Noel Hill.
Suffield Point near ice dome	0.8	Modern storm beach.
	1.5	Raised beach, narrow.
	2.1	Raised beach, narrow.
	3.3	Raised beach, narrow.
	5.9	Raised beach, narrow.
	7.9	Raised beach, narrow.
	10.2	Raised beach, narrow.
	11.3	Raised beach, narrow.
	12.9	Raised beach, narrow.
	13.7	Raised beach, narrow.
	14.9	Raised beach, narrow.
	16.8-17.8	Raised beach, much wider, disappears under ice.
	35.9	Marine surface, cut into bedrock cliff.

Appendix A (continued)

Location	Altitude (meters)	Description
Suffield Point (cont'd)	39.0	Marine surface, cut into bedrock cliff.
	44.6	Marine platform, extensive.
Ardley Peninsula north side	0.0-0.5	Narrow strip which is apparently storm beach, forms low tombolo across to Fildes Peninsula at low tide.
	3.6	Raised beach, forward slope at angle of 25°-30°.
	6.4-7.2	Raised beach, wide, continuous.
	10.4-14.2	Raised beach, narrow, crest with slightly rounded profile.
	17.6	Raised beach, continuous, well developed, dissected by meltwater channels, more weathered surface than those below this altitude.
	29.1	Raised beach, fairly continuous frost scattered surface.
Fildes Peninsula across from Ardley Island and to the west.	1.8	Modern storm beach.
	2.4-3.1	Raised beach, continuous.
	3.5-3.9	Raised beach, continuous.
	5.9-6.2	Raised beach, continuous.
	7.8-8.2	Raised beach, continuous.
	11.6-18.1	Raised beaches, several beaches occur at this altitude and grade into one another, surface of beach is extensive, continuous, developed under meltwater channels.
	25.6	Marine surface, narrow, truncated by deep channel at rear of beaches.
	37.8	Marine surface, narrow, rear covered by solifluction.
	56.4	Platform or extensive marine platform.
	76.5	Marine surface, very thin and poorly developed, some striated cobbled, continuous beaches deposited on bedrock surface.
	105-115	Marine platform, extensive but discontinuous, highest planar feature between volcanic plugs.

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