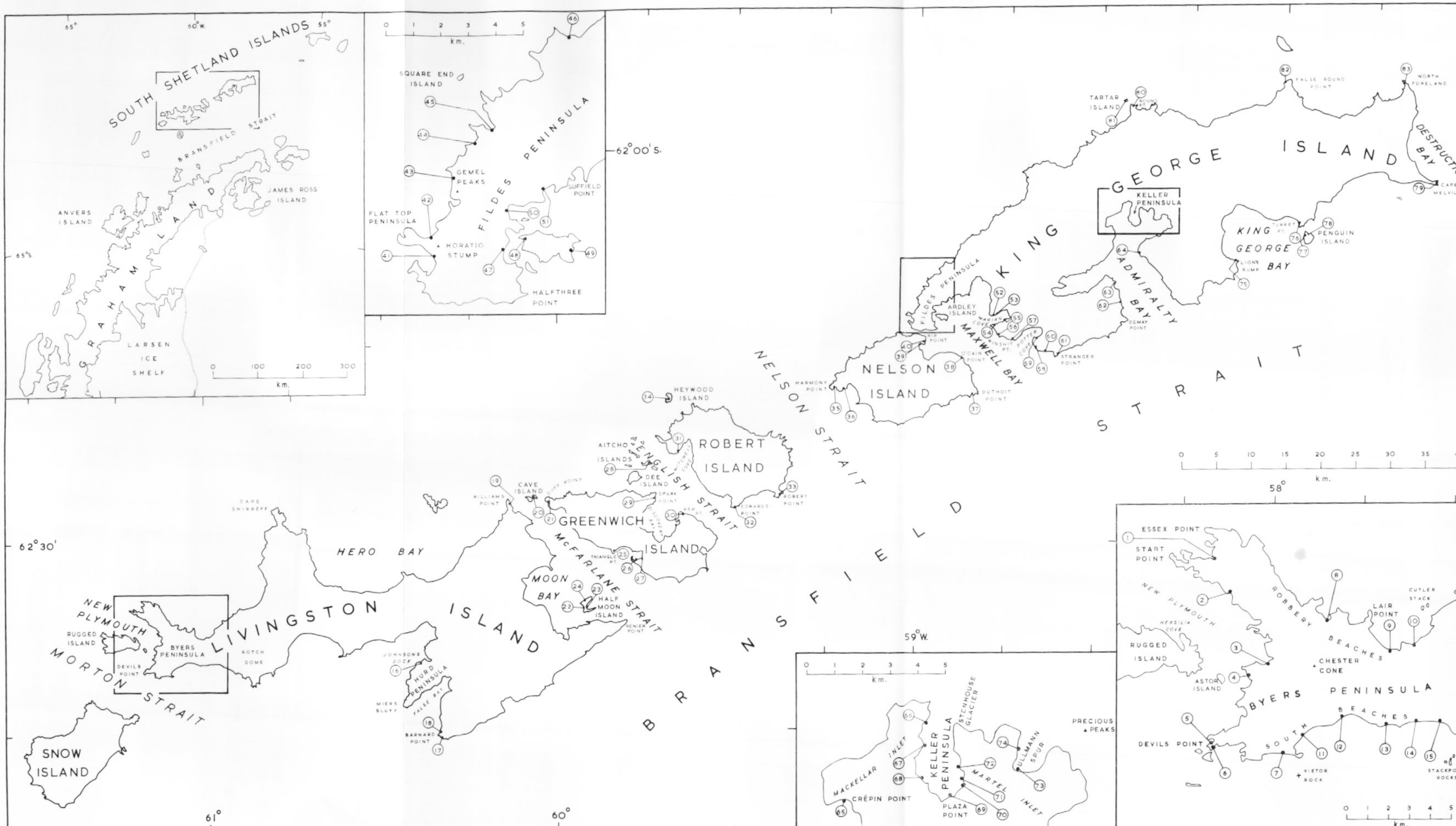

Fig. 1. Sketch map of the South Shetland Islands showing the sites visited by the authors in 1965–66. The numbers locate the sites which are referred to throughout the text and in Table I.

[face page 45

Sites in the South Shetland Islands

Livingston Island

Byers Peninsula

1. Bay between Start and Essex Points.
2. North shore of New Plymouth.
3. East-north-east of Astor Island.
4. East of Astor Island.
5. North of Hell Gates.
6. Near Hell Gates.
7. West of Vietor Rock.
8. Two bays west of Lair Point.
9. Bay east of Lair Point.
10. Near ice edge; south of Cutler Stack.
11. West end of South Beaches.
12. West-central South Beaches.
13. Central South Beaches.
14. East-central South Beaches.
15. East end of South Beaches.

Eastern part of island

16. Hurd Peninsula; south of Johnsons Dock.
17. Southern Barnard Point.
18. Western Barnard Point.
19. Williams Point.

Central Islands

20. Cave Island.
21. Duff Point.
22. West side of Half Moon Island.
23. East side of Half Moon Island.
24. Northern Half Moon Island.
25. Triangle Point.
26. Spit Point, Yankee Harbour.
27. Eastern Yankee Harbour.
28. Unnamed island *c.* 1 km. north-west of Cecilia Island, Aitcho Islands.
29. Spark Point.
30. Ash Point.
31. Western Mitchell Cove.
32. Edwards Point.
33. Robert Point.
34. Heywood Island
35. Western Harmony Point.
36. Eastern Harmony Point.
37. Duthoit Point.
38. O'Cain Point.
39. South-eastern Rip Point peninsula.
40. North-eastern Rip Point peninsula.

King George Island

Fildes Peninsula

41. Bay south of Horatio Stump.
42. Near Horatio Stump.
43. Bay near Gemel Peaks.
44. Small bay south-south-east of Square End Island.
45. Large bay south-east of Square End Island.
46. Near ice edge; north-western Fildes Peninsula.
47. Bay west of Ardley Island.
48. Western Ardley Island.
49. Eastern Ardley Island.
50. Large bay north-west of Ardley Island.
51. Bay south-west of Suffield Point.

Western part of island

52. Outside moraine; North Spit, Marian Cove.
53. Inside moraine; North Spit, Marian Cove.
54. South Spit, Marian Cove, Barton Peninsula.
55. Inner Marian Cove, Barton Peninsula.
56. South-western Barton Peninsula.
57. Winship Point, Barton Peninsula.
58. West shore, Three Brothers Hill peninsula.
59. Potter Cove, Three Brothers Hill peninsula.
60. South shore, Three Brothers Hill peninsula.
61. Stranger Point.

Central part of island

62. Near Sphinx Hill, Admiralty Bay.
63. Point Thomas, Admiralty Bay.
64. Point Hennequin, Admiralty Bay.
65. Crépin Point, Admiralty Bay.
66. Within moraine; north-western Keller Peninsula.
67. Within moraine; central-western Keller Peninsula.
68. Within moraine; south-western Keller Peninsula.
69. Outside moraine; southern Keller Peninsula.
70. Outside moraine; south-east Keller Peninsula.
71. Near British station; south-eastern Keller Peninsula.
72. Within moraine, eastern Keller Peninsula.
73. Southern Ullmann Spur.
74. North-western Ullmann Spur.

Eastern part of island

75. Lions Rump.
76. Turret Point.
77. North-western Penguin Island.
78. North-eastern Penguin Island.
79. Cape Melville.
80. Round Point.
81. Tartar Island.
82. False Round Point.
83. North Foreland.

RAISED MARINE FEATURES AND PHASES OF GLACIATION IN THE SOUTH SHETLAND ISLANDS

By B. S. JOHN *and* D. E. SUGDEN

ABSTRACT. Four distinctive landform groups have been recognized in the South Shetland Islands:

i. Flights of surfaces and platforms cut in rock occur between *c.* 275 m. above and 110 m. below sea-level. Those above *c.* 120 m. are thought to be *subaerial*, while those below *c.* 120 m. represent phases of *marine planation* at 85–102, 27–50, 11–17 m., at sea-level, and at a variety of depths below sea-level. In view of their association with a succession of volcanic rocks containing a Pliocene *Pecten* conglomerate, the surfaces and platforms are thought to reflect the irregular uplift of the South Shetland Islands in Plio-Pleistocene times.

ii. Glacial landforms reflect the occurrence of two distinct phases of glaciation. During the first major phase, an ice cap 65 by 250 km. in size lay with its axis over the submarine platform north-west of the islands and was responsible for most of the glacial erosion. Active melt-water erosion accompanied wasting of the ice cap. The second lesser glaciation, which was responsible only for the deposition of till, took the form of an expansion of local island ice caps. Both phases of glaciation post-dated the cutting of the main surfaces and platforms. Possibly glaciation did not commence until the Pleistocene.

iii. Pockets of beach material over-ridden by ice were found *in situ* between *c.* 55 and *c.* 275 m. a.s.l. They represent a non-glacial interval between the two phases of glaciation when relative sea-level was high and there was little ice in the islands. It is not clear to what extent this interval may be regarded as a full "interglacial".

iv. Undisturbed raised beaches occur up to an altitude of *c.* 54 m. and they reflect the recent isostatic recovery of the land accompanying deglaciation. Major beaches at *c.* 18·5 and *c.* 6 m. represent important stillstands and probably transgressions of the sea. The higher beach is difficult to explain except by envisaging a rapid eustatic rise of sea-level but the lower one is clearly related to an associated re-advance of the glaciers which temporarily checked the process of isostatic recovery.

After a reconstruction of the stages of landscape evolution, the South Shetland Islands evidence is reviewed in the light of evidence from elsewhere in Antarctica and Fuego-Patagonia. Attempted correlations encounter many difficulties, and the writers conclude by pointing out some of the problems that need further investigation.

THE South Shetland Islands lie between long. 62°45′ and 53°30′W., and lat. 61° and 63°30′S. They are located about 160 km. north of the tip of the Antarctic Peninsula from which they are separated by the deep trough of Bransfield Strait (Fig. 1). The major features of the islands are those of a glacierized coastal landscape (Fig. 2). Each island supports an active ice dome and ice cliffs fringe most of the coastline. Generally, these ice domes are interrupted only by a few projecting inland nunataks and ice-free coastal peninsulas, but at the eastern end of Livingston Island, and to a lesser extent on the south-east coast of Greenwich Island, there is spectacular "alpine" scenery with intensive valley glaciation, while the higher ice cap of King George Island is fringed in places by steep outlet glaciers. The islands are separated by three major straits while Admiralty and Maxwell Bays are morphologically similar; these features trend generally south-eastward from the island group into the steep northern side of Bransfield Strait. The islands rise above a shallow submarine platform which is extensive on the northern flank of the group and whose presence is indicated by a broad area of skerries and broken water in contrast to the deep water off the southern coasts (Fig. 2).

The ice-free peninsulas of the central South Shetland Islands have variable orientations. Byers Peninsula (Livingston Island) and Fildes Peninsula (King George Island), the largest ice-free areas in the islands, are located beyond the westernmost extremities of their island ice domes, and many of the other larger ice-free peninsulas face the south-west and south. It is in these ice-free coastal areas that most of the accessible morphological features, such as glacially sculptured forms, ancient subaerial surfaces, raised marine platforms and well-preserved raised beach series, are well exposed. Accordingly, it was in these areas that the present study was concentrated (Fig. 1).

Adie (1964*a*) has stressed the paucity of observations on the geomorphological features of the South Shetland Islands. Raised beaches were occasionally recorded prior to field work by the British Antarctic Survey but subsequently landscape features have only been studied as a by-product of geological and glaciological investigations. Raised beaches and other elements

Fig. 2. Air photograph (towards the north-east) across Greenwich, Robert and Nelson Islands from above the south-east coast of Livingston Island. The mountains of Livingston and Greenwich Islands, and the skerries off the north-west coasts can be clearly seen. 19 January 1957; 4,115 m. (Photograph from Hunting Aerosurveys Ltd., by permission of the Government of the Falkland Islands Dependencies.)

of the landscape of the South Shetland Islands have been referred to by Hattersley-Smith (1949), Bibby (1961), Ferrar (1962), Barton (1965) and Hobbs (1968). A factual summary of the work undertaken by earlier workers, together with an attempt to correlate sea-level oscillations and glacial stages, has been given by Adie (1964*b*).

Structure and geology

The South Shetland Islands are an integral part of the Scotia Ridge, a tectonic feature which sweeps from the Antarctic Peninsula as a series of *en échelon* arcs through the South Shetland, South Orkney and South Sandwich Islands and South Georgia to the tip of South America (Adie, 1964*a*). The South Shetland Islands are largely volcanic and they appear to owe their existence to several stages of volcanic activity along lines of structural weakness trending east-north-east to west-south-west. There is a major fault zone parallel to the south-eastern boundary of the islands, and geophysical evidence indicates that the island group has been uplifted by 2 km. and displaced laterally from the floor of Bransfield Strait (Griffiths and others, 1964). Local faulting within the islands follows a similar trend; on King George Island, Barton (1965) has suggested that there are local faults exploited by volcanic activity, while Hobbs (1968) has illustrated several major faults on Livingston Island. In addition to the dominant east-north-east to west-south-west fault trend there are areas of local cross-faulting, as on Fildes Peninsula and Barton Peninsula (Schauer and Fourcade, 1964; Barton, 1965). Most of the faulting in this area appears to have been Tertiary or older but the possibility of later local faults cannot be discounted.

The geology of King George and Livingston Islands is now moderately well known

(Hawkes, 1961; Barton, 1965; Hobbs, 1968). On King George Island there is a well-documented sequence of volcanic rocks ranging in age from Jurassic to Tertiary and Quaternary; the oldest of these rocks form a broad belt trending parallel to the structure from Barton Peninsula across the head of Admiralty Bay to False Round Point and North Foreland, with the younger rocks exposed along the shores of Admiralty Bay towards the south-east. On Livingston Island, the distribution of strata of different ages is not so well known (Dalziel, 1969). In general, folded and faulted older volcanic rocks appear to be represented in the eastern mountainous area, with younger volcanic and sedimentary rocks exposed over the lower western and northern parts of the island (Hobbs, 1968). The few field observations on Greenwich, Robert and Nelson Islands suggest that their geology is related to that of the larger islands, comprising mainly sequences of Tertiary volcanic rocks (Adie, 1964*a*).

According to Barton (1965), there was considerable volcanic activity during the Pliocene and Pleistocene. It is believed that during the Pliocene a "*Pecten* conglomerate" was inter-bedded with andesites, tuffs, agglomerates and olivine-basalts at Lions Rump on King George Island. This deposit can be dated by its Pliocene Mollusca and Foraminifera (Adie, 1964*a*; Barton, 1965). In addition, Pliocene to Recent volcanic vents are aligned in a belt along the south coast of King George Island, the most spectacular being the fresh cone of Penguin Island (Barton, 1965). Volcanic activity in this area is still continuing; there are reports of vulcanicity on Bridgeman Island as recently as 1880, and in 1967 and 1969 eruptions were experienced on nearby Deception Island.

Morphogenetic environment

In an Antarctic context, the South Shetland Islands lie in the maritime zone; to the north is the turbulent Drake Passage, to the east the cold reservoir of the Weddell Sea and to the west the warmer Bellingshausen Sea. Southwards the climate becomes increasingly severe through the Antarctic Peninsula to the west Antarctic ice sheet. The whole of the west coastal zone of the Antarctic Peninsula is subjected to the effects of warm, saturated air masses approaching from the north and west. This area has the greatest frequency of depression tracks in the Antarctic (Lamb, 1964) and precipitation is far higher than on the east coast of the peninsula. The ice caps of the South Shetland Islands may receive up to 100 cm. water equivalent in a year, while on lee slopes precipitation may rise locally to 150 cm. (Robin and Adie, 1964). Most of this precipitation falls as snow but there are minor contributions from summer rainfall during the passage of warm depressions and rime-ice deposition especially during the winter. The latter is important both because of its direct contribution to precipitation and because it tends to consolidate existing snowfall. Rime ice also "masks" high peaks in this maritime environment, increasing the albedo and decreasing ablation (Koerner, 1964; Robin and Adie, 1964). The South Shetland Islands experience higher overall temperatures than elsewhere in Antarctica but nevertheless the mean annual temperature is about -3° C, with the $+1^\circ$ C isotherm for the warmest month parallel to the island group and a little to the south.

As far as a geomorphological study is concerned, the most important effect of the climate is the ice cover. The island ice caps are thought to be in a state of near equilibrium (Robin and Adie, 1964); outflow of ice from the ice domes is balanced in part by wave-sapping of the coastal ice cliffs. The island group lies within Linton's (1964) zone of active glacierization in the Antarctic Peninsula and the conditions existing in these islands may be closely comparable with those of Anvers, Adelaide, and other islands forming the west coastal belt of the peninsula (Bryan, 1965; Rundle, 1967; Sadler, 1968). Glacierization is less complete today than formerly and on the scattered ice-free areas of the South Shetland Islands the subaerial processes of periglaciation are rapidly modifying the more ancient elements of the landscape.

The South Shetland Islands are vulnerable to the processes of marine erosion. In most years the shores of the islands are ice-free for about 6 months in the summer, and in mild winters fast ice may exist along the coasts for only short periods. As a consequence, marine action is concentrated on the exposed north-western coasts with huge breakers driven by westerly winds surging through reefs and shoals on to the rocky shores. On the south-east coast and in the straits and bays of the island group, there is more shelter and a higher frequency of fast ice, but marine action is still more important than on the ice-bound coasts of the Antarctic Peninsula. 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".

Landform groups

The denudational processes mentioned above have combined in attacking the geological structure of the South Shetland Islands to produce their characteristic scenery. In each ice-free area the role played by the agents of modification has varied, but the overall similarities of rock type, structure and erosional processes have resulted in four distinct landform groups which can be recognized everywhere:

i. The surfaces and platforms* which are fundamental subaerial and marine features of the South Shetland Islands.
ii. The glacial features (erosional and depositional) which have sometimes been modified by periglacial processes.
iii. The "residual beaches"† which are inconspicuous but significant features in some localities.
iv. The undisturbed raised beach series which are characteristic of the sheltered coastal areas.

In this paper each landform group is analysed in turn. An examination of their interrelationships has led towards an understanding of the sequence of events responsible for the islands' morphology. The conclusions reached may be relevant not only to the Bransfield Strait area but also to the Antarctic Peninsula as a whole.

SUBAERIAL AND MARINE EROSIONAL LANDFORMS

Most of the previous workers in the South Shetland Islands have recorded the presence of flat coastal platforms, but higher irregular surfaces have received less attention. The platforms recorded previously range from one high feature at *c.* 152 m. a.m.s.l.‡ on Cape Melville to the lower platforms just above sea-level and those which are submerged; in addition, there are higher surface remnants in many localities. For the purpose of analysis these landforms may be subdivided into three categories:

i. Surfaces and platforms at 120 m. and above.
ii. Surfaces and platforms below 120 m.
iii. Submerged offshore platforms.

The sub-division at 120 m. is to some extent arbitrary but there is a distinct difference in appearance between the irregular surfaces above this altitude and the relatively undissected platforms below.

Surfaces and platforms at 120 m. and above

The high surfaces of the South Shetland Islands incorporate features of different characteristics and altitudes and are grouped, for the most part, on the southern shore of King George Island and the western end of Livingston Island (Table I). The highest surface remnants occur above 200 m. on King George Island. The best developed of these is in the vicinity of Noel Hill, where a long flat-topped ridge dominated by the hill summit has a general altitude of 275 m. The ridge surface has a maximum relief of *c.* 15 m., and it is truncated on two sides by steep cliffs (Fig. 3). There are other high surfaces in Admiralty Bay and on the higher parts of north-west Byers Peninsula and Rugged Island.

Surfaces between 120 and 200 m. are easier to discern than those above 200 m. The planed-off volcanic plug of Flat Top Peninsula is a spectacular example and another fine surface occurs at *c.* 152 m. on Cape Melville (Barton, 1965). The latter surface is truncated on either side by vertical cliffs and it rises in altitude towards the cape's extremity. The surface is slightly undulating and traces of depressions running across the peninsula can be seen on aerial

* Throughout this paper a *platform* means a flat regular area cut into bedrock, whereas a *surface* is a gently undulating area approximating to horizontal.

† A *beach* is understood as a *deposit* laid down by marine action, usually in the littoral zone.

‡ All altitudes given in this paper are above mean sea-level.

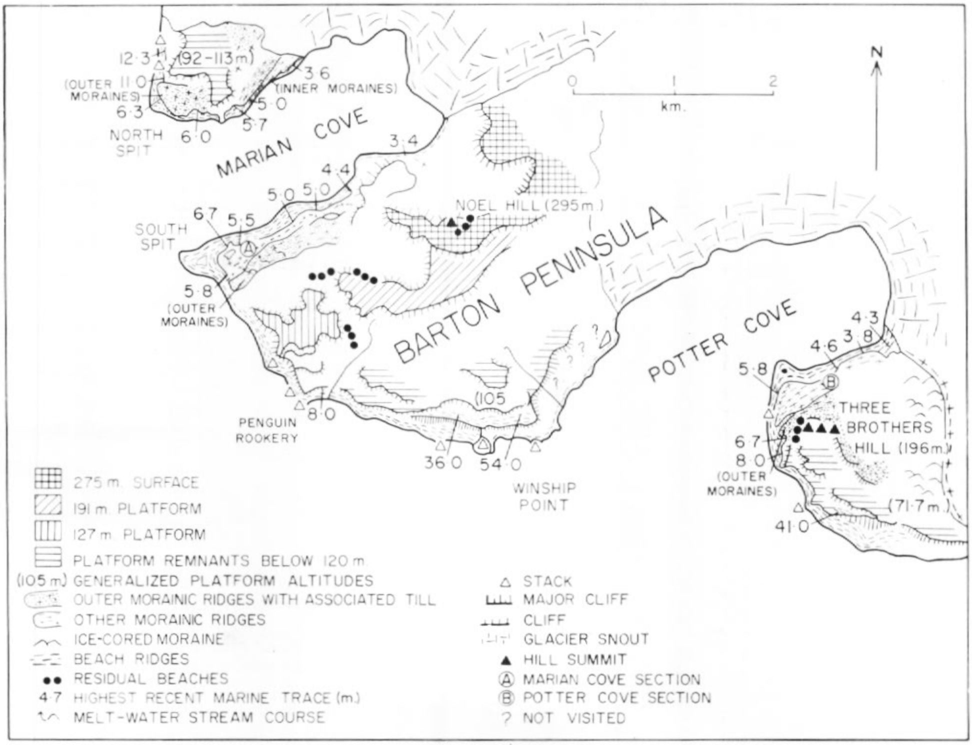

Fig. 3. Morphological map of the Marian Cove–Potter Cove area of King George Island, showing high platforms, residual beaches, recent moraines, undisturbed raised beaches and other features.

photographs. Barton (1965, p. 28) considered that this surface may not be an erosional feature, for it is "cut in flat-lying bedrock"; however, an inspection of the north flank of Cape Melville from the sea indicated that the surface truncates the bedding of the basalts in the cliffs. Byers Peninsula displays other surface remnants below 150 m. but in a different landscape setting. In the north-west there is an undulating landscape with broad flat-floored valleys and gentle hills; in places there are extensive benches only slightly above the valley floors. The general level of these valley features is 128–143 m., which accords well with the altitudes of surface remnants on the north and west sides of Rugged Island. Probably all these features are related to an ancient river pattern in the north-west peninsula; the other benches of western Livingston Island and Rugged Island in the height range 128–143 m. may be remnants of a surface which developed at approximately this altitude.

In addition to the many gently undulating surfaces, there are two noticeable instances where regular platforms are preserved in the range 120–200 m. On Barton Peninsula a platform at 191–198 m. occurs just south of the 275 m. surface, from which it is sometimes separated by steep cliffs (Fig. 3). It is preserved as a narrow spur with an overall east–west orientation. Unlike the undulating surfaces at approximately this altitude, there appear to be no traces of old stream courses, but instead there are occasional slight steps and scallops up to 3 m. high. As on many of the lower platforms of the South Shetland Islands, there are several upstanding residuals up to 18 m. high with sharp breaks of slope at their bases. Another well-preserved platform remnant occurs on the peninsula at *c.* 127 m.

Surfaces and platforms below 120 m.

In general, the erosional features in this altitudinal range are better developed and more extensive than those above 120 m., and they tend to form platforms rather than surfaces.

TABLE I. SURFACES AND PLATFORMS IN THE SOUTH SHETLAND ISLANDS

Locality (Name and number —see Fig. 1)	*Altitudes* (m.)		*Description*
	Above 120 m.	*Below 120 m.*	
LIVINGSTON ISLAND			
Byers Peninsula (1–15)	210–250		Possible summit surface, also represented on Rugged Island
	134–140		Bench on flank of Chester Cone
	128–143		River valleys and extensive benches in north-west peninsula (also on Rugged Island)
		85–100	Extensive regular platform forming core of peninsula. Well-marked residuals. Some stream dissection
		28–50	Regular platform, sloping gently seawards. Backed by prominent cliff. Some stream dissection
		11–17	Regular platform associated with stacks. Little stream dissection
		c. present sea-level	Extensive regular platform associated with stacks. Traces of stream dissection
Hurd Peninsula		over 30·5	Good platform in vicinity of Sally Rocks (altitude estimated visually)
Barnard Point (17–18)	*c.* 150		Sloping spur above point; an apparent remnant of subaerial landscape
		15·0–18·3	Small rock platform associated with stacks and veneered with beach material. Close to Charity Glacier
		7·3–9·2	Small rock platform near Charity Glacier; possibly also beneath beach material on point
Williams Point (19)		39·7–42·7	Dissected platform on north tip of point
		33·6–36·6	Regular platform separated from 39·7–42·7 m. platform by 5 m. cliff
CENTRAL ISLANDS			
Meade Islands		30·5–45·8	Well-preserved platform remnant on island summit (estimated altitude)
Duff Point (21)		9·2 and below	Undulating bedrock surface with stacks; veneer of beach deposits
Triangle Point (25)		10·7	Bedrock ridge veneered with beach and morainic deposits
Aitcho Islands (28)		39·7–45·8	Island north-west of Cecilia Island has undulating surface truncated by steep cliffs. Some flats

TABLE I (*cont.*)

Locality (Name and number —see Fig. 1)	*Altitudes* (m.)		*Description*
	Above 120 m.	*Below 120 m.*	
CENTRAL ISLANDS (*cont.*)			
Dee Island		90–91·5	Surface remnants, separated from 82 m. platform by small cliffs
		82·5	"Col" platform in centre of island. Dissected and supporting marine conglomerate
		39·7–47·3	Traces of dissected platform "step" on southern flank of island
Spark Point (29)		25·3–27·4	Bedrock ridge with gently undulating surface truncated on either side by cliffs. Passes beneath ice
Ash Point (30)		above 38·5	Sloping platform at base of point
		12·2	Rock platform with stacks beneath beach material
Mitchell Cove (31)		108·5	Undulating surface east of The Triplets, with lake basin and valleys up to 12 m. deep
		39·7–42·7 33·6	West side of cove; sharp break between two platform remnants; upper (west) remnant is jagged and dissected, while lower (east) remnant has good flats
		10·0–12·5	Probable rock platform beneath beach material
Edwards Point (32)		*c.* 27·4	Convex spur crest with cliff to west and beach series on slope to east
Robert Point (33)		45·7–105·4	Deeply dissected landscape of valleys and steep hillsides
Heywood Island (34)		38·2–39·7	Undulating surface; best seen north of cove. Accordant flats on isolated hills
		25·6–29·9	Most prominent platform on south of island
		13·8, 8·5–11·9	Platforms exposed on north side of cove. 13·8 m. platform virtually cut away by 8·5–11·9 m. platform
Harmony Point (35–36)		35·1–41·2	Dissected platform in centre of ice-free area
		30·5–33·6	Cliff-top flat in north-west and west; flat and undissected
		11·6–13·5	Narrow but well-preserved platform; best seen in Harmony Cove. Stacks on front edge
Duthoit Point (37)		78·5	Extensive undulating surface with shallow gullies and low rock knolls
		27·8–35·1	Extensive well-preserved platform with veneer of beach deposits

TABLE I (*cont.*)

Locality (Name and number —see Fig. 1)	*Altitudes* (m.)		*Description*
	Above 120 m.	*Below 120 m.*	
CENTRAL ISLANDS (*cont.*)			
		c. 10·4	Flat tops on stacks near point
O'Cain Point (38)		70·0–76·2	Flat ice-covered area; possible surface
		33·6, 39·6, 42·6	Flat relatively undissected platform remnants, in part beneath ice
		11·0–12·2	Small platform on narrow col at north end of point
Rip Point peninsula (39–40)		100	Undulating surface with several flats. Cut across dipping bedrock. Dissected in places by deep gullies
		70·0	Slight platform trace near ice margin at south end of ice-free area
		39·7–42·8	Many undulating benches and surface remnants on periphery of ice-free area
		30·5–31·3	Well-developed platform at west end of Fildes Strait
		13·4, 8·5–10·4	Traces of small rock platforms close to Rip Point
KING GEORGE ISLAND			
Fildes Peninsula (41–51)	*c.* 170		Possible summit surface on northern upland block
	155		Flat Top Peninsula. A volcanic plug with a platform planed across top
	c. 150		Slight surface traces on flank of summit; southern upland block
	c. 135		Extensive surface on west side of northern upland block; truncated by cliffs 60 m. high
	122–128		Irregular surface traces on southern upland blocks
		110–115	Surface remnant; south-west coast
		c. 98	Undulating basin floor with surface relief of 5 m.
		50–58	Summits of flat cols of two through valleys. Dissected surface remnants associated with major break of slope near east coast
		35–48	Extensive on both sides of peninsula. In west where it is 8 by 1 km. in extent it is gently undulating, undissected, backed by 60 m. cliffs and truncated by 33 m. cliffs. More dissected on east side of peninsula

TABLE I (*cont.*)

Locality (Name and number —see Fig. 1)	*Altitudes* (m.)		*Description*
	Above 120 m.	*Below 120 m.*	
KING GEORGE ISLAND (*cont.*)			
		(35–38)	Fresh, flat outer limit of main platform
		11–17	Fresh platform with associated stacks and backing cliffs truncating many melt-water channels. Well-preserved on east coast. Occurs in places on south and west coasts
North Spit area (52–53)		92–113	Backbone of ice-free area; dissected surface remnants truncated by steep slopes
		39·7–44·2	Small platform remnant in embayment at west end of ice-free area
		6·1–7·6	Small wave-cut platform near mouth of Marian Cove
Barton Peninsula (54–57)	275		Surface on flank of Noel Hill. Summit of hill stands above surface like a residual. Steep flanking cliffs
	191–198		Apparent platform. Surface relief *c.* 3 m.; some steps and also residuals up to 18 m. high
	c. 127		Platform north of penguin rookery. Surface hollows and residuals
		103·7–106·9	Surface and platform remnants. Dissected by gullies but sometimes backed by cliff line
		30·5–45·8	Narrow platform on south coast of peninsula, associated in part with bedrock ridge. Structural influence?
		6·1, 3·4–3·9	Small traces of coastal platforms in south
		3·4–3·9	Narrow platform in Marian Cove trough
Three Brothers Hill peninsula (58–60)		97·6	Possible high surface? Some remnants above general level of peninsula
		71·7	Surface beneath moraine
		39·7–41·2	Cliff-top platform separated from lower seaward platform by small cliff
		30·5–33·6	Platform notably fresher than 39·7–41·2 m. platform
		18·3–19·5	Undulating hummocky surface beneath Three Brothers Hill. Veneer of moraine
Stranger Point (61)		97·6	Possible high surface beneath moraines
		71·7	Extensive cliff-top surface, probably extending beneath moraine

TABLE I (*cont.*)

Locality (Name and number —see Fig. 1)	*Altitudes* (m.)		*Description*
	Above 120 m.	*Below 120 m.*	
KING GEORGE ISLAND (*cont.*)			
		41·2–45·8	Regular extensive platform truncated by fresh cliff line
		11·0–12·2	Coastal flat truncated in one locality by cliffs. Basis for raised beach series
		2·4–3·5	Variety of small platform remnants and flat-topped stacks
Sphinx Hill area (62)		*c.* 55·0	Mounds with accordant summits represent remnants of dissected surface
		24·0–36·6	Undulating gentle surface on cliff top
Point Hennequin (64)	*c.* 290		Surface extending beneath ice
	165–177		Bench; possible structural control
		41·2–53·5	Small benches; possible structural control. Upper platform is cut across a spur
		3·5–4·6	Traces of platform beneath raised beaches; also planed-off stacks
Western Keller Peninsula (66–68)		32–35	Small platform remnant near southern tip of peninsula
		6·1–7·6	Slight platform traces on small spurs
Eastern Keller Peninsula (69–72)		7·6–9·2	Platform beneath station hut
		2·7	Narrow platform backed by cliff
Ullmann Spur (73–74)		5·2–5·5	Narrow platform remnants in west
Lions Rump (75)	above 150		High surface cut across suite of rocks inter-bedded (?) with *Pecten* conglomerate
		61–91·5	Surface cut across bedded andesites on cliff top
Turret Point (76)		52·0	Undulating bedrock surface, truncated in east by sea cliffs
		19·8, 24·4, 30·5	Moderately dissected platforms up to 100 m. wide separated by small cliff lines
		11·0–12·2	Rock floor beneath higher "flats" on raised beach series
Penguin Island (77–78)		33·6–51·9	Sloping surface on south-west side of ash cone. Probably a structural bench
		10·7–18·3	Undulating extensive surface north of fresh ash cone. Possible structural control

TABLE I (*cont.*)

Locality (Name and number —see Fig. 1)	*Altitudes* (m.)		*Description*
	Above 120 m.	*Below 120 m.*	
KING GEORGE ISLAND (*cont.*)			
Cape Melville (79)	*c.* 152		Narrow peninsula with fine surface cut across gently dipping basalts. Peninsula flanked by vertical sea cliffs
Tartar Island (81)		21·3–24·4	Flat top on island; truncated by steep cliffs
False Round Point (82)		36·6–39·7	Isolated platform remnants (often very flat) separated by gullies. Floors of gullies are flat and flanked by cliffs
		32·0–33·6	Possible lower platform remnants
North Foreland (83)	above 150		Gently sloping spur, apparently subaerial
		c. 35·1	Higher undulating platform remnant at north tip of North Foreland; separated by small cliff up to 6 m. high from 30·5–33·6 m. platform
		30·5–33·6	Slightly irregular platform; best preserved in east

Before discussing their wider distribution, it is helpful to look in some detail at a sample area, Byers Peninsula; here the low platforms of the island group attain perhaps their best development and present the most convincing clues as to their origins.

Byers Peninsula

The landscape of Byers Peninsula is bleak and desolate with extensive flat platforms generally uninterrupted except for occasional upstanding residuals (usually volcanic plugs). The landscape is essentially stepped with major cliff lines between platforms trending approximately parallel to the present coastline (Fig. 4).

Central (85–100 m.) platform. This platform forms the core of the peninsula and is a bleak area of approximately 40 km.^{2} (Fig. 5). It extends from the Rotch Dome ice cap to the base of the subsidiary north-western peninsula. Where the platform is at its widest, in the vicinity of the spectacular residual of Chester Cone, it has a general altitude of *c.* 100 m. but it falls in all directions from this central area. From the range of altitudes recorded in the south-west, it seems that the platform may be a composite feature and slight traces of a small cliff line north and west of Chester Cone may support this speculation. Surface relief on the platform is variable with its minimum development in the vicinity of Chester Cone. However, towards the platform's periphery broad open valleys up to 15 m. deep become steep-sided gorges where they cut through the platform edge. In spite of occasional intricate channel patterns, the valleys appear to radiate from the vicinity of Chester Cone. From many localities there is evidence that the platform is planed across the dipping strata of the peninsula (Hobbs, 1968).

The cliff line which marks the outer edge of the central platform is everywhere spectacular and approximately parallel to the present shoreline. In the north the high rampart of cliffs is particularly impressive when seen from below, and it often attains a height of 45–52 m. with angles as steep as 35°. The west-facing bays have arcuate cliff lines below the central platform up to 36 m. high and sloping at 30–40° in places, and where a lower platform has been cut out,

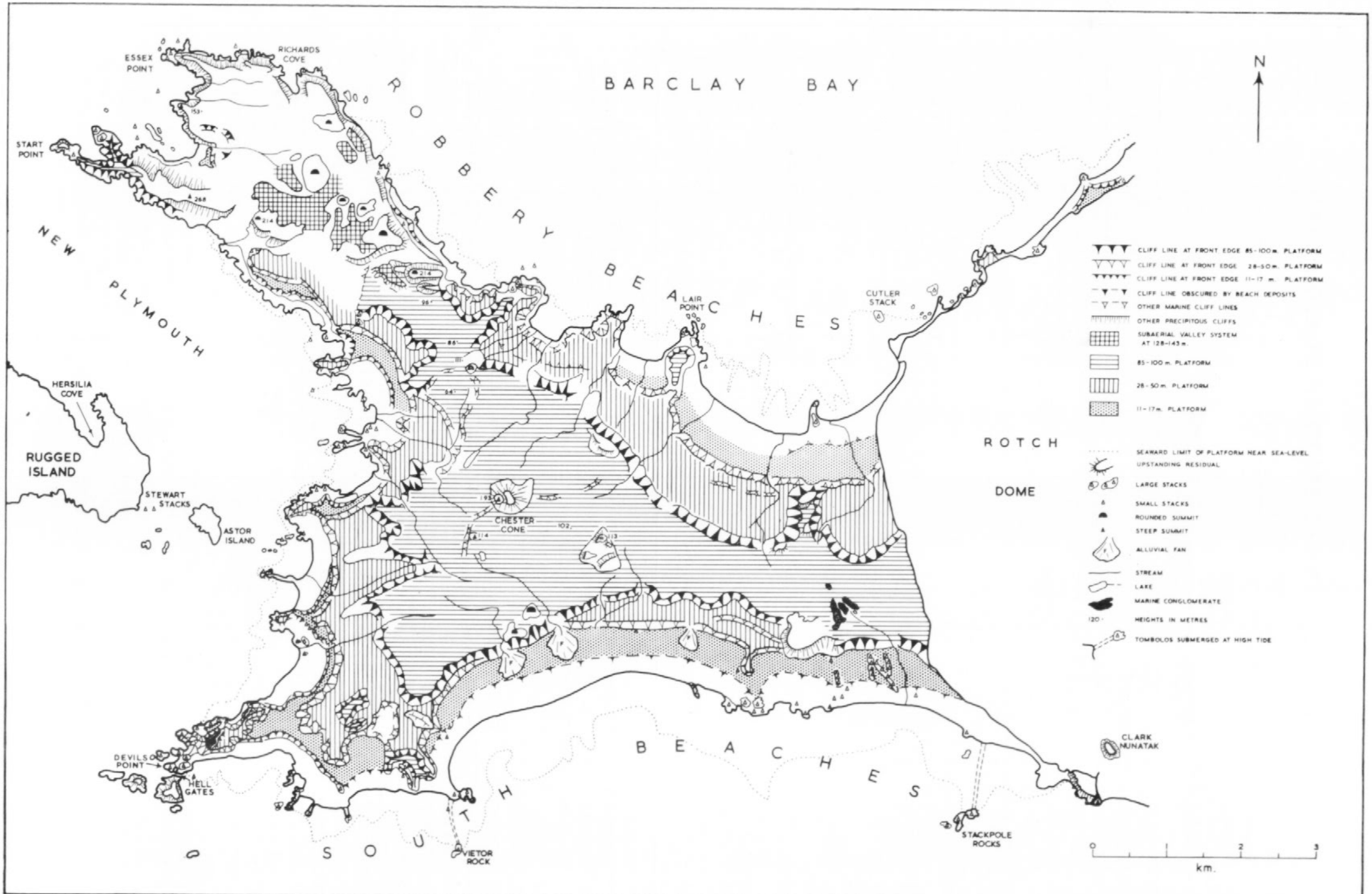

Fig. 4. The su[illegible]es and platforms of Byers Peninsula, Livingston Island. T[illegible] stepped succession of levels separated b[illegible] cliff lines approximately parallel to the coast is striking. Mari[illegible] conglomerates occur on the 85–100 m. platform in the east and near Devils Point in the south-west.

Fig. 5. View (towards the south) of the flat and undissected central 85–100 m. platform of Byers Peninsula. The Chester Cone residual rises sharply to an altitude of 193 m.

cliffs are over 60 m. high. At one locality, overlooking New Plymouth, there is a high stack associated with the cliff line.

28–50 m. platform. This is located on the coastward margins of the central platform (Fig. 4). It is not extensive in the south, occurring only as a limited shelf with a front edge at 34 m. But in the north, west and south-west the platform is well developed with its front edge between 29 and 35 m., and its back edge is seldom above 45 m. The platform slopes gently seawards at angles of *c*. 0·5–1°. As on the central platform, there is some evidence that the 28–50 m. platform is a composite feature. There is a slight cliff line on the bench in the south, and in the north the platform has a continuous break of slope with a degraded front face just below 37 m. The only irregularities on this fine platform are those which can be related to stream dissection with gullies occasionally up to 8 m. deep. However, these gullies do not destroy the overall flat appearance of the platform, and there is a marked contrast between its surface and the heavily dissected edge of the central platform. There are few residuals rising from the platform although there are occasional isolated remnants of the central platform.

The cliff line at the edge of the 28–50 m. platform is even more closely parallel to the present shore than is the edge of the central platform. It is not as spectacular a feature as its higher neighbour, but it is generally over 12 m. high, and near the south and west coasts it is occasionally over 18 m. high. The slope of the cliff is sometimes as great as 30° and beneath the snow banks in the north it is possibly near vertical, especially on its upper part.

11–17 m. platform. This platform, which is covered with raised beach material, is well developed in the south and north. In the west and north-west it is not so prominent a feature but a fine remnant occurs at the base of Devils Point peninsula (Fig. 6). In general, it is notably fresher in appearance than the 28–50 m. platform and is associated with stacks which rise abruptly 2–4 m. above its surface. This platform is remarkably flat with a seaward slope seldom exceeding 1° or 2° and few gullies dissecting its surface. Its back edge occurs at a consistent altitude of 13–17 m. and its front edge generally lies at *c*. 11 m. This front edge is often indistinct and covered with beach deposits.

Platform at about sea-level. An extensive platform at about sea-level occurs beyond the present shore (Fig. 4). Around most of the coastal area it is exposed at low-water mark (l.w.m.)

Fig. 6. View (towards the west) of the 11–17 m. platform (foreground) near Devils Point, Byers Peninsula. In the background is a remnant of the 28–50 m. platform and an "island" of the 85–100 m. platform. The summit is capped by a marine conglomerate.

as an almost flat expanse of rock interrupted only by a few upstanding stacks. In the south a remnant of this platform about 800 m. wide is exposed at l.w.m. spring tides and east of Hell Gates a further expanse of the platform cuts across varied strata (Fig. 7). In the Hell Gates area there is a notch on many stacks just above high-water mark (h.w.m.) and it is probable that elsewhere too the platform extends above h.w.m. beneath the beach ridges of the present shore. The platform is best developed in the bays and elsewhere it extends as a narrow shelf just offshore. In the south and north the platform is dissected and deep re-entrants which are never exposed at low water appear to be the seaward continuations of gullies on the present shore (Fig. 4). It seems that this platform is more deeply dissected than that at 11–17 m.

Elsewhere in the South Shetland Islands

Throughout the rest of the island group erosion surfaces and platforms below 120 m. are widely distributed (Table I). They are most frequent in the lower altitude ranges and are particularly numerous around the central straits and in Maxwell Bay. With a few notable exceptions, the platforms are not as well developed as on Byers Peninsula but their characteristics are comparable.

There are relatively few features in the 90–120 m. range, a surprising fact in view of the fine platform at 85–100 m. on Byers Peninsula. Most of the remnants at this altitude occur on the shores of Maxwell Bay and possibly the remnant at North Spit is the nearest correlative of the Byers Peninsula 85–100 m. platform. Surface remnants in the 45–90 m. range are commoner but there is a lack of well-planed features.

In contrast, platform remnants in the range 27–50 m. (comparable with the platform at 28–50 m. on Byers Peninsula) have a wide distribution and are striking features of the landscape (Hattersley-Smith, 1949; Barton, 1965). There are marked groups of remnants around Maxwell Bay and on the exposed northern coasts of the islands but, contrary to Barton's suggestion, several fine platforms also occur on the southern coasts. A platform at this altitude is most perfectly developed on the west coast of Fildes Peninsula, where it is almost 8 km. long and over 1 km. wide (Fig. 8). As is the case with the Byers Peninsula platform, it is cut indiscriminately across the bedrock structure, and it has an almost flat outer edge (Fig. 9). In places, steep-sided residuals such as Gemel Peaks stand above the platform. Almost as spectacular are the platforms at Williams Point, False Round Point and North Foreland.

Fig. 7. View (towards the south-east) of an extensive rock platform cut across bedrock structure in the bay east of Hell Gates, Byers Peninsula. The platform is exposed only at low tide.

Fig. 8. The 35–48 m. coastal platform of Fildes Peninsula viewed towards the north-east from near Horatio Stump. The platform is backed by 60 m. cliffs which lead up to the 135 m. surface. In the left middle distance is the residual of Gemel Peaks.

Fig. 9. View (towards the south-west) of the flat outer edge of the 35–48 m. platform on the west coast of Fildes Peninsula. In the background is the planed surface of Flat Top Peninsula at 155 m.

A significant feature of the platform remnants at 27–50 m. may be the apparent "break" which occurs at *c.* 37 m. The minor cliff lines on the 28–50 m. platform of Byers Peninsula are matched on the west coastal platform of Fildes Peninsula by a sharp break between a flat cliff-top zone up to 185 m. wide and a more undulating platform which slopes up gradually to the foot of the northern upland block at *c.* 48 m. The cliff-top flat seldom rises above 38 m. and the outer edge of the undulating platform is generally at *c.* 40 m. There are further comparable breaks on the coastal platforms at North Foreland, Harmony Point, Williams Point and Mitchell Cove, while other platforms have traces of subsidiary cliff lines just below 40 m.

From Table I it can be seen that the 11–17 m. platform of Byers Peninsula has equivalents elsewhere, notably in Maxwell Bay and on the north and south coasts of the islands. While the glacial troughs of Admiralty Bay, Marian Cove and Potter Cove have no 11–17 m. platform, there are remnants in parts of the transverse straits. On Stranger Point, Barnard Point and at Harmony Cove, the platform remnants at 9–14 m. are fresh and undissected, and they support fragile stacks. The fine state of preservation of most of these platform remnants is in accord with the evidence from Byers Peninsula, reinforcing the impression that the features at 11–17 m. are much better preserved than those at higher altitudes.

There is an interesting distribution of platforms in the 3–8 m. range. Generally, they are narrow rock benches and, although they occasionally occur in exposed situations such as Stranger Point, they are best displayed in the sheltered inner reaches of Admiralty Bay and Marian Cove.

Platforms at about present sea-level occur in a wide variety of sites. They are generally of fresh appearance with many well-preserved stacks standing above sea-level. In places, as on the coast between Stranger Point and Potter Cove, this platform is up to 800 m. wide and appears to be dissected, but in most localities it is not as well developed as on Byers Peninsula. It is possible that this platform occurs around most of the coastline of the South Shetland Islands for, with the exception of a few ice streams, the continuous ice cliffs around the shores generally rest on a rock base, with associated pebble beaches, a characteristic noticed by Andersson (1906). An example of this is the south coast of Nelson Island between Duthoit Point and Ross Point, where over a distance of about 16 km. all but 1 km. of the continuous ice cliff rests on rock close to sea-level.

Submerged offshore platforms

The submerged platforms off the north coast of the South Shetland Islands may well be comparable to the surfaces and platforms above sea-level. Unfortunately, there is little detailed information on the extent or characteristics of these features and the following has been summarized largely from the Admiralty Chart and from recent echo-soundings undertaken by R.R.S. *Shackleton*. Approximate submarine contours have been interpolated from the charted soundings and the courses of some of the echo-sounding runs have been plotted on Fig. 10.

The offshore platform is an extensive feature. On the north coast of the island group the zone of skerries (rocky shoals, stacks and islands) is seldom less than 5 km. wide. Off the north coast of King George Island the skerries belt is generally *c.* 6 km. wide but at its maximum (at the north end of English Strait) it is *c.* 11 km. wide. The skerries constitute only a small part of the offshore platform which reaches a maximum width of over 45 km. off Robert Island and which covers an area of over 5,000 km.^{2} (excluding extensions north-east and south-west of the island group). The platform either slopes gently away from the islands or it remains almost flat from the island coasts to near the outer platform edge. On sounding runs approximately parallel to the coast the flatness of the platform is spectacular. For example, on run A the total relief is only 40 m. (22 fathoms) over 37 km., while on run E the platform has a total relief of only 14·5 m. (8 fathoms) over 40 km. A common feature of the echo-sounding runs is that the depth of the outer platform edge is generally between 364 and 546 m. (200 and 300 fathoms). However, on profile B the edge is somewhat shallower at 337 m. (185 fathoms).

There is a two-fold sub-division of the platform into a gently sloping area below about 109 m. (60 fathoms) separated from a flatter shallower area by a sharp break. From the soundings, the break does not appear to be marked by a cliff line, but there is no information on the bottom deposits of the area and it is quite possible that sediments mask a steep break of slope. Thus the "offshore platform" may be a composite feature. Holtedahl (1929) considered that there are two submerged "planes of abrasion" off the outer coast of the South Shetland Islands: one at a depth of 45–80 m. close to the coast and another at 240–280 m. The inner shallower feature probably includes the skerries belt but the lower "plane of abrasion" covers only part of the depth range of the offshore shelf.

The submarine platforms off the south coasts of the islands and in the straits are poorly developed in comparison with those off the north coasts. There are relatively wide platforms at the east end of King George Island and south of Byers Peninsula, but elsewhere the widest platform seems to be off southern Nelson Island, the south coast of King George Island and in the straits (Fig. 10). As noted by Hattersley-Smith (1949), the platform extends into southern Admiralty Bay and it is especially wide in Nelson Strait.

Relationships of surfaces and platforms to ice cover

Throughout the islands, surfaces and platforms in each altitudinal range disappear beneath local ice domes. For example, much of the 152 m. Cape Melville surface is still ice-covered, as can be seen from the cornice-capped cliffs beneath Melville Peak, and in Sherratt Bay there is a spectacular example of an ice-covered cliff line, where the Hektor Icefall extends parallel to the coast for *c.* 9 km. behind a broad shelf of piedmont ice (Fig. 11). There are other, less spectacular examples of ice falls which trend parallel to the coastline in the South Shetland Islands; one of them is the linear crevassed zone parallel to the coast on the west side of Walker Bay, Livingston Island, which can be traced clearly on air photographs. Furthermore, the platforms of Byers Peninsula pass beneath the ice edge of Rotch Dome with no sign of a break; the coastline north-east of Cutler Stack bears numerous examples of platform remnants and stacks emerging from cliffs of blue ice (Fig. 4). At Harmony Cove the 11–17 m. platform passes beneath the Nelson Island ice cap, while at O'Cain Point there is a fine example of stacks associated with an equivalent platform emerging from a decadent ice fall.

Marine conglomerates associated with platforms

In several localities in the South Shetland Islands, marine conglomerates are associated with the platforms. If these conglomerates can be dated accurately, this may assist in the interpretation and dating of the platforms themselves.

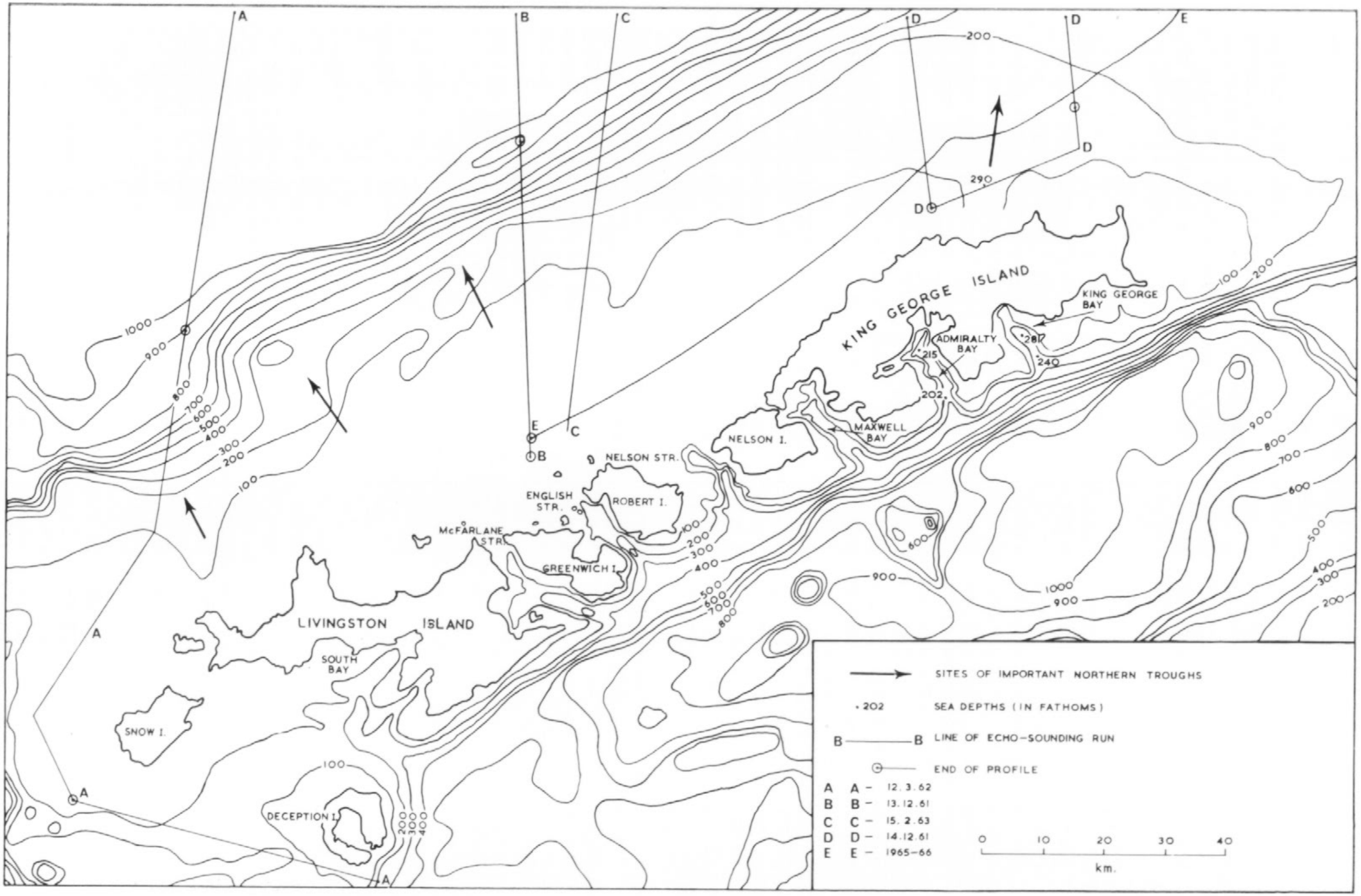

Fig. 10. A preliminary bathymetric map of the vicinity of the South Shetland Islands. The extensive submarine platform to the north-west and the striking array of troughs cut into the south-eastern flanks of the island group are important features of this area. The contours are interpolated from soundings on the relevant Admiralty charts, but recent corrections provided by W. A. Ashcroft (personal communication) are also included.

On eastern Byers Peninsula there are traces of an *in situ* beach conglomerate resting on the surface of the upper platform at an altitude of 76–87 m. a.s.l. (Fig. 4). This conglomerate consists of well-rounded pebbles generally 2–8 cm. in diameter and boulders up to 60 cm. in diameter set in a cemented gravelly matrix. The conglomerate has no clear bedding and it is at least 1 m. thick in its main exposure. It can be clearly distinguished from the dipping beds of tuffs, lavas and volcanic agglomerates in the vicinity (Hobbs, 1968). One exposure suggests that it is banked against a cliff face, while its distribution suggests that it occurs on a number of hill summits (Fig. 12). Thus it appears that the conglomerate is unrelated to the bedrock volcanic sequence and is much younger.

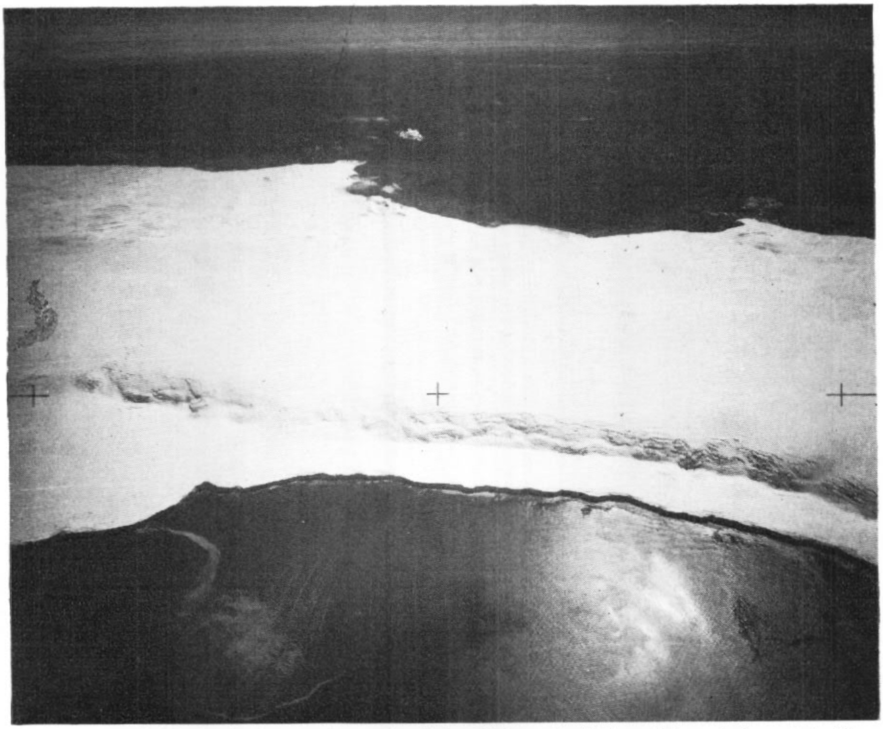

Fig. 11. Air photograph (towards the north-west) of the Hektor Icefall and ice piedmont in Sherratt Bay, King George Island. 20 December 1956; 4,115 m. (Photograph from Hunting Aerosurveys Ltd., by permission of Government of the Falkland Islands Dependencies.)

On the west-facing coast of Byers Peninsula, on the hill summit above Devils Point, a conglomerate of small well-rounded pebbles was discovered at *c*. 82 m. (Fig. 6). Solifluction deposits and a lack of exposures made it difficult to determine the conglomerate's stratigraphic position beyond that it rests on the basalt plug of Devils Point. It appeared to be at least 1 m. thick and patches, possibly derived from the hill summit, were found about 20 m. downslope. The lithology of the conglomerate contrasted strongly with the volcanic agglomerates, basalts and tuffs in the vicinity and it was tentatively assigned a marine origin. It was not possible to determine whether it pre-dated or post-dated the formation of the hill. The coincidence of the deposit with a possible small remnant of the 85–100 m. platform is worthy of comment, especially since its altitude (82 m.) is comparable to that of the other conglomerate recorded on Byers Peninsula (76–87 m.).

Conglomerate remnants were also found at altitudes of 100–114 and about 82 m. on Dee Island in English Strait. The lower deposit is the most extensive, lying in a col on a flat platform surface between two cliffed residuals. Smooth, well-rounded beach cobbles and boulders up to 1·3 m. in diameter are set in a compact matrix, apparently of volcanic material. The conglomerate appears to post-date the platform on which it rests, since it seems to have been banked against the cliffs which overlook the col.

These three beach conglomerates are possibly related to a similar deposit at Lions Rump, where the Pliocene *Pecten* conglomerate at 45 m. a.s.l. is interbedded with andesites, agglomerates and tuffs of the Lions Rump Group (Barton, 1965).* This conglomerate contains well-preserved fossils of Mollusca and Pliocene Foraminifera which have faunal equivalents in the well-known *Pecten* Conglomerate of Cockburn Island (Adie, 1964*b*). According to Barton (1965), the bed is overlain by over 80 m. of andesitic agglomerates. Surfaces at 60–90 and 150–180 m. appear to be cut across the sequence of volcanic rocks (Table I).

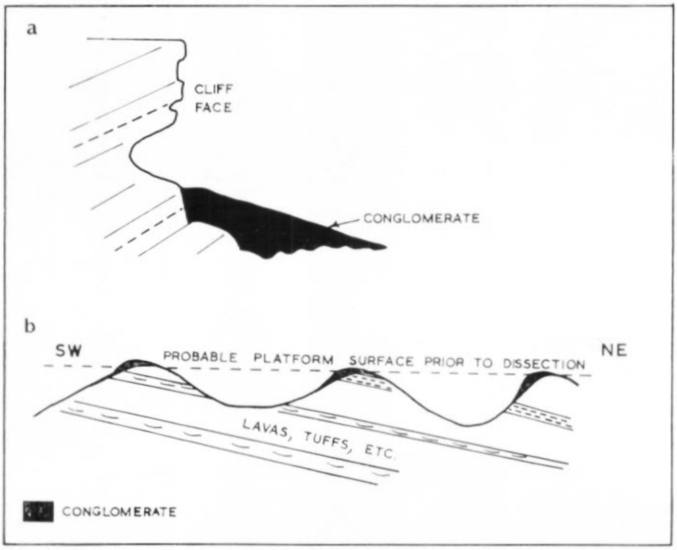

Fig. 12. Sketches showing the generalized stratigraphical relations between the marine conglomerate and the bedrock on the central platform, Byers Peninsula. It is banked against a cliff (a) and it also occurs on successive hill summits (b). It appears to post-date the lavas and tuffs and may be related to the formation of the platform.

Origins of surfaces and platforms

There has been little doubt in the minds of previous writers that the coastal platforms of the South Shetland Islands were cut by marine processes (Hobbs, 1959; Adie, 1964*a*, *b*; Barton, 1965). On morphological grounds alone the evidence strongly supports a marine interpretation. The best-developed platforms are all located close to the present coast and, as is especial[ly] well illustrated on Byers Peninsula they are separated by steep cliffs which are parallel to t[he] present shore. Residuals are commonly associated with the higher platforms, and spectacular stacks with platforms closer to sea-level. Also, the slight seaward slope of the platforms and the fact that they truncate bedrock structures support a marine origin.

It is not possible to consider the mechanics of marine erosion here. By their extent, the submerged platforms may indicate that in part they have resulted from deep-water tidal scour (King, 1963), although, like the platforms above sea-level, some appear to have shoreline features such as minor cliff lines and stacks, especially close inshore.† There is little doubt that the most prominent raised platforms on the islands were cut close to sea-level, because they are associated with stacks, residual hills and cliff lines, all of which indicate shallow-water

* In 1966, P. S. Pilkington found a block of light-coloured sandstone with *Pecten* impressions in a moraine at 60 m. a.s.l. at Lions Rump. This block can only have come from a higher altitude and indicates that there are at least two beds of the *Pecten* conglomerate.

† In the South Orkney Islands, Adie (1964*a*) recorded the presence of submerged caves and cliff lines, as discovered by skin-divers. There may be similar features off the shores of the South Shetland Islands.

wave erosion. The great extent of the platforms in places may indicate that they were cut partly during marine transgressions (Flemming, 1965).

While the majority of the lower platforms in the island group seem to be raised marine features, there is evidence that many higher surfaces above 120 m. may have been initiated subaerially. The shallow valleys in north-west Byers Peninsula and on the 275 m. surface around Noel Hill seem to indicate prolonged phases of river erosion, possibly under a humid climatic regime. In addition, most of the surface remnants above 120 m. are too undulating and discontinuous to resemble wave-cut platforms, although the well-developed platform at 191–198 m. on Noel Hill may be an exception.

It is difficult to assess the role of periglacial processes in the shaping of subaerial landscape features but weathering and mass wasting must have contributed to the reduction of up-standing hill masses and the regularization of relief, especially at higher altitudes. It is notable that no evidence was seen to suggest that any of the platforms or surfaces could be attributed to altiplanation under periglacial conditions.

There is still a belief in an ice-eroded strandflat in west Antarctica. Holtedahl (1929) discussed *in extenso* the cutting of strandflats on the Antarctic Peninsula coast by fringing glaciers, and the question has received further attention from Fleming (1940), Nichols (1960), Adie (1964*a*) and Dewar (1967). There is little evidence that erosion by fringing glaciers can have been effective in the South Shetland Islands. From a glaciological point of view it is difficult to envisage how fringing glaciers could erode variously orientated but extensive rock platforms parallel to the present shoreline. Furthermore, fringing glaciers could hardly have achieved the planation of peninsula tops, as on Byers Peninsula. The platforms have morphological characteristics which seem to point unequivocally to a marine origin.

Significance of surfaces and platforms

It seems likely that both the subaerial surfaces and marine platforms developed at a time when the climate was less severe than at present. In view of their associated fluvial landforms and the traces of river patterns, the subaerial surfaces are unlikely to have developed in a glacial climate; and the marine platforms must have been cut at a time when marine processes were little impeded by the presence of sea ice or by an extensive ice cover on the islands.

The coastline of the South Shetland Islands appears to have been in approximately its present position for a great length of time. The parallelism of the lower cliff lines with the present coast implies that the outline of the islands has changed little since platform cutting commenced; therefore, the submerged platform in its broad outlines must have been cut at an early stage. It is, however, impossible to estimate just how much modification of the submerged platform has occurred during successive fluctuations of sea-level.

The major phases of marine erosion are represented by platforms at 182–197, 85–102, 27–50, 11–17 m., around present sea-level and down to −110 m. (with the latter probably a composite feature). The individual remnants of the island group are best interpreted as having been cut during stillstands over a long period of fluctuating sea-level. The more extensive platforms probably represent prolonged stillstands or transgressions, but the smaller platforms at intermediate heights may indicate shorter stillstands or they may be the remnants of once extensive platforms which have been virtually cut away by subsequent phases of erosion.

It has been suggested, on the basis of evidence from Byers Peninsula and elsewhere, that the 85–102, 27–50 and 11–17 m. platforms are successively less well preserved with increasing altitude. Therefore, it may in general be implied that the lower the platform, the younger its age, with subaerial modification of the higher platforms being more severe than modification of the lower platforms. This means that there has been an overall fall of sea-level in the South Shetland Islands since the first platforms were cut.

However, this overall regression appears to have been marked by many complex fluctuations. If the 191–198 m. platform on Noel Hill is accepted as the highest marine feature recorded in the South Shetland Islands and that at −110 m. as the lowest, the minimum amplitude of sea-level movements is about 300 m. There has been a marine transgression between the cutting of the submerged platforms and the present day. Furthermore, the freshness of the 11–17 m. platform and the remnants at 30–40 m. is in contrast to the more dissected platform remnants both above and below. Possibly they were cut later than the main sequence of platforms and represent later fluctuations of sea-level. There may well have been other marine transgressions on a large scale which are less easy to identify from the present landscape of the island group. Certain platforms may have been subjected to marine erosion on more than one occasion and it is quite possible that many of the highest platforms have been modified to such an extent that they are no longer recognizable as marine features.

Ages of surfaces and platforms

Some clues have already emerged concerning the ages of the surfaces and platforms. Because of their discontinuous and uneven nature, the undulating surface remnants above 120 m. appear to be older than the lower freshly preserved platforms. Since the high features were probably cut subaerially by river action, all that can be said with certainty is that when they were formed sea-level was below the lowest part of the remnant. It is possible, however, that the flatter remnants were cut initially quite close to sea-level and they are the equivalents in age of marine-cut platforms at slightly lower altitudes. Since it is impossible to prove the horizontality of the high surfaces, it must be admitted that they could pre-date any crustal tilting and block faulting in this area.

More detail is added to the question of dating when the relationship between erosional landforms and bedrock geology is analysed. On Fildes Peninsula and elsewhere, platforms cut across faults of supposed Middle Tertiary age (Barton 1965); and the volcanic rocks across which most of the surfaces and platforms are cut, have been assigned on the basis of their petrology and fossil content to the Eocene, Oligocene and Miocene (Adie, 1964*a*). Thus all the surfaces and platforms of these islands may be younger than the Middle Miocene. Furthermore, it is significant that the *Pecten* conglomerate of Lions Rump has been dated as Pliocene. If this dating is correct and if the conglomerate is truly interbedded, the erosion surface above the Lions Rump succession which lies at 150–180 m. must also be Pliocene or younger. Tentatively, it can be suggested that the surfaces and platforms of the South Shetland Islands may be no older than Pliocene in age.

A minimum age for the cutting of the platforms and surfaces is difficult to assess from the evidence available at present. The present-day distribution of surfaces, platforms and cliff lines under the ice domes of the islands indicates that these erosional features were cut at a time when the ice cover was less extensive than it is today; probably they pre-date the most recent phase of glaciation. It has been suggested above that the climate during the early development and modification of the landscape was somewhat warmer than that of today, and it is therefore reasonable to propose that the surfaces and platforms are, at least in part pre-glacial. The existence of the marine conglomerates on the platform surfaces of Byers Peninsula and Dee Island is significant, for if the conglomerates can be dated, the minimum age of the platforms can be fixed.

If the Pliocene is accepted as the lower age limit and the onset of glaciation the upper limit for the major surfaces and platforms of the South Shetland Islands, the Plio-Pleistocene appears to have been the period of initial landscape development. This dating is supported by work undertaken in the Antarctic Peninsula. King (1964) and Linton (1964) have suggested that the high plateau of the Antarctic Peninsula was formed as a plain close to sea-level in late Tertiary times and was uplifted by tectonic activity during the end Tertiary. On geophysical grounds, it has been independently suggested by Griffiths and others (1964) that the South Shetland Islands have also been uplifted. The higher surfaces on the South Shetland Islands may be equivalent in age to the late Tertiary surface of the Antarctic Peninsula; the isolated high remnants in the island group may be all that remains of that surface. During a long period of tectonic uplift the original surface was dissected and possibly disrupted while successively lower platforms were eroded during stillstands. Each successive phase of platform cutting was accompanied by subaerial modification of earlier higher surfaces and platforms.

There is evidence for transgressions and some trimming of platforms during subsequent phases of landscape development. This may imply that Pleistocene eustatic fluctuations of sea-level as envisaged by Adie (1953) in the Falkland Islands and Fairbridge (1961) on a much wider scale, may have coincided with periods of tectonic uplift and stillstand to complicate the latter stages of development. Possibly these fluctuations may have been associated with the history of glaciation.

Glacial Landforms

Much of the land area of the South Shetland Islands is covered by ice and there is widespread evidence that glaciers were formerly more extensive across not only the ice-free peninsulas but also the adjacent shallow submarine platforms. In addition, there are indications that directions of ice flow were once quite different from those of today. The evidence falls into two main categories: features due to extensive glaciation and those resulting from local glaciation.

Evidence of extensive glaciation

Ice moulding

On most of the ice-free peninsulas in the vicinity of the transverse straits there is evidence of moulding by ice. Fildes Peninsula has an irregular bedrock surface with a relief of tens of metres scoured to form numerous convex hillocks and bedrock hollows often occupied by lakes. Structural lines have frequently been exploited to form straight narrow gullies crossing hillocks and hollows indiscriminately. Frequently, the land surface consists of bare rock slabs which in places are smoothed and striated. The scouring generally seems to be aligned in a direction transverse to the main trend of the peninsula. On Ardley Island, for example, there is a deep narrow trench holding a lake at least 10 m. deep which is aligned broadly west-north-west to east-south-east. On the upland immediately east of Horatio Stump a residual rises above the overall surface level of 120–130 m. to 150 m. and this is one of several elongated along a west-north-west to east-south-east axis; from its shape and ice-smoothed surface it appears to be a rock drumlin. Comparable forms occur occasionally among the skerries off the north-west coast of King George Island and one rises as smoothly as a whaleback from the sea a little south of Flat Top Peninsula. Similar topography occurs on the western flanks of Barton Peninsula, where rounded smoothed summits rise above an irregular rocky surface, and polished and striated rock surfaces can often be seen beneath a thin veneer of coarse boulders. On Harmony Point and on Spark Point, grooved smoothed surfaces are common on low prominences which rise above an undulating rock surface. On Duff Point similar topography extends uninterruptedly beneath the sea, where a series of rounded low skerries makes the north side of McFarlane Strait notoriously dangerous for navigation.

In the west of the central South Shetland Islands, on Byers Peninsula, there are less obvious signs of moulding by ice, and flat platform surfaces are continuous and broken only by stream gullies. Although there are several prominent residuals which resemble *roches moutonnées*, the possibility that they owe their characteristic form at least partly to structure cannot be discounted. It is notable that over much of Byers Peninsula the strata have an overall north-eastward dip (Hobbs, 1962), and in many cases the orientation of apparent *roches moutonnées* seems to be related to this regional dip.

Glacial troughs

Perhaps the most spectacular features of the South Shetland Islands are the straits and troughs which cut deeply into the island group. Admiralty Bay is easily recognizable as a trough cutting about 16 km. into the centre of King George Island (Fig. 13). At its head it consists of several subsidiary troughs forming Ezcurra Inlet in the west and the arms of Martel Inlet in the north-east. At its entrance, Admiralty Bay forms a broad inlet 4–8 km. wide with relatively gentle flanking slopes. The water of the trough remains shallow for several hundred metres from each shore but then the bottom plunges steeply to a depth of *c*. 368 m. The bottom deepens northwards and reaches a maximum depth of *c*. 392 m., representing over-deepening of *c*. 24 m. (personal communication from W. A. Ashcroft). Within about 1 km. of the southern tip of Keller Peninsula it is still over 360 m. deep and an arm of deep water also extends up Ezcurra Inlet. In this vicinity, Admiralty Bay is fjord-like and steep rocky walls rise abruptly from the water's edge to heights of approximately 300 m. The top of the fjord walls, mantled with ice overspilling from the plateau, sharply truncates the upper surface of the island. The head of each inlet rises steeply to the main island plateau and is covered by seracced glaciers cascading down to the fjord waters. Between many of the inlets are foreshortened arêtes, such as Ullmann Spur, Stenhouse Bluff and Keller Peninsula.

An examination of the submarine contours of the waters surrounding the South Shetland

Fig. 13. Air photograph (towards the north-west) of the trough of Admiralty Bay incised into the interior of King George Island. It is *c.* 16 km. from Demay Point (left foreground) to the head of Mackellar Inlet at the head of the trough. 20 December 1956; 4,115 m. (Photograph from Hunting Aerosurveys Ltd., by permission of the Government of the Falkland Islands Dependencies.)

Islands reveals that Admiralty Bay is but one of seven similar features cut into the southern and south-eastern flanks of the islands (Fig. 10). Soundings are scattered and, although the interpolated contours must be regarded as generalized, there is enough detail to show the striking pattern of the troughs. The straits between the central islands begin as troughs *c.* 90 m. deep near their northern ends and deepen south-eastwards, reaching depths of 450–545 m. where they debouch into the great rift of Bransfield Strait. Both English and McFarlane Straits appear to be overdeepened, especially at points of constriction near their exits. Beyond the heads of most of the troughs in the straits there is shallow water with many rocks and islands in all degrees of submergence, but at the head of Maxwell Bay there is an almost complete arc of land represented by Fildes Peninsula and Rip Point. Towards the extremities of the island group are two further troughs leading up to active glaciers. The trough in King George Bay has a maximum depth of 514 m., while its threshold is only 440 m. deep and it extends to the ice piedmont fringing the northern coast of the bay (personal communication from W. A. Ashcroft). In the west, a trough lies between Deception Island and Barnard Point, and two tributary troughs lead into the glacier-occupied troughs at the heads of South and False Bays, respectively.

For most of their lengths the troughs are incised into a submarine surface, as in the southern reaches of Admiralty Bay. This was strikingly illustrated in November 1965 when R.R.S. *Shackleton* traversed the False Bay trough from Barnard Point towards Miers Bluff on an echo-sounding run. For several hundred metres west of Barnard Point the water remains shallow and is measurable in tens of metres, then suddenly in two steps the bottom falls to a depth of over 210 m. It rises again just as abruptly off the tip of Miers Bluff. Again, for almost one-third of the way from Robert Island to Nelson Island across Nelson Strait the bottom lies at a depth of less than 35 m. It then falls abruptly to a depth of over 396 m. but rises to within 30 m. of the surface just off the coast of Nelson Island.

It appears that similar troughs are cut into submarine surfaces north of the islands. There is very little evidence but a few echo-soundings suggest the presence of two asymmetric troughs north-west of English and Nelson Straits, respectively; in both cases the eastern slope is steeper than the western one (Fig. 10) (personal communication from W. A. Ashcroft). Just beyond the exit of one trough is a mound sufficiently large to be picked out on the Admiralty Chart. Another magnificent trough was revealed by echo-sounding run D off the north coast of King George Island (Fig, 10); less than 12 km. offshore the trough cuts clearly into a platform *c.* 180 m. below sea-level and reaches a depth of 530 m. There could possibly be more troughs north of the islands but while so little is known about the bottom topography their presence must remain speculative.

There seems little doubt that the submarine troughs in the South Shetland Islands have been cut by ice. Such an interpretation has long been accepted for Admiralty Bay (Holtedahl, 1929; Linton, 1964; Barton, 1965), and the similarity of the other troughs cut into the south-east flank of the island group points to the same origin (Holtedahl, 1929). The alignment of main or tributary troughs to active glaciers and the overdeepened profiles often at points of constriction are characteristics only easily explained by glacial erosion. There is no reason to suggest that the northern troughs are of a different origin, although the evidence is scanty. Not only is the trough off the north coast of King George Island aligned to the most active glacier on the north-western coasts of the South Shetland Islands, but it is just possible that the rise beyond the mouth of another northern trough is a terminal moraine. Taken together, the South Shetland Islands troughs suggest an approximately radiating pattern which may in itself be regarded as a diagnostic feature of glacial erosion (Linton, 1957).

Melt-water channels

At the head of the Maxwell Bay trough, the ice-free areas of Fildes Peninsula and the Rip Point peninsula are dissected by a complex series of dry channels (Fig. 14). The map does not attempt to portray every channel in the area, for, in the time available in the field, it was inevitable that certain channel systems were examined in less detail than others. However, the map contains sufficient detail to give a clear overall pattern.

Two striking features are immediately apparent:

i. The channels show a marked preferential alignment across the peninsulas from west-north-west to east-south-east, although they vary from an approximate alignment of north-west to south-east in the north to a direction nearer west–east in the south.
ii. There is a marked contrast between the straight decisive channels of the north-west with amplitudes of *c.* 30 m. and the complex anastomosing patterns of the eastern side of the peninsulas with amplitudes up to 78 m.

It is useful to consider examples from both sides of Fildes Peninsula in more detail.

In the extreme south-east corner of Fildes Peninsula, there is a fine system of channels over 1 km. in length trending east from the main peninsula watershed (a).* The system begins in the west at an altitude of *c.* 78 m. where three channels cross a col. One, 3 m. deep and with a flat floor 6 m. wide, has a humped long profile rising from the west for about 9 m. before falling eastwards, while two further gullies are cut into the southern slopes of the col, the highest crossing at *c.* 87 m. All three channels converge to form a prominent V-shaped gash up to 60 m. deep which falls down the east slope of the peninsula. At *c.* 55 m. the channel leaves the hills and runs eastwards over a surface which falls to *c.* 39 m. before being truncated by cliffs near the present coast. The channel gradient decreases abruptly on reaching this surface and the single gully gives way to several flat-bottomed anastomosing distributaries which are incised about 6–12 m. into the surface. The pattern becomes increasingly complex nearer the sea, where the channels are joined by gullies from an adjacent northern system (b). In this vicinity the pattern of channels is so dense that the only remnants of the original surface are a series of elongated, ice-smoothed rock knobs standing above an alluvium-floored basin. In several cases, subsidiary channels leave the main system well above the channel floor. They can be followed eastwards, where they often re-unite haphazardly, generally with ungraded confluences. All of the channels are truncated by marine cliffs at altitudes of *c.* 21 m. or

* Letters refer to channels on Fig. 14.

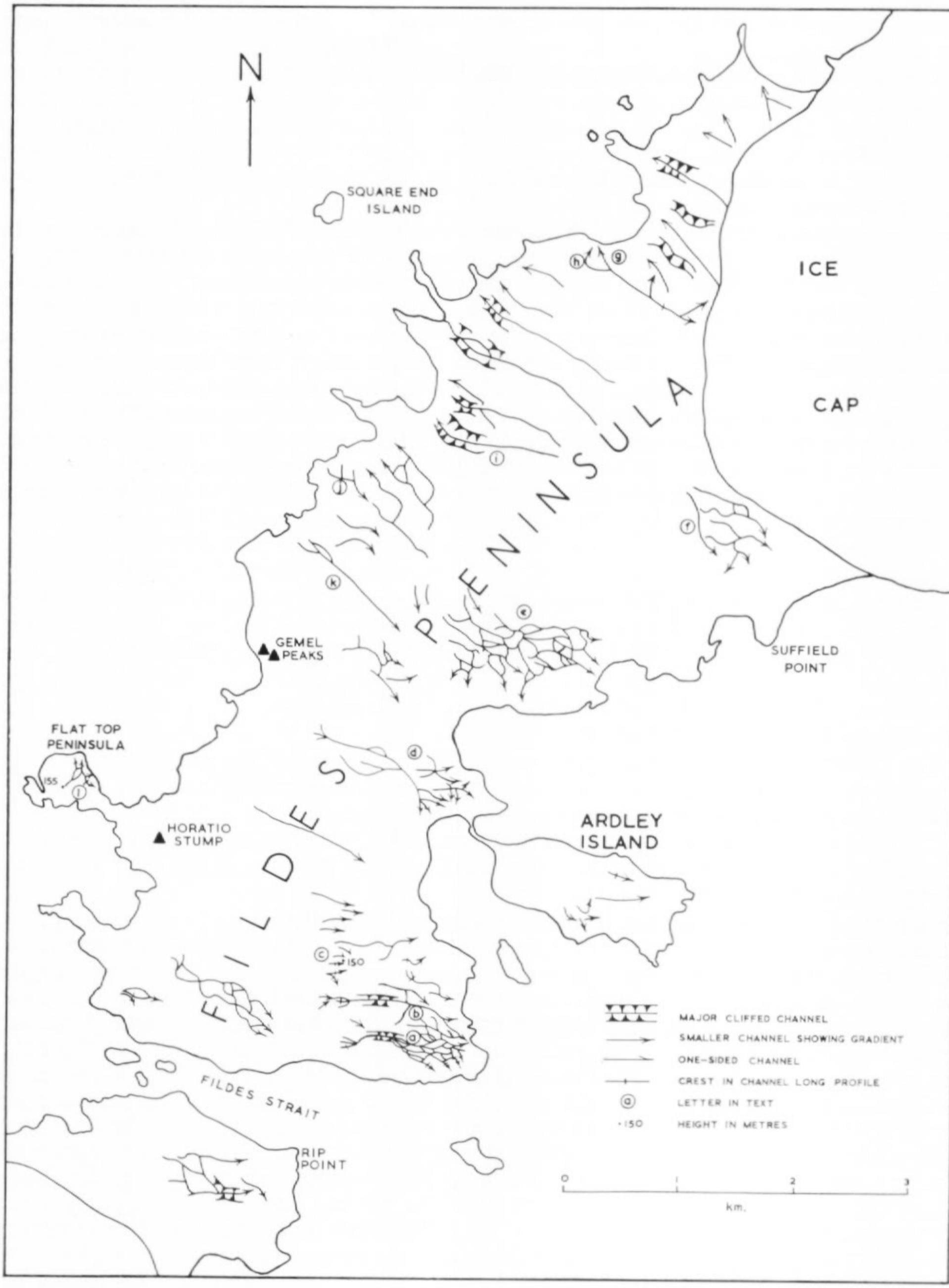

Fig. 14. The pattern of melt-water channels on Fildes Peninsula, reflecting a transverse movement of melt water from north-west to south-east. Each anastomosing pattern in the east is related to a col breaching the upland axis of the peninsula.

higher, and it is notable that not a single channel cuts into the 11–17 m. platform which is well developed in this area. Today, even at the height of the summer melt, this impressive channel system contains little more than an insignificant trickle of water. Other large channel systems (c, d, e and f) are aligned to the lowest cols on the peninsula. There is no reason to suspect that they differ in origin from similar though smaller forms at a wide variety of altitudes (Fig. 15). On Flat Top Peninsula and in the hills of southern Fildes Peninsula there are numerous dry gullies, several crossing cols at *c.* 103 m. and others nicking summit crags as high as 150 m. (c) and 164 m. (l). These channels often have convex long profiles, bifurcating courses, flat floors with one or both sides cut into rock, and they may sometimes be traced eastwards into systems at lower altitudes.

The channels of north-west Fildes Peninsula are different in form and situation. They are cut mainly into the surface of the 35–48 m. coastal platform, which is almost horizontal in this area, and they are truncated by 30 m. cliffs rising precipitously from near sea-level. In the north-west over a distance of 4 km. no less than 14 prominent channels breach the cliff top and generally their floors slope north-westwards from the surface of the platform to an altitude of 3–18 m. The finest in this area (i) has a flat floor 91 m. wide near the sea where it is bounded by sheer cliffs 30 m. high. Then with a remarkably consistent width of *c.* 60 m. the floor rises inland at a regular gradient of 2·5°, gradually attaining the altitude of the platform. The sides are cliffed and steadily decrease in height as the platform surface is reached. About 1 km. from the coast the channel is indistinguishable from the platform surface and it joins the featureless approaches to the col south of the ice margin.

Not all channels in the north-west are simple or slope westwards. In the north a channel 50 m. wide (g) slopes seawards, but an arcuate channel also sloping seawards (h) leaves from high on its side and meets it once more near the sea, isolating a remnant of the coastal platform. The major channel can be followed inland over a low col at 37 m. into a channel 30 m. wide which bifurcates and falls eastwards beneath the ice. Farther south there is another complex channel system, where several channels displaying an anastomosing pattern slope east-

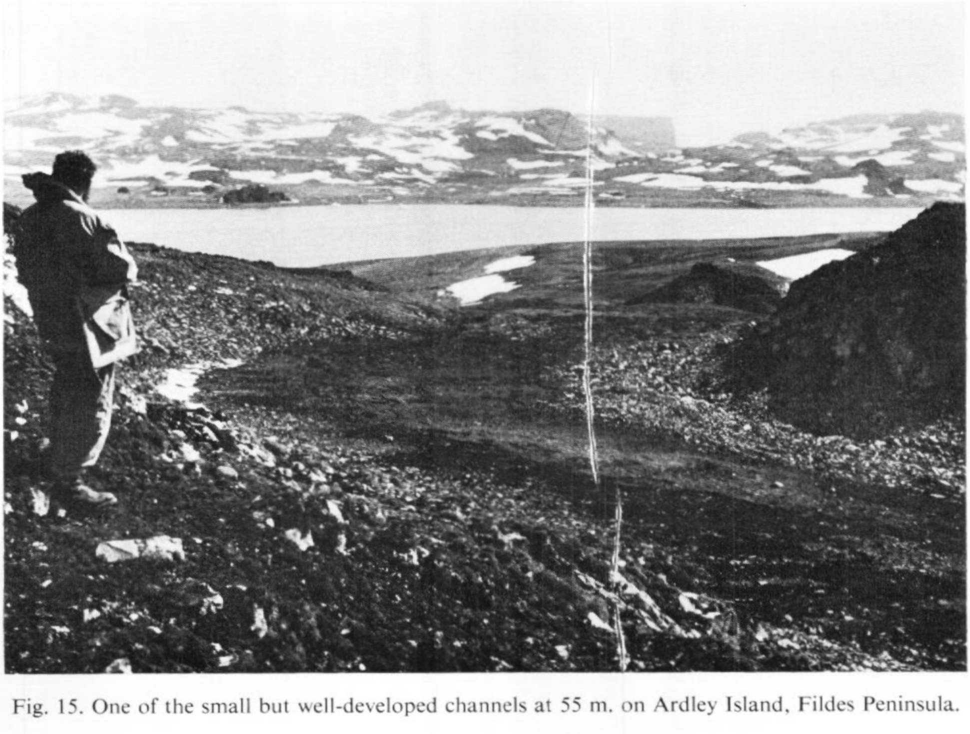

Fig. 15. One of the small but well-developed channels at 55 m. on Ardley Island, Fildes Peninsula.

wards (j). Still farther south a broad shallow channel follows a fault line (Barton, 1965) and falls in altitude from a point near the west coast by means of an elongated lake-filled depression towards the east (k). It forms one of the many channels aligned to the central col of Fildes Peninsula.

The overall form and continuity of the channel systems on Fildes Peninsula and near Rip Point suggest the influence of abundant water in their formation. Only a few channels hold streams today and even in summer these streams are intermittent and quite inadequate to explain the sizes of the channels they occupy. It seems that only melt water derived from a considerable ice mass would be sufficiently powerful to cut the channels. Although a few of them could be explained by melt water flowing subaerially, those with humped long profiles and ungraded bifurcations suggest that a subglacial origin is more likely. The sub-parallel nature of the channels, their alignment to major relief trends and their presence in such unlikely positions as hill crests and cliff tops are all features consistent with a subglacial origin (Gjessing, 1960; Sissons, 1960, 1961; Price, 1963; Sollid, 1963–64).

The existence of channels mostly orientated seawards on either flank of Fildes Peninsula might seem to suggest the former presence of a local ice cap with its axis trending parallel to the length of the peninsula. However, it is notable that the channels are aligned to cols on the higher parts of the peninsula and they appear to reflect a transverse movement of melt water *across* the peninsula rather than a source on the peninsula itself. Again, the scale of channel development seems to have been too great for a restricted local ice cap. Moreover, the altitude of some higher subglacial channels in the east and on Flat Top Peninsula suggests a minimum ice-surface altitude at about 240 m. when the channels were formed. This clearly suggests the presence of more than a local ice cap. It seems likely that the channels reflect the movement of ice from the north-west over both Fildes Peninsula and the Rip Point peninsula into the Maxwell Bay trough. Not only is there other glacial evidence of ice movement in this direction, but such movement would explain the alignment of the main channels to the major cols in the north, to the cols of central Fildes Peninsula and to Fildes Strait. The presence of some of the higher channels suggests that the ice was sufficiently thick to have submerged both peninsulas.

There is no reason to suppose that the melt-water channels of this area are the only ones in the South Shetland Islands. On Byers Peninsula there are gullies which almost certainly cannot be explained by normal gully erosion but, because of a thick snow cover, insufficient information could be obtained to assess their significance. Furthermore, it is notable that Fildes Peninsula is the only extensive accessible land area at the head of a major trough or strait. The comparable north-western ends of the other straits are submerged but when seen from the air they appear to have traces of similar channel patterns. On certain points adjacent to the ends of the straits, as on Williams Point, there are channels which are similar to those on Fildes Peninsula.

Form of the ice cap

The landforms of glacial erosion in the South Shetland Islands give a guide to the probable form of the ice at the time of their formation. With few exceptions, they point to a movement of ice dominantly *across* the axis of the island group. The evidence of scouring and melt-water channels on Fildes Peninsula points to ice over-running from the north-west, while throughout the island group this is confirmed by the evidence of the transverse troughs. Three of these, in McFarlane, English and Nelson Straits, extend as far north as the north-western coasts of the islands, again suggesting that the centre of ice dispersion lay north-west of the shores of the islands. It is tempting to suggest that the ice cap, which perhaps originated in the islands, stabilized its position on what is now the broad submerged platform to the north-west (Fig. 16). Such a view is supported, perhaps tentatively at this stage, by the presence of several troughs flowing off the platform edge to the north and north-west. The ice cap appears to have been centred on the relatively flat block of land between the abrupt fault scarp of Bransfield Strait in the south-east and the steep continental slope to the north-west.

An ice cap in such a position would have its long axis lying north-west of the islands, where the submarine shelf is broad, but in the vicinity of western Byers Peninsula and eastern King George Island, where the shelf is narrow, the axis probably lay over the islands. It is notable that the position of the northern trough off King George Island fits in well with this pattern,

Fig. 16. A reconstruction of the north-west ice cap in the South Shetland Islands, based on erosional landforms. The seaward limits of the ice cap are assumed to have been determined by the 100 fathom (185 m.) line.

while the lack of major ice-eroded forms on Byers Peninsula suggests that this part of Livingston Island may have been approximately beneath the axis of the ice cap, where ice movement would have been at a minimum. Probably the ice cap was *c.* 65 km. across at its widest point and *c.* 250 km. long. However, the latter figure is tentative, since it is difficult to know how far the ice extended beyond each extremity of the South Shetland Islands. It was possibly linked to the Graham Land ice cap at its western end via a narrow bridge of relatively shallow sea in the vicinity of Low and Hoseason Islands, as suggested diagrammatically by Voronov (1965).

It is emphasized that the possible existence of this ice cap is based on the evidence of erosional landforms alone. It is not easy to decide how many phases of glaciation are represented by such landforms, and it must be admitted that there may have been several glaciations of this nature.

Evidence of local glaciation

Erratics and till

Ice-free areas which are not covered with beaches or scree are usually strewn with a scatter of erratic blocks and till which reflects recent ice movement in the South Shetland Islands. On Byers Peninsula, a number of erratics of fine-grained igneous rock were found resting on volcanic tuffs and agglomerates west of Chester Cone. Although no quantitative tests were made, it was noticeable that the erratics, which were derived from Chester Cone itself, became progressively less angular and their edges more rounded and abraded with increased distance westwards. No similar erratics were found east of the hill and presumably the erratics were moved by westward-moving ice and suffered abrasion in the course of transport. On many platforms throughout the islands there are patches of till consisting of a wide variety of rock types, sizes and shapes set in a stiff clayey matrix. Many of the stones are faceted and some of the fine-grained ones are clearly striated. Histograms of stone roundness were compiled for six samples and they resemble characteristic till histograms with high proportions of sub-angular and angular fragments (Reichelt, 1961) (Fig. 17). For example, widespread deposits

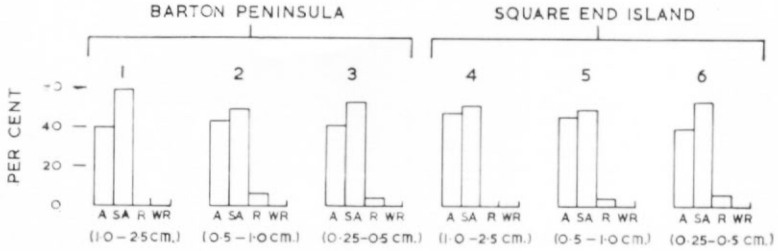

Fig. 17. Histograms for till from an altitude of 191–198 m. on Barton Peninsula (1–3) and from Square End Island (4–6). Each sample comprised 100 pebbles in a specific size range. They were visually classified into four groups after Reichelt (1961): A angular; SA sub-angular; R rounded; WR well rounded. The dominance of sub-angular fragments with a considerable but smaller proportion of angular constituents is characteristic of glacial till.

were seen on all surfaces and platforms above 27 m. on Byers Peninsula, above 30 m. on Fildes Peninsula, Harmony Point, Williams Point and O'Cain Point, and above 60 m. on Barton Peninsula and in the Three Brothers Hill area.

Morainic ridges

With the exception of the outlet glacier margins, no morainic ridges were observed beyond the ice edge. This is of particular interest for such large ice-free areas as Byers and Fildes Peninsulas. However, the edges of the ice caps are usually marked by prominent moraines where they terminate on land. The peripheral moraine on Byers Peninsula rises 60–75 m. above the adjacent land surface and surmounts a snow or ice slope with angles of *c.* 10°. Behind this moraine is the ice-cap surface rising gently inland. The ice surface is rarely as high as the crest of the moraine (Hobbs, 1968); in places on south-east Byers Peninsula it is at least 15 m. lower, although elsewhere 6–12 m. is commoner. It is difficult to estimate the number of ridges present, since many minor features may be masked by snow, but on Byers Peninsula there appears to be one major ridge with two crests; the constituent material of the outer crest is always more shattered than that of the fresh inner crest. In northern Byers Peninsula this twin moraine divides into five separate ridges, the fresher of which are nearer the ice cap. Similar ice-edge moraines occur in a wide variety of sites in the South Shetland Islands; for example, on Cape Shirreff, Elephant Point, O'Cain Point, Fildes Peninsula and Stranger Point. All rise above the ice surface which they fringe and, as Hobbs (1968) noted in relation to the examples on Livingston Island, they appear to represent a phase when the ice caps were somewhat thicker.

In the vicinity of outlet glaciers, ridges which are the representatives of this ice-edge moraine can be traced beyond the ice margin. On Stranger Point one ridge occurs at the ice edge and it can be followed westwards on to the Three Brothers Hill peninsula, where it divides into two moraines, the inner of which is still ice-cored and actively slumping. These merge with valley glacier lateral moraines in Potter Cove. On the surface of a volcanic plug in south-east Byers Peninsula two main moraines fringe an outlet glacier of Rotch Dome; the outer moraine is composed largely of frost-shattered fragments and is covered by vegetation, while the inner one is fresh and ice-cored. There is a similar two-fold sub-division in the moraines on the south side of Charity Glacier (Barnard Point), on the flank of the glacier east of Ash Point, at Lions Rump, and on both sides of the glacier near Point Thomas in Admiralty Bay.

This two-fold sub-division does not occur everywhere, and there are many sites where there are no obvious ice-cap moraines. Spark Point, Edwards Point, Harmony Point and Barton Peninsula are examples. In other places there may be several distinct ridges of moraine, for example, near Johnsons Dock on Hurd Peninsula two clear moraines lie beyond a third one at the ice edge. Furthermore, the larger glacial troughs with glaciers at their heads, such as Admiralty Bay and Marian Cove, bear evidence of several retreat stages.

The constructional morainic forms in the South Shetland Islands imply thinning of the local island ice caps and the withdrawal of their glacier outlets towards local ice centres. The same can be said of the till cover, for there is no reason to suppose that its origin is different from that of the moraines. No significant difference between the compositions of the till and adjacent moraines was found. In places where there were no constructional forms, such as Barton Peninsula and Harmony Point, the till could be traced to the ice edge. Only in one place, near Chester Cone on Byers Peninsula, was evidence found of the direction of movement of ice that laid down the till; this direction can best be explained by envisaging an extended local ice cap over western Livingston Island. Thus, in spite of a paucity of data on erratic distributions, it seems likely that the glacial drift cover of the South Shetland Islands can be attributed to the action of local ice caps centred, as today, on the individual islands.

The features of glacial erosion and glacial drift in the South Shetland Islands suggest the influence of two distinct phases of glaciation. The erosional features reflect the presence of a large early ice cap north-west of the islands, while the drift cover is best explained by invoking a slightly advanced position of the existing local island ice caps in more recent times.

Relative ages of phases of glaciation, surfaces and platforms

The association between the forms of glacial erosion and the surfaces and platforms confirms the tentative conclusion reached in the previous section: that the glaciations post-date the cutting of all the major platforms. The existence of ice and till resting on most platforms shows that the platforms pre-date the last phase of glaciation. Furthermore, the distribution of erosional landforms cut by the earlier glaciation shows that they have modified almost all platforms and are thus younger. For example, the complex patterns of melt-water channels on Fildes Peninsula are particularly well marked where they are incised into the surface of the 35–48 m. platform but they also occur on a variety of surfaces and platforms at higher altitudes. Furthermore, ice moulding and melt-water erosion from the north-west ice cap affected the skerries and the submerged platform on which they stand. It seems that the north-west ice cap moved over most of the surfaces and platforms at some time after they had achieved their approximate form and distribution of today.

It is possible, however, that there are one or two minor exceptions. For example, the narrow 11–17 m. platform on eastern Fildes Peninsula is not only fresh in form but its backing cliffs commonly truncate melt-water channels in places. No direct evidence of moulding by ice from the north-west was found on this platform. These characteristics show that this relatively minor platform may post-date the major glaciation. In support of such a view is the notable contrast in freshness between the 11–17 m. platform and others immediately above and below it, as on Byers Peninsula.

There is also evidence to suggest that platforms at *c.* 3–8 m. may have been formed between two glaciations. The platforms are limited in occurrence but they have been noted in some glacial troughs where they form narrow benches. In view of their position inside these troughs, they must post-date the erosion of the troughs. But frequently these platforms, such as a 6 m. remnant on the north shore of Marian Cove, are striated and moulded, suggesting that they pre-date the last glaciation.

RESIDUAL BEACHES AND THEIR BEARING ON GLACIAL PHASES

The residual beaches are significant, if unobtrusive, features of the landscape in the South Shetland Islands. Their distribution is restricted and perhaps for this reason they have escaped the attention of previous workers in this area. They add important evidence concerning the interval separating the two phases of glaciation recognized in the preceding section.

Pockets of water-rounded cobbles which are everywhere surrounded by till occur at a variety of sites in the Maxwell Bay area (Fig. 18). Their altitudinal range is considerable and, although most of them lie near 55–60 m., some occur as high as 275 m. The best preserved remnants are on Barton Peninsula and it is useful to discuss two examples in detail. One remnant occurs at an altitude of 143 m. on the north-western flank of an ice-smoothed hill, approximately 1·5 km. east-south-east of South Spit (Fig. 3). The deposit lies at the foot of a 6 m. cliff cut into the ice-smoothed slope and it is restricted to a small bedrock bench about 10 by 50 m. in extent. On the bench there is a high percentage of well-rounded and rounded cobbles, mostly

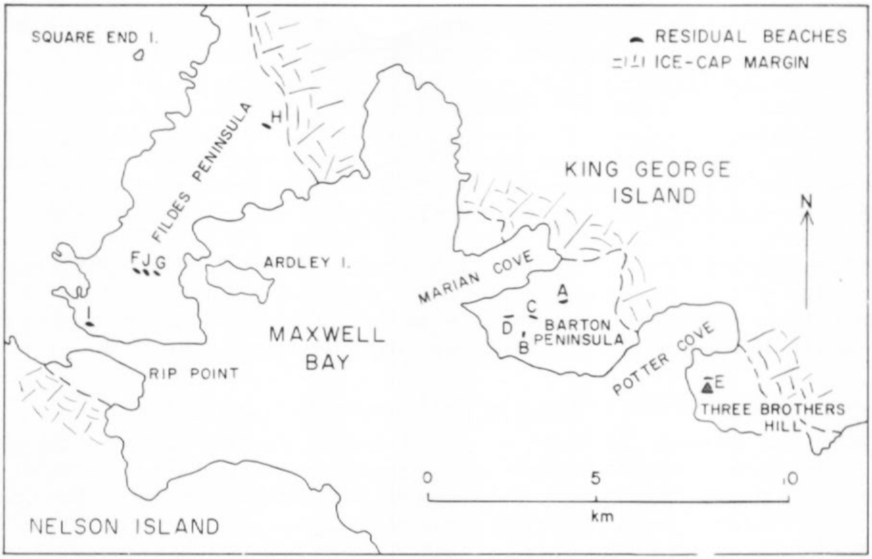

Fig. 18. Altitudes (determined by aneroid barometer) and sites of residual beaches on King George Island around Maxwell Bay.

Site	*Altitude* (m.)	*Locality*
A	275	Barton Peninsula; southern slope of Noel Hill summit.
B	166	Barton Peninsula; undulating rock surface 1 km. north-east of penguin rookery.
C	150	Barton Peninsula; north slope of peninsula at southern entrance to old nivation hollow.
D	143	Barton Peninsula; north slope of peninsula west of C.
E	104–118	Foot of northern cliff of Three Brothers Hill volcanic plug.
F	66	Fildes Peninsula, northern flank of through valley north of Horatio Stump.
G	60	Fildes Peninsula, northern flank of through valley north of Horatio Stump.
H	60	Fildes Peninsula, at foot of narrow east–west ridge on western side of broad col near ice-cap margin.
I	55	Fildes Peninsula, gully overlooking western end of Fildes Strait.
J	55	Fildes Peninsula, northern flank of through valley north of Horatio Stump.

10–30 cm. in diameter, set in a sandy and gravelly matrix. A histogram for a random sample of surface pebbles 2–5 cm. in diameter gives the remarkable result that 60 per cent of the pebbles are well-rounded and only 22 per cent are angular or sub-angular. This represents a higher percentage of well-rounded pebbles than on many present-day beaches (Fig. 19). As on present-day beaches, pebbles tend to be concentrated into patches of fairly uniform size. The pebbles, mostly consisting of fine-grained igneous rocks, are fresh in appearance and only a minority is split by frost. None is striated. The hillsides surrounding the deposit are covered with shattered andesite bedrock, scree and solifluction material. Well-rounded cobbles occur only down-hill from the deposit, where they are incorporated in solifluction tongues.

The highest residual beach occurs at an altitude of 275 m. on the surface surrounding the southern slopes of Noel Hill (Fig. 3). The deposit extends round the flank of the hill for a distance of about 40 m. in the south but re-appears 150 m. away on a col farther east. Generally, it forms a terrace 10–20 m. wide. The terrace surface is disturbed by solifluction and frost-heaving, and there are many angular and sub-angular blocks over 30 cm. across, apparently solifluoted from above. In heaving centres, however, finer material is exposed and it is here that one discovers water-rounded material. In places 50 per cent of the surface stones under 15 cm. in diameter are either rounded or well-rounded, but more typical proportions are illustrated by the histograms in Fig. 19. On counts of five different pebble sizes, the proportion of rounded and well-rounded material varies between 30 and 54 per cent. The high percentages of angular and sub-angular fragments appear to reflect the presence of soliflucted rock frag-

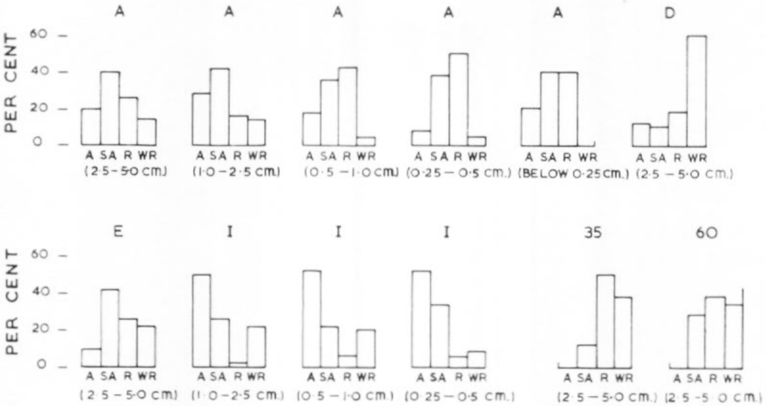

Fig. 19. Pebble-roundness histograms for samples from residual beach deposits. The site letters refer to Fig. 18. The histograms are compared with those for two present beach deposits at Harmony Point (35) and Three Brothers Hill peninsula (60), and the samples frequently contain comparable proportions of well-rounded and rounded pebbles. (A angular; SA sub-angular; R rounded; WR well rounded.)

ments from up-slope. Most cobbles consist of hard, fine-grained igneous rock and, although some are weathered, most are remarkably fresh. Again, none is striated.

The remaining residual beaches round Maxwell Bay are similar. On Barton Peninsula a remnant occurs at 150 m. a short distance east of the 143 m. deposit, which it closely resembles. Figs. 20 and 21 show the terrace form of the deposit and the high proportion of well-rounded pebbles on the surface. On Three Brothers Hill peninsula a deposit between altitudes of 104 and 118 m. nestles beneath an overhang at the foot of the precipitous north-eastern cliff of Three Brothers Hill. Protected from falling scree by the overhang, well-rounded and rounded cobbles, mainly 2–10 cm. in diameter, comprise nearly half the surface pebbles of the deposit (Fig. 19). On Fildes Peninsula, small scattered concentrations of well-rounded cobbles sometimes occur beneath south-facing bluffs of andesite and basalt.

While the visual impression gained in the field was that the residual deposits are true raised beaches, the possibility of an alternative origin must be considered. Ordinary subaerial river action is unlikely since nowhere do the deposits lie in or near river gullies; instead they tend to occur on hill slopes or, near Noel Hill and Three Brothers Hill, they are banked against the highest summits of the respective peninsulas. The pebbles are generally too well-rounded and regular to be explained by fluvio-glacial action (Tricart and Schaeffer, 1950); furthermore, the sites and form of the various deposits are difficult to explain by fluvio-glacial action. There seems no possibility that the deposits can be related to weathered conglomerates, for they generally lie on bedrock consisting of andesite and basalt. Rather, the high proportions of well-rounded and rounded pebbles, the rough arrangement into patches of consistent pebble size and the sandy shingly matrix with well-rounded components are characteristics shared by the beach deposits along the present shores of the South Shetland Islands. Furthermore, the apparent association of the 143 m. beach on Barton Peninsula with a small cliff line, and the Three Brothers Hill beach with an undercut cliff, is most readily explained by marine action. There seems little doubt that the residual deposits are true raised beach deposits.

There is evidence that the beaches have been over-ridden by ice since their formation. In addition to the pockets of beach material which appear to be *in situ*, well-rounded cobbles can be traced into adjacent zones of till where they are usually striated. Many striated cobbles occur in till on the 275 m. surface south and south-west of Noel Hill and they become increasingly common the nearer they are to the terrace deposit. No cobbles were seen in the till on the 275 m. surface north-east of the hill. On Three Brothers Hill peninsula, a prominent moraine sweeps round the northern flanks of the volcanic plug in the vicinity of the 104–118 m. deposit. East of the plug it contains virtually no well-rounded cobbles. Immediately it passes the vicinity of this deposit, it contains well-rounded cobbles comprising 10–20 per cent of the

Fig. 20. Part of the 150 m. residual beach (Fig. 18, C) on Barton Peninsula. The terrace built of cobbles contrasts with the angular scree behind it.

Fig. 21. Detail of the surface of the 150 m. residual beach (Fig. 18, C) on Barton Peninsula. The hammer shaft is 35 cm. long.

total number of pebbles 2 to 15 cm. in diameter. Although the moraine does not visibly touch the 104–118 m. deposit, it is only about 10 m. lower and its cobbles are probably derived from a similar deposit beneath the scree surface. On Fildes Peninsula, on the western approaches to the northern col near the ice edge, a few scattered striated cobbles occur in till. These increase in frequency of occurrence as a residual beach deposit at 60 m. is approached at the base of a narrow rock ridge. Few cobbles occur on the north side of the ridge near the ice. It appears, therefore, that striated cobbles lying in till and moraine may often be traced as erratic "fans" to their sources in the residual deposits.

It is notable that the beaches often lie in sites which might be expected to escape erosion during a relatively feeble local glaciation. On Fildes Peninsula they lie in protected pockets below south-facing bluffs. Indeed, so predictable is this association that four beach remnants were discovered by the specific examination of "likely" sites. There may well be more. On Barton Peninsula two beaches lie in hollows, while that at 275 m. lies in a site likely to have been covered by barely moving ice. In view of the composition and sites of the beaches, there seems no reason to doubt that they are *in situ* remnants of a formerly more extensive beach cover subsequently disturbed by over-riding ice.

It seems that related beaches may have existed in all parts of the South Shetland Islands. Admittedly, no other beaches comparable to those around Maxwell Bay were discovered but this may be because they were snow-covered when visited; it is almost certain that, if any beach pockets exist on Byers Peninsula, they would have been obscured by snow when visited in December 1965. However, striated marine cobbles occur in till and moraine at a wide variety of localities throughout the island group (Fig. 22). Histograms for a spot sample from a till pocket at an altitude of 21 m. on Tartar Island show a characteristic till distribution of pebble shapes, but with a significant proportion of rounded ones (12–26 per cent) and, in two cases, small percentages of well-rounded ones (2–4 per cent). Striated beach cobbles occur on the 35 m. platform at Harmony Point, at 72 m. on Robert Point, at 31 m. on Williams Point and at a variety of altitudes on Byers Peninsula. They were found in all moraines fringing the island ice caps but their densities vary from place to place. The cobbles, generally consisting of fine-grained igneous rock, are remarkably fresh in character. Unfortunately, little quantitative work was done on these cobbles, but on south-east Byers Peninsula the depth of chemical

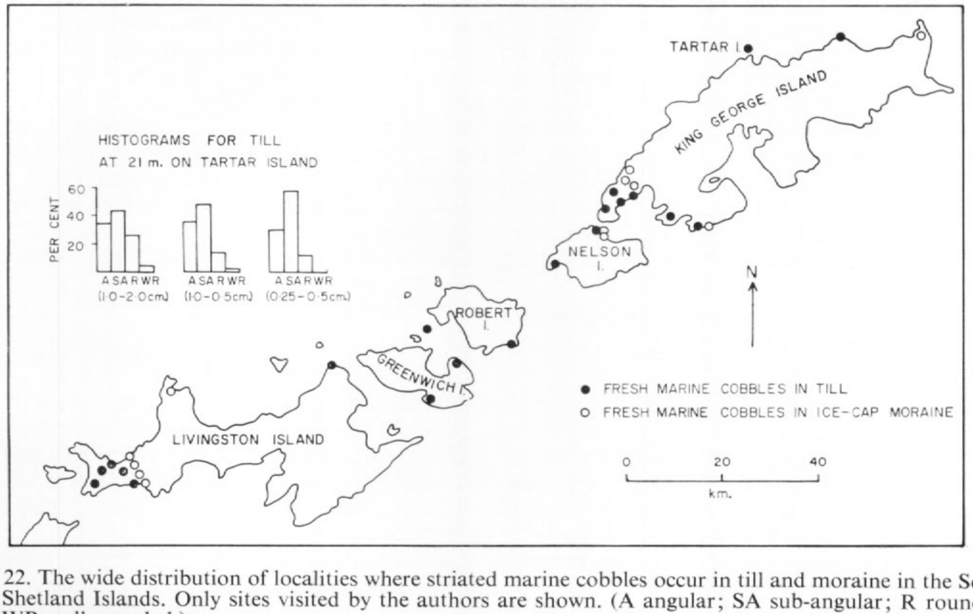

Fig. 22. The wide distribution of localities where striated marine cobbles occur in till and moraine in the South Shetland Islands. Only sites visited by the authors are shown. (A angular; SA sub-angular; R rounded; WR well rounded.)

alteration was measured on cobbles of the same rock type taken both from a moraine and from the present-day beach. Although the method used was relatively sensitive when tried on undisturbed raised beaches at successive altitudes, there was no noticeable contrast in freshness between the cobbles in the moraine and those on the present beach.

Hobbs (1968) suggested that the cobbles in till on Livingston Island might have been derived from conglomerates interbedded with volcanic rocks beneath the ice. Although this may explain some of the more weathered cobbles on Livingston Island, it seems an inadequate explanation when considered in the light of evidence for the whole of the South Shetland Islands. Had the cobbles been derived from conglomerates, occasional blocks of unbroken conglomerate would be expected to occur in moraine; however, none was seen. It seems too much to suggest that every cobble was plucked cleanly from a conglomerate matrix. Lastly, it is significant that in freshness and form the bulk of the cobbles resemble those of the Maxwell Bay beaches and associated erratic "fans". Their form and distribution is best explained, as in Maxwell Bay, by an advance of ice over widely distributed beach deposits.

Significance of residual beaches

The high altitudes of the residual beaches around Maxwell Bay reflect great variations in the relative positions of land and sea. At the time of the formation of the highest beach, relative sea-level must have been 275 m. higher than today. This large fluctuation of relative sea-level took place at some stage between the two phases of glaciation recognized earlier. The distribution of the beaches and the incorporation of their constituents in till show that they pre-date the "local" glaciation, while their sites on the glacially moulded flanks of Barton and Fildes Peninsulas indicate that they post-date the major glaciation from the north-west which accomplished the bulk of this erosion. At the time of the 275 m. sea-level there can have been little ice on the islands, if only because of the very small area of land exposed above the sea.

In view of their relative ages, it is difficult to understand why the beach cobbles both in the residual beaches and in the till are so fresh, and in places comparable to those on present-day beaches. Since the cobbles tend to consist of hard fine-grained igneous rock, it might be suggested that all pebbles other than these resistant rock types have been destroyed by weathering. However, as in south-east Byers Peninsula, cobbles of the same rock type show the same degree of chemical alteration both in young moraine and on the present-day beach, which suggests that both groups have been exposed to subaerial weathering for comparable periods. It seems necessary to infer that, in spite of their age, the residual beaches have been exposed to subaerial weathering for only a short time. It is difficult to explain this paradox, but perhaps the beaches were protected by ice or *névé* soon after their formation. Possibly during a phase when relative sea-level fell and deposited successively lower beach deposits, ice covered the newly exposed land immediately and thus protected the beaches from subaerial weathering. It is interesting to note that, if sea-level was to fall today, a comparable advance of the ice would take place. For many kilometres the present beach ridge is backed by ice or *névé* cliffs, implying that it is the sea which controls the ice margin, at least under present-day conditions. If sea-level were to fall, the ice cliffs would advance over the present beach.

The altitude of the beaches cannot be explained with any certainty but there seem to be three main possibilities:

i. An extensive eustatic rise in sea-level.
ii. Isostatic recovery.
iii. Tectonic uplift.

Eustatic movements alone can hardly explain the presence of a beach at 275 m. The fact that the beach post-dates a major glaciation and pre-dates only a relatively minor glaciation suggests that it occurred at some interval relatively late during the glacial epoch. However, in the later Pleistocene, even as early as the Sicilian transgression, the sea appears never to have been over 100 m. above present sea-level (Fairbridge, 1961). On its own this is clearly inadequate to explain the majority of the residual beaches.

It is tempting to attribute the greater part of the uplift to isostatic recovery. It could be argued that the rapid melting of the main South Shetland Islands ice cap, as indicated by the abundance of melt-water channels, would be accompanied by large-scale and rapid isostatic rebound. However, it is doubtful whether such a relatively limited ice cap could depress the land by as much as 275 m. Assuming that the ice cap occupied the whole of the South Shetland Islands platform and rested on surfaces now 184 m. (100 fathoms) below sea-level, its maximum breadth would be *c*. 65 km. It is possible to estimate the likely maximum thickness of the ice cap by superimposition of modern ice-cap profiles. Robin (1962, 1964), who has emphasized the similarity of ice-sheet and ice-cap profiles in the Arctic and Antarctic in a wide variety of situations, drew actual profiles and, if these are applied to the postulated South Shetland Islands ice cap, they suggest a maximum ice thickness of about 1,000 m. If the profiles calculated by Voronov (1965) after comparison with various Antarctic profiles are used, the maximum thickness of the South Shetland Islands ice cap could be about 900 m. Assuming that isostatic equilibrium is reached and that the maximum amount of depression of the land can only be approximately one-third the thickness of the overlying ice, the maximum amount of crustal depression would be about 300 m. However, these calculations are for the areas underlying the axis of the ice cap which formerly lay to the north-west of the islands. The relevant beaches were deposited on the periphery of the ice cap in an area unlikely to have been depressed to such an extent. Thus, even without considering problems of eustatic sea-level movements which, if borne in mind, would probably necessitate an increase in the total estimate, isostatic recovery of 275 m. at the periphery of such a small ice cap seems excessive.

It is necessary, therefore, to consider the possibility of tectonic movements as an explanation for the uplift of at least the higher residual beaches. Unfortunately, however, there is little conclusive evidence either in favour of, or against, a view of recent tectonic activity in the South Shetland Islands. The apparent horizontality of the lower marine platforms means that there has been little differential tectonic movement since the platforms were cut; since this took place at some time before the main glaciation from the north-west, the evidence seems to imply that there has been no large-scale tectonic tilting since the main glaciation. But this does not rule out the possibility of the islands moving up as one block. The position of the South Shetland Islands on the flank of a tectonic trough associated with recently active volcanoes such as Deception and Bridgeman Islands makes an hypothesis of recent tectonic uplift attractive. In this context, it is interesting to note the view that the growth of the Antarctic ice sheet and the consequent isostatic depression of the centre of the continent may be compensated by tectonic uplift in the peripheral zones of Antarctica (Kapitsa, 1964; Ushakov and Lazarev, 1964; Voronov and Ushakov, 1965). Perhaps such a process has contributed to the uplift of the high South Shetland Islands residual beaches.

Nature of the non-glacial interval represented by residual beaches

The presence of the residual beaches in the South Shetland Islands points to a widespread marine inundation at some stage between the main north-western glaciation and the smaller local glaciation, for little ice can have existed in the islands at the time. It is not clear to what extent this may be regarded as an interglacial or an interstadial phase. It might be argued with Hollin (1962) that movements of sea-level themselves are sufficient to cause the collapse of large ice sheets and that an initial eustatic rise precipitated the collapse of the main ice cap. However, this seems unlikely in the South Shetland Islands, since the presence of abundant melt-water channels on Fildes Peninsula indicates that climatic amelioration was responsible, at least in part, for the disappearance of the main ice cap. There is considerable doubt, however, as to the size of this climatic fluctuation, and this depends on one's interpretation of the evidence of the 275 m. beach. If its altitude is explained by direct isostatic rebound, the beaches probably immediately followed or were contemporaneous with deglaciation. If they were covered by *névé* soon after they emerged, this would seem to suggest a relatively minor climatic fluctuation in the periphery of Antarctica. However, if the view is accepted that the 275 m. beach owes even part of its altitudinal position to isostatic/tectonic uplift induced by the *increase* in ice load in central Antarctica, the evidence would then seem to suggest a climatic fluctuation of sufficient size to influence the centre of the main Antarctic ice sheet. Clearly, the full significance of the non-glacial interval will not be clarified until further evidence becomes available.

UNDISTURBED RAISED BEACHES AND THEIR RELATIONSHIP TO RECENT GLACIATION

The undisturbed raised beaches are relatively minor features of the South Shetland Islands landscape but they are widely distributed, especially in coastal embayments. Generally, they form series of ridges roughly following the contours of the underlying rock surface, and it is useful to describe briefly a typical example. On Barnard Point, beaches rest on a low rock foreland at the foot of the steeper, more accentuated relief culminating in Mount Friesland (Hobbs, 1968) (Fig. 23). There are four clear ridges trending approximately parallel to the

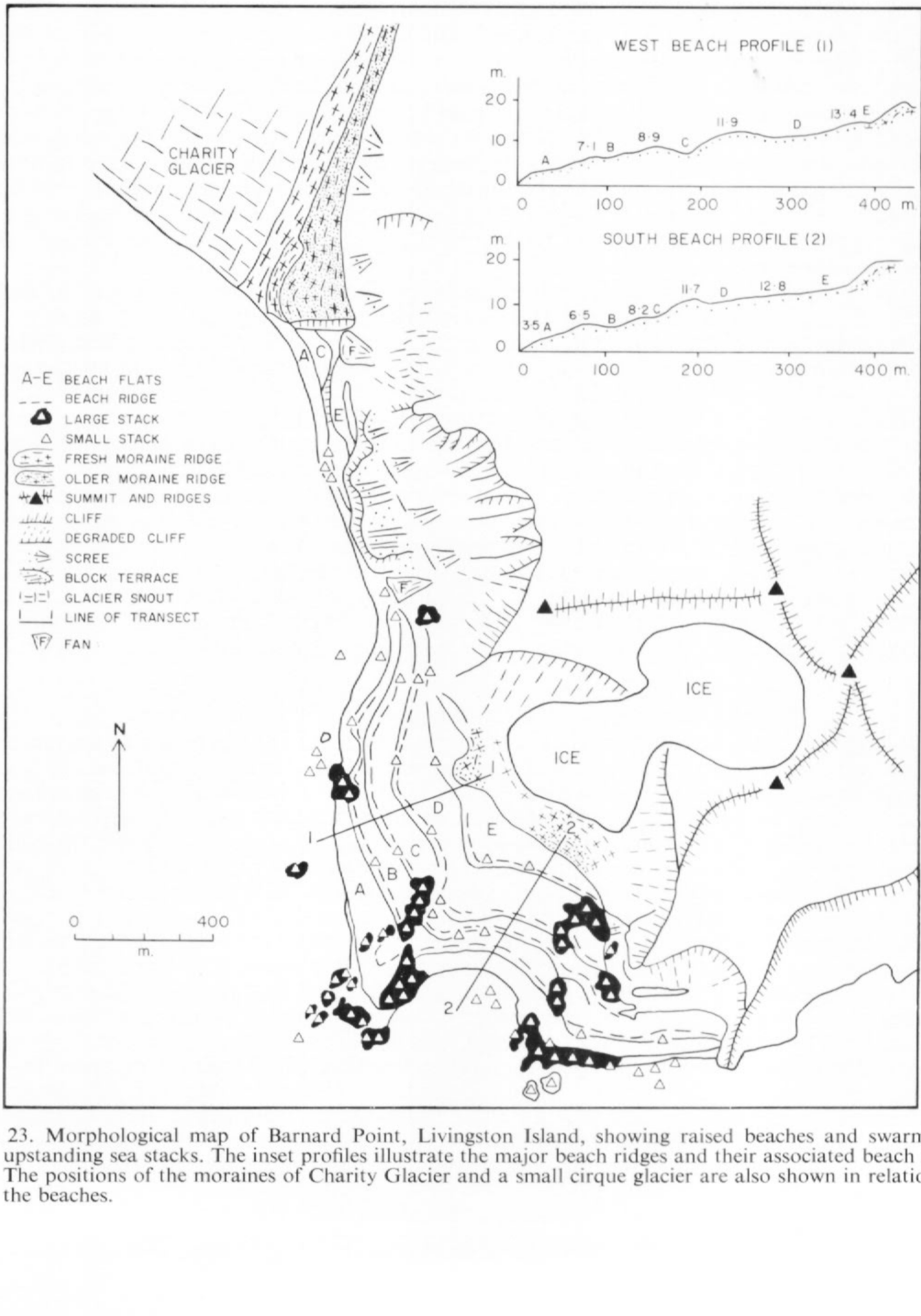

Fig. 23. Morphological map of Barnard Point, Livingston Island, showing raised beaches and swarms of upstanding sea stacks. The inset profiles illustrate the major beach ridges and their associated beach flats. The positions of the moraines of Charity Glacier and a small cirque glacier are also shown in relation to the beaches.

Fig. 24. Aerial view (towards the south) of arcuate raised beach ridges on Spark Point, Greenwich Island.

Fig. 25. View (towards the north-east) of raised beach ridges on South Beaches, Byers Peninsula. The beaches are resting on the 11–17 m. rock platform with upstanding sea stacks.

present shore at altitudes of 6·5–7·1, 8·2–8·9, 11·7–11·9 and 12·8–13·4 m. There is a flat terrace behind each ridge, generally 0·5–1 m. lower than the ridge crest. In addition, there are sloping beach "flats" at the present shore and above the highest beach ridge at *c.* 18 m. Both ridges and flats are built mainly of well-rounded and rounded cobbles of varying size set in a sandy or shingly matrix. With the minor exception of the 18 m. terrace, the beaches are continuous and are broken only by swarms of rock stacks rising 3–12 m. above the underlying rock surface. The upper limit of the beaches is generally well marked by a sharp contrast between beach cobbles on the one hand and mixed morainic debris, scree or block terraces on the other. Such a description could apply to many localities throughout the South Shetland Islands, and in Figs. 24 and 25 two other sites are illustrated, one on Spark Point and one on Byers Peninsula.

In any assessment of raised beaches it is helpful to attempt a correlation from one place to another on the basis of morphological form and altitudinal similarity. However, such a correlation is open to many dangers.

i. Beaches are discontinuous and the absence of a particular beach at a site may simply reflect the influence of underlying topography. In many instances a beach resting on a gently sloping rock surface peters out when it is followed on to a precipitous shoreline, presumably because there is nowhere for beach material to rest.
ii. A beach may be absent because remnants associated with a high sea-level relative to the land may have been removed by a subsequent lower sea-level. Thus on any peninsula the highest visible beach need not necessarily represent the highest beach-forming sea-level.
iii. Although altitudinal correlations are useful over short horizontal distances, they are beset with problems and can only be a rough guide. Variations of up to 2 m. in the altitude of single beach ridges were recorded on western Keller Peninsula, reflecting variations in fetch, offshore topography and availability of material.
iv. On a wide-reaching correlation, it is difficult to know the relationship between a beach flat and a beach ridge. Generally, observations suggest that a beach flat is likely to occur at an altitude slightly lower than a related ridge. However, until more is understood about beach-forming processes in this area, this association must be regarded as tentative.

With these problems in mind, an attempt has been made to plot and correlate the altitudes of the beach remnants in the South Shetland Islands (Fig. 26). So far as is possible, beaches have been correlated with those on adjacent sites on the basis of form, but altitude has also been taken into account. In many cases it has been possible to trace a beach over a comparatively large area through a series of adjacent localities. These are correlated in Fig. 26 with solid lines to signify a measure of confidence in the correlation. Other less certain correlations, such as those between beaches on the isolated northern points of King George Island, have been marked either as tentative or else not attempted.

Although raised beaches occur at a wide variety of altitudes between present sea-level and 54 m., most of them occur near sea-level; remnants become more scattered and are less well preserved with increasing altitude, but the gradation is not regular. On grounds of morphological freshness and distribution, the beaches can be subdivided into two main groups:

i. Beaches above an altitude which varies locally between 17 and 20 m. Their distribution is restricted and remnants occur only on a few scattered peninsulas and offshore islands. Beach forms are recognizable though poorly preserved.
ii. Beaches below 17–20 m. These are widespread and occur on almost all ice-free areas. Generally, the beaches are continuous over comparatively great distances. Beach form is well-preserved.

Beaches above 17–20 m.

Beaches above 17–20 m. were found on 12 peninsulas and offshore islands (Fig. 27a). A concentration of the highest remnants occurs on the ice-free peninsulas of Maxwell Bay but other remnants are present near Horatio Stump on Fildes Peninsula, in south-west Byers Peninsula and on Heywood Island. Lower remnants occur on Harmony Point and Edwards

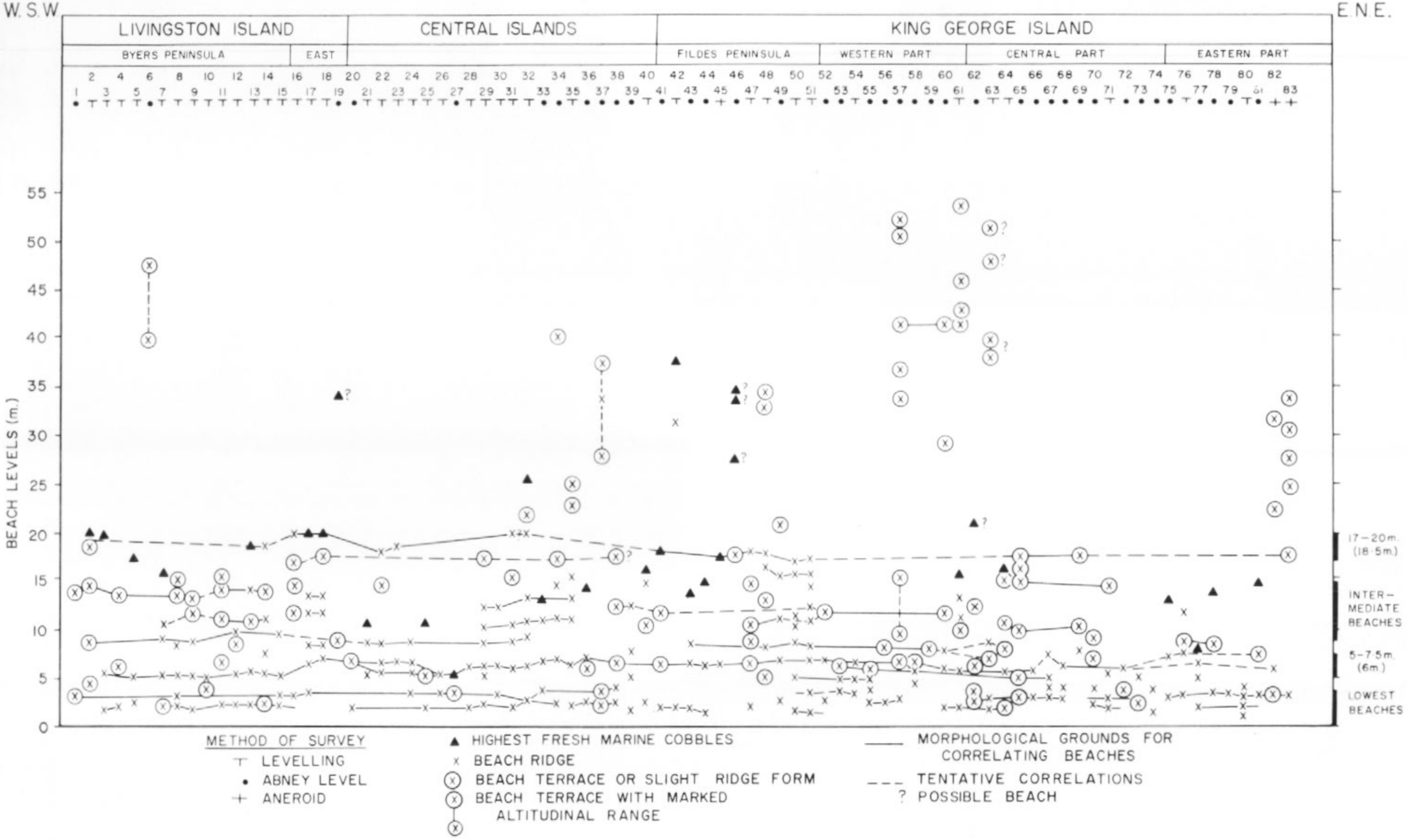

Fig. 26. A correlation of the altitudes of undisturbed raised beaches in the South Shetland Islands, arranged along the axis of the island group from west-south-west to east-north-east. The key to site numbers is given in Fig. 1 and the explanation.

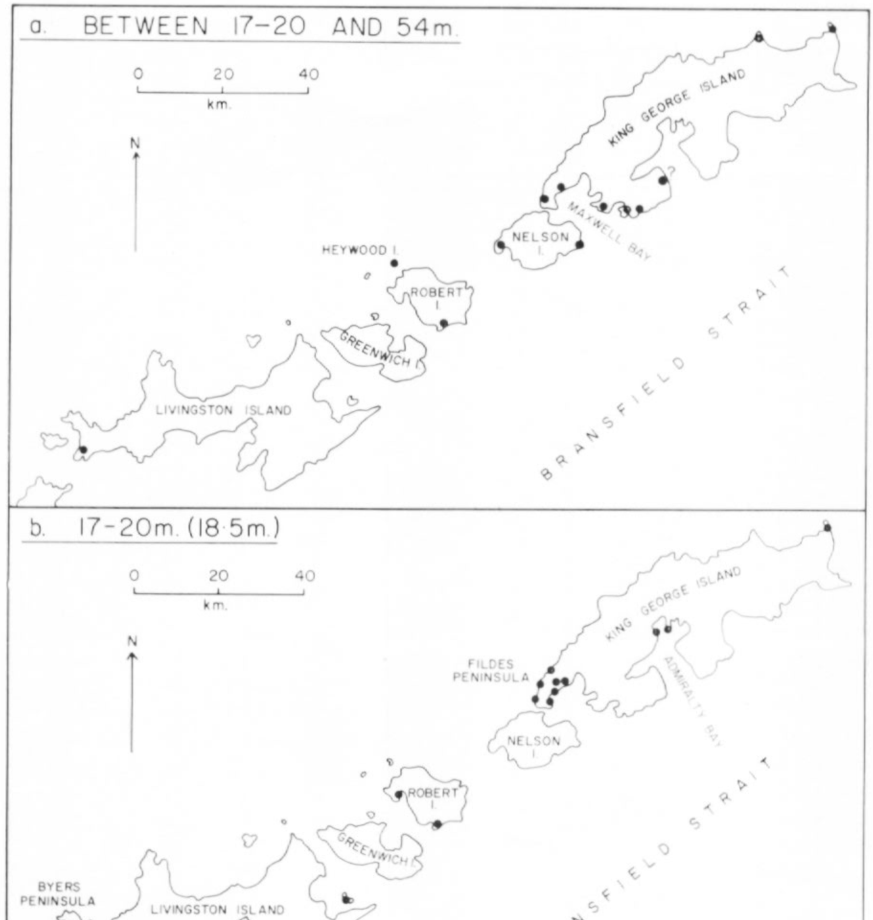

Fig. 27. The distribution of raised beaches in selected altitudinal ranges in the South Shetland Islands: a, beaches between 17–20 and 54 m.; b, beaches at 17–20 m. (18·5 m. beach); c, beaches at 5–7·5 m. (6 m. beach). Only sites visited by the authors are shown.

Point. The material in most of the deposits closely resembles that found on present-day beaches, and consists mainly of well-rounded and rounded cobbles lying in a sandy shingly matrix. Although pebble size varies from 1 cm. to over 50 cm., most cobbles tend to be 2–7 cm. in diameter. The surface cobbles are often split by frost but excavation reveals that beneath the surface cobbles are often fresh and largely undisturbed. Few large or angular blocks are present in these deposits (Fig. 28).

Although modified by subsequent erosion, the morphological expression of the deposits is often recognizable as a beach. On North Foreland, near the base of the peninsula, the beaches have been partially removed by solifluction but they form four sub-parallel horizontal terraces between 24 and 35 m. On False Round Point, a beach 2 m. thick forms a terrace associated with a washing limit on several adjacent hillocks at 33 m. Beach material on Duthoit Point is mixed with frost-shattered debris on a 27·8–35·1 m. platform, but a ridge at 35 m. is sufficiently well preserved to impound an elongated lagoon 20 by 5 m. in size. On Harmony Point, beaches at 23 and 25 m. form the upper beaches of a series extending from the present shore and, although they are less well preserved than the lower beaches, they form clearly marked discontinuous terraces (Fig. 29).

At four sites on the northern and western shores of Maxwell Bay and at a fifth possible site near Point Thomas in the southern reaches of Admiralty Bay, the upper beaches take on a different and more puzzling aspect. They are most extensive along the southern shores of Barton Peninsula, Three Brothers Hill peninsula and Stranger Point, where they occur in patches over a distance of 8 km. Here they rest on an undulating sloping platform which is abruptly truncated by cliffs on its seaward side and backed by degraded cliffs on the landward side. The beaches consist of elongated hummocks and low ridges generally between altitudes of 35 and 54 m. They are highlighted by their vegetation cover of light green *Usnea*, which contrasts with the more subdued and darker-coloured moss around them. In places the beaches are built of sands and gravels, but more typically they comprise evenly graded pebbles 2–7 cm. in diameter sometimes set in a shingly matrix. Most of the pebbles on the surface are angular and sub-angular, and consist of flakes with edges imperfectly rounded, similar to pebbles along the present shore in this area. A number of angular fragments have been derived from well-rounded cobbles, presumably by frost-splitting. Excavation showed that the proportion of angular fragments decreased with depth and that below *c.* 15 cm. well-rounded or rounded cobbles were more common.

The contrast between the Maxwell Bay beaches and beach remnants at comparable altitudes elsewhere in the South Shetland Islands presents a problem. At first it was suspected that they might be the deposits of giant petrel nests accumulated over the centuries. Although this may be true of some mounds, the beach forms, the shingle components and the continuity over several kilometres suggest that a marine origin is more likely. The flaky pebbles probably reflect the influence of the local Jurassic volcanic rocks in the area, since they are especially noted for their susceptibility to frost action and their tendency to weather into flakes (Barton, 1965).

There is no good evidence that any of the beaches above 17–20 m. are continuous features recurring at approximately the same altitude. It may be significant that beach remnants occur at *c.* 40 m. along the northern shores of Maxwell Bay and at similar altitudes on Heywood Island and south-west Byers Peninsula. However, it would be more realistic to describe the overall pattern as a haphazard series of dissected beach remnants, with little sign of a prolonged marine stillstand or of a clear upper marine limit. From the number of remnants at *c.* 40 m., there can be little doubt that at one stage sea-level was at this altitude in relation to the land; probably it extended at least as high as 54 m., as indicated in the Barton Peninsula area.

Beaches below 17–20 m.

The beaches below 17–20 m. differ from the higher ones because they are fresher in appearance, more continuous and can be traced from point to point as distinct levels. Since there is a complex mass of beach remnants, they are best examined within four main groups:

i. Remnants at 17–20 m. (the "18·5 m. beach").*

* For simplicity, generalized altitudes are used for these beaches except where specific occurrences are mentioned.

Fig. 28. Raised beach cobbles, some of which have been split by frost action to form flakes, at 23 m. on Harmony Point, Nelson Island. The hammer shaft is 35 cm. long.

Fig. 29. The discontinuous terrace of the 23 m. raised beach on Harmony Point, Nelson Island.

ii. Intermediate beaches between 17–20 and 5–7·5 m.
iii. Remnants at 5–7·5 m. (the "6 m. beach").*
iv. Beaches below 5–7·5 m.

Remnants at 17–20 m. (*18·5 m. beach*) (*Fig. 27b*)

This beach is best displayed on Fildes Peninsula, especially on the eastern shore where it sweeps across several embayments as an almost continuous crest roughly parallel to the present shore. In the north it extends up to the ice edge which it meets at right-angles. The ridge crest is at 17·3–18 m. over a distance of nearly 8 km.* In almost every embayment the ridge has a prominent back slope varying between 4 and 6 m. in height and resembling an arcuate dam with its convex side facing inland. The ridge is everywhere built of well-rounded and rounded cobbles and shingle. Along the cliffed western shore of Fildes Peninsula there is no clear ridge but in several embayments in the cliff line cobbles and terrace forms have an upper limit of *c.* 18 m. With one exception near Horatio Stump, this beach is the highest fresh beach on Fildes Peninsula; inland the ground surface is covered with till, striated rock surfaces and solifluction debris. At the foot of the back slope of the ridge in eastern Fildes Peninsula, the contrast between till and beach material is remarkably abrupt (Fig. 30).

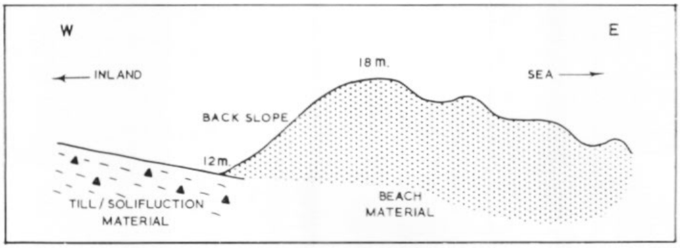

Fig. 30. Diagram illustrating the nature of the junction between the 18·5 m. beach and till and solifluction material behind; eastern Fildes Peninsula. The height of the beach ridge back slope is 6 m.

At many other sites the 18·5 m. beach is also the highest fresh beach form (Fig. 31). The highest beach remnant on the west side of Mitchell Cove is at 20 m. In McFarlane Strait, tombolo ridges of well-rounded cobbles link two bedrock mounds to form Half Moon Island; the ridges, the highest on the island, lie at 18 and 18·8 m. on either side of a lagoon impounded by the 3 m. back slope of each ridge. South of Johnsons Dock on Hurd Peninsula, Livingston Island, the highest beach occurs at 19·9 m. and it has a back slope of *c.* 3 m. giving way to a zone of moraine. Cliff lines on Byers Peninsula have prevented the formation of the beach in many places but remnants occur at 18·6 m. on South Beaches and on the north shore of New Plymouth, and at 19·9 m. in the embayment west of Chester Cone. Inland of these three sites the peninsula is covered with till.

At two sites visited the 18·5 m. beach is the highest fresh form in a beach series extending up to 25 m. or more. On Edwards Point there is a marked contrast between the fresh ridge at 19·7 m., which impounds a lagoon, and the soliflucted beach remnants at higher altitudes (Fig. 32). Another marked contrast in freshness of form is provided by beaches on western Ardley Island and this is confirmed by quantitative work on pebble roundness (Fig. 32). The transect runs from sea-level over a series of fresh ridges and terraces, the highest of which is at 17·7 m. Within a few metres of the 17·7 m. beach the transect passes upwards on to shattered beach material preserved mainly on gentle slopes and flats, but with little beach form. The histograms for 50 surface pebbles from sample sites on each beach reflect a greater degree of frost-shattering with increasing altitude, but there is a dramatic break between 17·7 m. and 18·5 m.† On the fresh beaches below and including that at 17·7 m. there is a high percentage

* In the past this beach has been mistakenly recorded at 30·5 m. (Barton, 1965).

† On all beaches, including that at present sea-level, a few well-rounded and rounded cobbles are broken in half. These are difficult to classify by Reichelt's method but, for consistency, they were classified according to the original water-rounded form. Wherever a cobble was split more than once, it usually assumed a sub-angular or angular shape and was recorded as such.

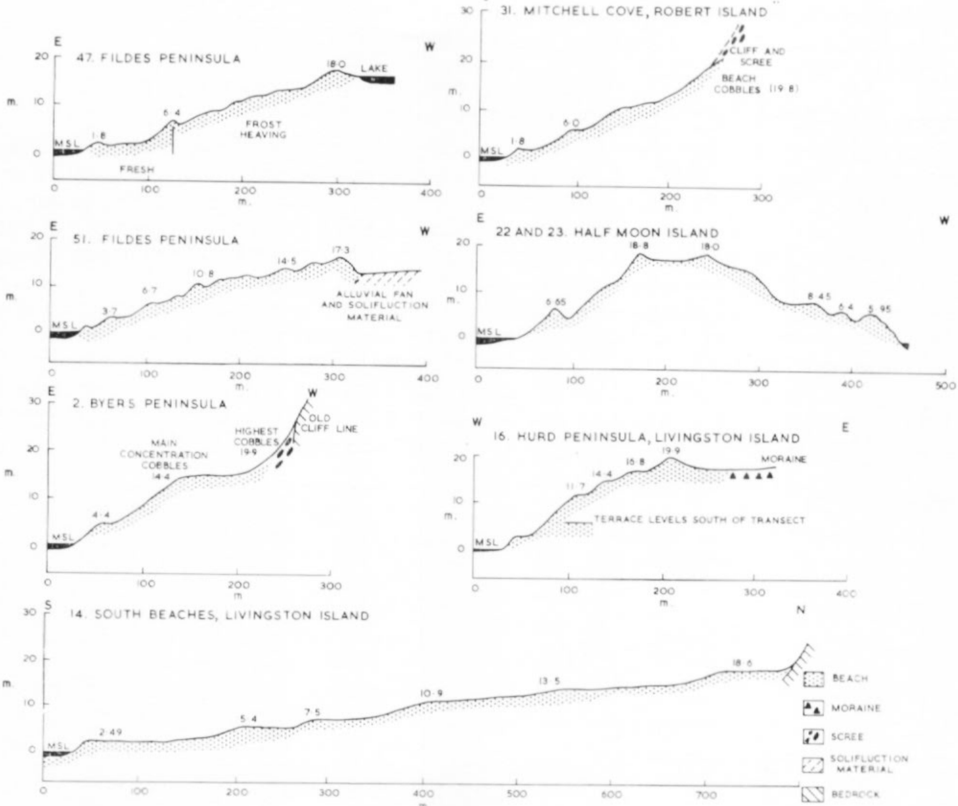

Fig. 31. Profiles of selected raised beach series showing how remnants of the 17–20 m. (18·5 m.) beach are frequently the highest in the series.

of rounded and well-rounded pebbles; in the sample from the 17·7 m. beach, 84 per cent of the pebbles are recognizably rounded or well-rounded. But at an altitude of 18·5 m., only 12 m. away from the 17·7 m. sample, frost splitting has been so effective that the bulk of the pebbles (82 per cent) are angular or sub-angular. Only relatively few rounded or well-rounded pebbles can be seen on the surface, although they are commoner with depth. At 32·7 and 34·2 m., the amount of frost splitting is even more marked. Clearly, there is an important contrast in freshness between the 17·7 m. beach and those at higher altitudes on the same transect.

Thus it appears that the remnants between 17 and 20 m. are the highest fresh beaches over wide areas, notably on Fildes and Byers Peninsulas. Where higher beaches occur at a single locality, a beach at this height is the highest one with a fresh form. Where the underlying rock surface is favourable, the beach has a prominent back slope. These characteristics and the similarity of altitude in adjacent areas suggest that the various remnants were built by the same sea-level at approximately the same time. There is possibly some significance in the fact that the remnants tend to be higher in the west than in the east. On Livingston Island the beach is near 18·5–20 m., whereas on King George Island it tends to be nearer 18 m. (Fig. 26).

Intermediate beaches between 17–20 and 5–7·5 m.

Within this altitudinal range there is a complex pattern of beaches; on Fildes Peninsula there are sometimes five ridges, in English Strait three ridges, on Byers Peninsula often only two ridges, while on points in south-eastern and northern King George Island there are notably few ridges. It is not possible to correlate the beaches in this altitudinal range throughout the islands with any confidence but certain forms seem to be important locally.

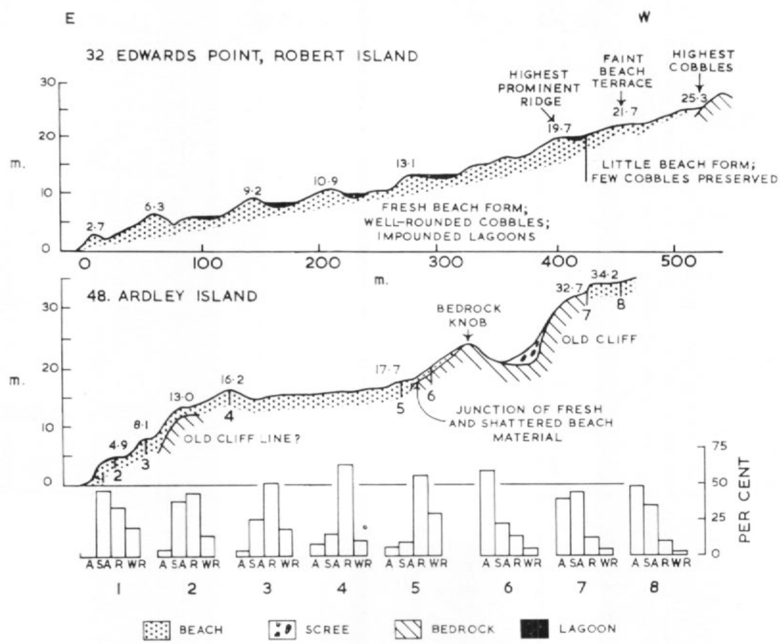

Fig. 32. The contrast in freshness between beaches above and below 17–20 m. on Edwards Point, Robert Island (32), and western Ardley Island (48). On Edwards Point (above) ridges up to an altitude of 19·7 m. are sufficiently fresh to impound lagoons. On western Ardley Island (below) the histograms for roundness (A angular; SA sub-angular; R rounded; WR well rounded) compiled from 50 pebbles taken from each numbered site show a marked contrast in frost-shattering between points 5 and 6. Horizontal scales are the same for both transects.

A beach on western Livingston Island occurs repeatedly between altitudes of 13·4 and 14·4 m. Often it is insignificant but on several transects on Byers Peninsula and on Barnard Point it is a clearly marked ridge (Figs. 23, 31 and 33). A beach ridge or terrace occurs at 12–13 m. on Ash Point, Spark Point and Harmony Point (Fig. 33). On points on the southern coast of King George Island there are occasional ridges at *c.* 12 m. and a series of terraces at *c.* 11·7 m., for example on Turret Point (Fig. 33). The latter generally rest on bedrock platforms and it is difficult to know to what extent they owe their altitude and occurrence to the underlying rock surface. It might be suggested that the beach remnants at 11·7–12 m. on the eastern Island sites and at 13·4–14·4 m. on the western sites constitute one beach whose altitude falls gently eastwards. Though this is possible, it is important to note that a prominent ridge occurs at 13·3 m. on Stranger Point, King George Island, and this could be correlated with the Byers Peninsula beach at the same altitude. Furthermore, a prominent ridge or terrace on Barnard Point and near Johnsons Dock at 11·7 m. appears to have no equivalent on the nearby Byers Peninsula but it could be correlated with the 11·7 m. terraces on King George Island.

On six transects on Byers Peninsula, a beach ridge occurs between altitudes of 8·5 and 9·6 m. (Fig. 33). On the ground it can be traced as a prominent feature and it disappears only where the underlying rock surface gives it no foundation. A beach between 8 and 9·6 m. occurs as a clearly defined ridge on ten transects at localities from Barnard Point to Harmony Point (Fig. 33). Although there seems no reason why these should not represent one beach, the representative on King George Island is not obvious. A series of ridges and terraces occurs on the south-western points between 7·6 and 8·7 m., whereas there are ridges on Fildes Peninsula at *c.* 11 m. and terraces in Admiralty Bay between 9·9 and 10·8 m.

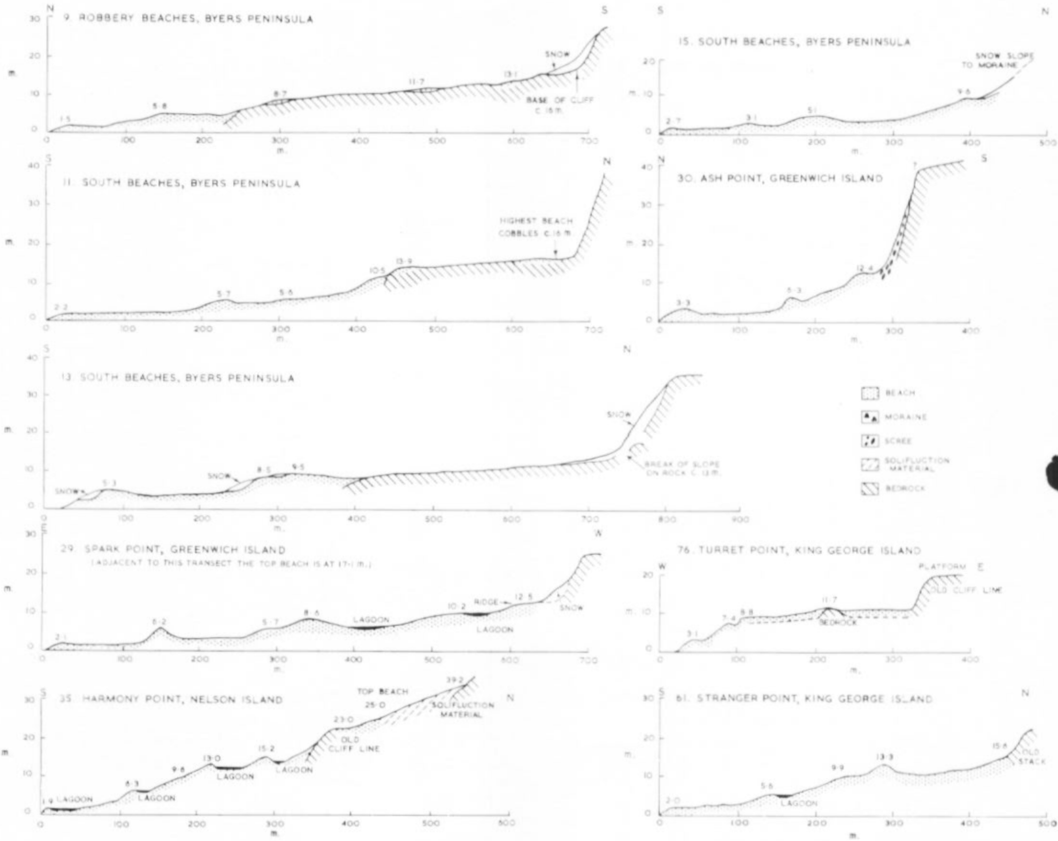

Fig. 33. Profiles of selected raised beach series showing beach ridges at a variety of altitudes below 17–20 m.

Remnants at 5–7·5 m. (6 m. beach) (Fig. 27c)

Beach ridges or extensive terraces at this altitude occur on all but a few points. On Byers Peninsula, no less than nine transects show that a prominent ridge, often with a back slope of 1–2 m., has its summit at 4·8–5·8 m. (Figs. 31 and 33). It is continuous and constant in altitude for a distance of over 8 km. On Barnard Point and around the central islands, 16 transects show that a ridge between 5·3 and 7 m. is prominent and usually the best developed in the series. In addition, four other sites have a well-marked terrace within the same altitudinal range. On points in south-west King George Island, eight transects bring out the presence of prominent ridges with crests between 5·5 and 6·7 m., and six transects reveal the occurrence of equivalent terraces. On Fildes Peninsula, the ridge is generally continuous and distinct, although there are occasional exceptions. The most prominent ridge in Admiralty Bay, sometimes with a back slope approaching 3·6 m., is generally at 5·5–6 m., although on the west side of Keller Peninsula it rises locally to 7·5 m. Prominent ridges occur at 6·4 m. on Penguin Island, at 7 m. on Lions Rump, at 7·4 m. on Turret Point and at 5·8 m. on False Round Point; these are notable features on these barren areas.

The beach remnants described above share several morphological features:

i. In several cases the 5–7·5 m. remnants are clearly fresher in appearance than higher beaches in the same series. For example, on North Spit, Crépin Point, O'Cain Point and Winship Point a 6·1–6·7 m. beach is the highest fresh ridge form. In each case it is backed by an erosional slope cut into older beaches, whose forms are more subdued.

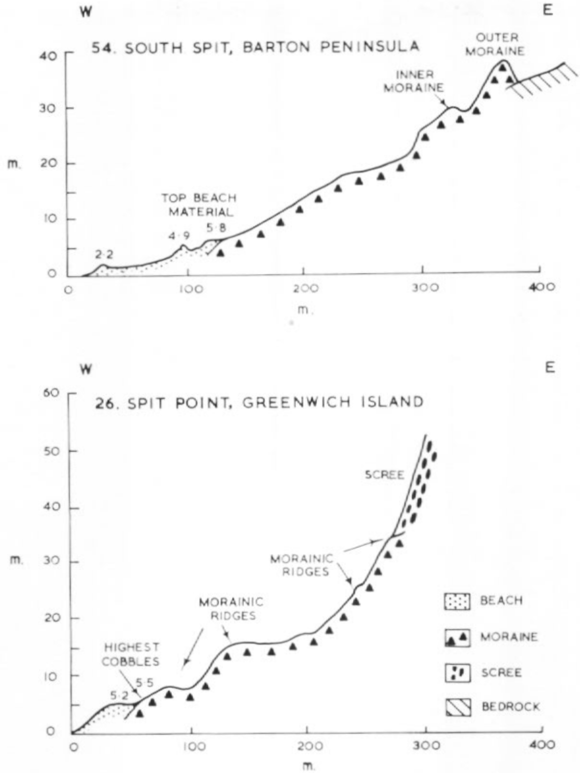

Fig. 34. The highest beaches within lateral valley moraines at 5·5–5·8 m. at South Spit, Barton Peninsula (54) and Spit Point, Greenwich Island (26).

In places the morphological contrast is emphasized further by the degree of frost-heaving. On eastern Fildes Peninsula, at Mitchell Cove and Ash Point, the beaches above *c.* 6 m. are affected by heaving and distinct patterned ground occurs. The ridges at *c.* 6 m. and below are free of any such disturbance. In several of the coves on the western side of Fildes Peninsula, solifluction has all but obliterated beach traces above *c.* 6 m. but the ridge or terrace at this altitude is quite fresh in every case. In other places the contrast may be in the degree of colonization by vegetation or in the degree of splitting of beach cobbles by frost action.

ii. In several areas a lower terrace or ridge occurs on the landward side of the ridge at 5–7·5 m. There are examples on transects at Barnard Point, South Beaches, Spark Point and Edwards Point. This is a significant association, since elsewhere on the transects each successive beach ridge nearer the sea tends to be lower than the one on its landward side.

iii. In troughs on King George Island and in Yankee Harbour, a beach at *c.* 6 m. is associated with valley glacier moraines and is the highest beach within the moraines (Fig. 34).*

* Ferrar (1962) recognized two main series of beaches on the south side of Marian Cove. They comprised a lower series below an altitude of 7·5 m. and an upper series between altitudes of 9·1 and 88 m. They were thought to fall into four main groups and to be related to advances of the King George Island ice cap. However, in spite of a careful search, it was not possible to find any trace of the "upper series". Rather, each of the beaches as mapped by Ferrar correlated with breaks of slope within an area of moraine on the south side of Marian Cove. Some terraces with a surface veneer of striated sub-angular boulders owe their form to the underlying glacially moulded rock surface; some can be related to slump features or to the flattish tops of subsidiary lateral ridges; still others correspond to flats forming parts of old lateral melt-water systems. The impression that each flat was covered with till was confirmed by a series of quantitative tests following Reichelt's method. There is no evidence to suggest the existence of high beaches within the limits of the moraine or to substantiate the interrelated advances of the ice, as previously envisaged.

Typically, behind the back slope or terrace there is an abrupt contrast between beach material and till.

iv. On all of the major islands, beach remnants at 5–7·5 m. were found to be associated with whalebones buried in the surface. It is notable that none was found embedded in any higher beach.

In view of the form, prominence, extensiveness, freshness and distinctive associations of the 6 m. beach, it probably represents one beach. Although the altitudinal range may seem excessive for a single beach, much of this is accounted for by the local high point on west Keller Peninsula which can be attributed to local conditions. Taken as a whole, the beach altitude is remarkably constant throughout the islands. However, it is noticeable that in general the remnants are at *c.* 5 m. in western Livingston Island and at *c.* 6·5 m. in many parts of King George Island, and this may reflect a slight tilt (Fig. 26).

Fig. 35. The 1·8 m. beach occurs at the foot of the ice cliff at the eastern end of South Beaches, Byers Peninsula. There is a similar relation between the ice cliff and the sea on most coasts of the South Shetland Islands.

Beaches below the 6 m. beach

Beaches below *c.* 6 m. seem to comprise two main components at altitudes of approximately 3·4 and 1·8 m. In places, however, there is only one beach, often at an intermediate altitude. Generally, the beaches form ridges as on Round Point or broad terraces with a slight back slope as on South Beaches. The beaches are extensive throughout the island group, occurring on most points. In Admiralty Bay, at Marian Cove and Potter Cove, they extend to within a few metres of the glacier snouts. At several other localities, recent lateral moraines are truncated by both beaches, for example adjacent to Charity Glacier (Fig. 23), and on eastern Ash Point, Lions Rump and north-eastern Byers Peninsula.

The lower 1·8 m. beach is often washed by waves during high tides at the present day. It is interesting to note that for many kilometres this beach truncates the ice domes and weaker outlet glaciers in the islands. Fig. 35 shows how an outlet glacier of Rotch Dome east of Clark Nunatak on Byers Peninsula rests its ice cliff on the beach, and a similar photograph could have been taken almost anywhere on the coasts of Nelson and Robert Islands, western Livingston Island or on the north coasts of Greenwich and King George Islands.

There is evidence to suggest that the 1·8 m. beach is accumulating rapidly in several places. A spectacular example is afforded at Tartar Island off the north coast of King George Island. An aerial photograph taken in 1956 shows that the island was separated from Round Point by a strait 830 m. wide. By January 1966, Tartar Island had become linked to Round Point by a tombolo 75 m. wide at its narrowest point and 300 m. wide at its southern end (Fig. 36).

Fig. 36. View (towards the south) of Round Point, King George Island (background), from Tartar Island in January 1966, showing the recently formed tombolo.

Two main ridges approximately 1·8 m. high are separated by a mass of ice-cored shingle and cobbles reminiscent of the miniature "knob-and-kettle" topography described by Nichols (1964). Brash-ice fragments, which are thick on the present western shore, probably account for the ice core. Similar ice-cored beach deposits occur on Point Hennequin and south-west Barton Peninsula, where beach deposits mingled with brash-ice fragments form a zone 12–15 m. broad trending parallel to the present shore. Since some surface ice fragments only c. 1–2 m. across are preserved in miniature kettleholes 15 m. from the shore, it is clear that deposition must have taken place recently, and almost certainly within the last decade.

Significance of undisturbed raised beaches

The raised beaches round the coasts of the South Shetland Islands resemble the beaches along the present-day shoreline and were formed when sea-level was higher relative to the land. Although smaller beaches may reflect the influence of such small-scale events as individual storms, when taken as a whole the more prominent beaches in the island group appear to fall into several distinct levels and reflect large-scale events. Prominent beaches occur widely throughout the islands and it is reasonable to interpret them as representing stillstands when the positions of land and sea remained approximately similar for some time.

Although there are many dangers in an areal morphological assessment, it is possible to suggest that the prominent and more extensive beaches, such as those at 18·5 and 6 m., represent stillstands of longer duration than those represented by minor beaches. The contrast in freshness above and below the 18·5 m. beach is indicative of a notable difference in age.

Although no absolute dates can be given here, the dissection and poor preservation of beach remnants above the 18·5 m. beach and the modification of their cobbles by frost-action is a reflection of relatively long exposure to weathering and erosion. In marked contrast, the fresher beach forms at *c.* 18·5 m. and the relative lack of modification of the constituent cobbles by frost-action point to a much shorter period of exposure to subaerial weathering. Before the sea finally retreated from the 18·5 m. beach, the beaches at higher altitudes had already been well modified. Similarly, the 6 m. beach is the uppermost of a series of beaches notably fresher than those above. Both the freshness of its form and the lack of subsequent modification by solifluction mark it out clearly as a significant element in the sequence.

This evidence can be interpreted in two different ways. It might be argued that, during a phase of overall sea-level regression, there were merely long stillstands during which these two beaches were formed. Alternatively, it could be suggested that both ridges represent transgressions when sea-level first rose, remained static and then fell relative to the land. It is difficult to find anything conclusive confirming either interpretation, although certain lines of evidence seem to point towards transgressions.

The 18·5 m. beach represents the abrupt upper limit of marine action in a wide variety of sites, and this characteristic has sometimes been used to indicate the existence of a marine transgression, for example, by Sissons (1966) in Scotland. Although this interpretation is not conclusive in the South Shetland Islands, it is strengthened by the detailed form of the beach. On Fildes Peninsula there are no fresh marine deposits inland from the ridge (Fig. 30) and the position of small perched blocks and till patches immediately behind it is evidence that the sea could not have extended farther inland since the till was deposited by ice. It is difficult to understand why a sea-level, which could throw up material to an altitude of 18 m., did not encroach on ground at only *c.* 12 m. immediately behind the ridge. Probably during times when the sea was at a sufficient height to penetrate behind the ridges these areas were covered by ice. It could be argued that the beach ridge was banked up against the ice front, but such a view raises the difficulty of explaining the broad sweep of the ridges which are conformable with the contours of the bays and display no signs of any irregularity due to the position of an ice front; their alignment suggests that the ice was ineffective at the time the beach ridges were built and could not have formed a barrier to the sea. The alternative and more likely explanation is that ice occupied the low areas behind the ridges until a time when relative sea-level had fallen below at least *c.* 12 m. Later, following deglaciation, the sea transgressed over the land, building up a beach ridge at 18 m.

The evidence associated with the 6 m. beach is less conclusive but again it may point to a transgression. Like the 18·5 m. beach, it is the highest beach in many areas and has a prominent back slope whose height is exceeded only by that of the 18·5 m. beach. The existence of a lower flat or ridge immediately behind the main ridge is perhaps comparable to the occurrence of till behind the 18·5 m. ridge. If there was a period of overall regression, it is difficult to understand why the sea should suddenly build up a higher ridge than usual. Perhaps the lower remnant on the landward side is most easily explained if the 6 m. beach is also regarded as marking the limit of a transgression. Possibly, therefore, both the 6 m. beach and the 18·5 m. beach represent marine transgressions.

Relationship of beaches to the positions of ice fronts

The importance of the beach evidence becomes clear when it is linked with the postulated positions of ice fronts during various sea-levels. Bearing in mind the difficulties outlined on p. 84, the distribution of beaches of a certain altitude gives some guide to the extent of the glaciers at the time of their formation, since it can be assumed that beaches will be formed only in ice-free parts of the island group. The South Shetland Islands peninsulas seem to offer a sufficient number of sites suitable for beach remnants to give a reasonably reliable view of glacier fluctuation during the regression. Broadly, the regression of the sea was accompanied by a decrease in the ice-covered area as follows:

54 to 18·5 m. times. All ground above the highest fresh beach in any area bears signs of a cover of ice and reflects a time when the local island ice caps were sufficiently extensive to cover most of the islands. The sites of the highest fresh beaches (*c.* 18·5 to *c.* 54 m.) are those points which one would expect to be first exposed by the withdrawal of the ice. They comprise peninsulas remote from the local centres of the island ice caps, such as south-west Byers Peninsula, Harmony Point and North Foreland, small isolated islands (such as Heywood Island) which could hardly be expected to support an ice cap when awash, and areas of accentuated relief, such as Three Brothers Hill peninsula and Barton Peninsula, which stand on the edge of the steep submarine slope of Bransfield Strait. It seems likely that, as the ice withdrew, relatively high sea-levels established beaches on exposed peninsulas and islands. The distribution of high beaches may have been more widespread than appears at present, for subsequent re-advances of the ice may have destroyed some remnants. However, there is little evidence of this and the fact that successively lower beaches occur on progressively more peninsulas seems to reflect a steady withdrawal of the ice during a period when relative sea-level fell to below 18·5 m.

18·5 m. times. An important phase of deglaciation then occurred, for in 18·5 m. times there were many more areas on which beaches could form, especially Fildes and Byers Peninsulas. In addition, many smaller islands and points and the outer reaches of larger glacial troughs became ice-free at this stage. It is possible that on many sites during 18·5 m. times the ice was no further advanced than it is today; indeed, in places it was less extensive than at present. For example, on Fildes Peninsula the 18·5 m. beach remnant occurs right up to the ice edge and appears to run beneath it at right-angles. The alignment of the ridge shows that the ice must have been less advanced when the beach was built and that, here at least, the ice has subsequently re-advanced. In the valley glacier troughs such as Admiralty Bay the remnants at 17·5 m. on Crépin Point and on the western side of Keller Peninsula, respectively 0·5 and 2·5 km. from the ice front, show that the glaciers were well withdrawn into their respective troughs.

18·5–6 m. times. The beaches lower than *c.* 18·5 m. but higher than 6 m. appear to reflect the further withdrawal of the ice. As a rule, the lower the beach, the more sites there are where it occurs. For example, on gently sloping sites such as Turret Point and Duff Point and at Williams Point the highest prominent beaches have altitudes of 11·7, 8·7 and 8·7 m., respectively, and probably reflect the time when the ice edge first exposed these points. However, it would be unwise to relate the highest beach too closely to the position of retreating ice edges, since in many cases the lack of specific beaches in the altitude range can be shown to be related to the underlying bedrock configuration.

6 m. times. A prominent glacier re-advance stage coincides with the 6 m. beach. The glacier positions can be relatively accurately pinpointed in glacial troughs. In Potter Cove, Marian Cove and Yankee Harbour the moraines lie at the mouths of the troughs. In Marian Cove, the highest beaches within the moraines are at 6·3 m. in the north and 6·7 m. in the south (Fig. 3), while outside they are higher. Cut into the outer flank of the northern moraine is a beach terrace at 11–12 m., but beyond the southern moraine in isolated embayments along a rocky coast beaches occur at a variety of altitudes above 7·7 m., including some as high as 54 m. near Winship Point. On Three Brothers Hill peninsula, the highest beach within the moraines of Potter Cove is 6·7 m., while a few metres south of the moraine is a beach at 8 m.; only 0·5 km. to the south, beaches occur up to an altitude of 41 m. On Keller Peninsula, the moraine where the British station is situated and a morainic ridge midway down the west side of the peninsula due west of Flagstaff Glacier are its representatives (Fig. 37). In both cases beaches within the moraine are at 7·5 m. or lower, while outside they are considerably higher. Since it seems clear that it was not until after 6 m. times that the sea was able to penetrate within the morainic limits and deposit beaches, the glaciers must have been at the site of the terminal moraines in approximately 6 m. times.

There is evidence to suggest that this glacier stage represents an important re-advance of the ice fronts, for in several places fresh marine deposits have been incorporated in the moraines representing the re-advance. For example, in a morainic ridge on the southern shore of Marian Cove (Fig. 3, site A) the following entry in a field book describes the constituent material: "The surface material consists of angular to sub-angular boulders up to 1·5 m. across and a mass of well-rounded, sub-angular and angular smaller stones 10–23 cm. across lying in a sandy clayey matrix." A spot sample showed that marine cobbles formed 10–20 per cent of the stones less than 23 cm. across. Similar exposures occur at low altitudes in north-eastern Yankee Harbour and southern Potter Cove, and together they suggest that the various glaciers have over-ridden beach material during a re-advance.

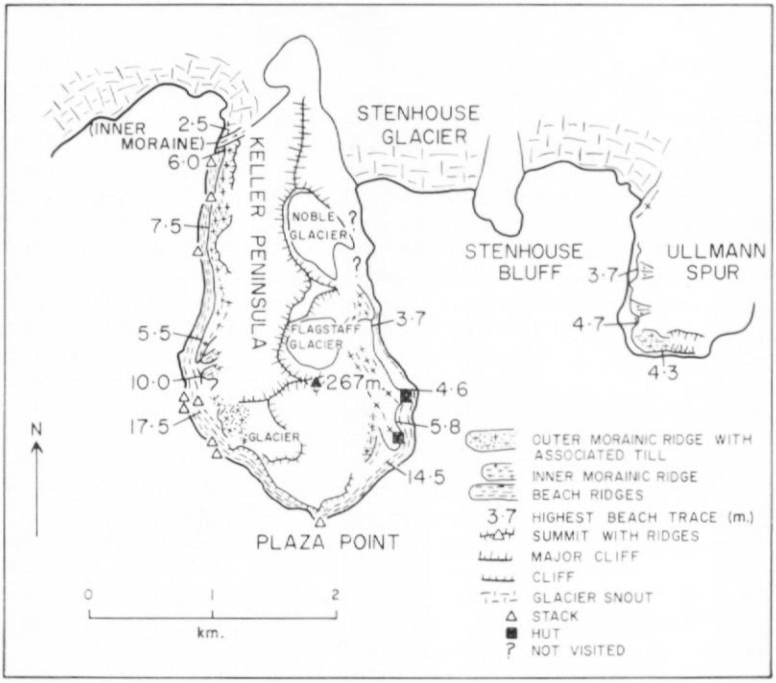

Fig. 37. Morphological map of Keller Peninsula, Admiralty Bay, King George Island, showing the beach altitudes and recent moraines, and illustrating the successively lower beaches within each moraine.

A section in Potter Cove confirmed this view (Fig. 3, site B). On the southern shore of the cove, a few hundred metres west of the Argentine station, a stream has been dammed artificially. A fine section has been cut through a morainic ridge with its surface at 6 m. at the point where the stream escapes round the west end of the dam. The vertical exposure is 2·7 m. in height and it displays marine deposits overlain by till (Fig. 38). At the bottom of the section is a dark silty layer (A) overlain by a sandy layer 0·6 m. thick (B), both bearing marine shells of *Laternula* type. Above this is a 5–8 cm. horizon of iron staining which coincides with a layer of seaweed fragments (C), and which may have been subjected to weathering. Above is a grey beach sand in lenses up to 60 cm. long and 7 cm. wide (D), which are contorted and which preserve complex bedding, suggesting that they are not *in situ* but have been subsequently disturbed. At the top of the section is a layer of till containing a variety of stone sizes and types, including striated cobbles, in a reddish sandy matrix (E). The section suggests that at one stage the sea penetrated well into Potter Cove somewhat above present sea-level, and that marine deposits were laid down during an overall marine regression. After a possible phase of weathering, further marine deposits were laid down, followed by a re-advance of the Potter Cove glacier which modified the upper layers through contortion but left the lower layers unmodified. From the position of the section within the outer re-advance moraines, it can be seen that the glacier re-advanced at least 800 m.

Thus there emerges evidence for an apparently widespread re-advance which reached its peak at approximately the time of the building of the 6 m. beach.

Post–6 m. times. The subsequent story is one of glacier withdrawal during a period of falling sea-level. Further emerging points, no longer protected by ice, were covered with low-lying beach deposits, as for example at Round Point on the north coast of King George Island. More important, the valley glaciers retreated to their approximate present-day positions, for successively lower beaches occur up the troughs. On the north shore of Marian Cove, for example, beaches at *c.* 5·7, 5 and 3·6 m. are each separated by distinct morainic ridges (Fig. 3).

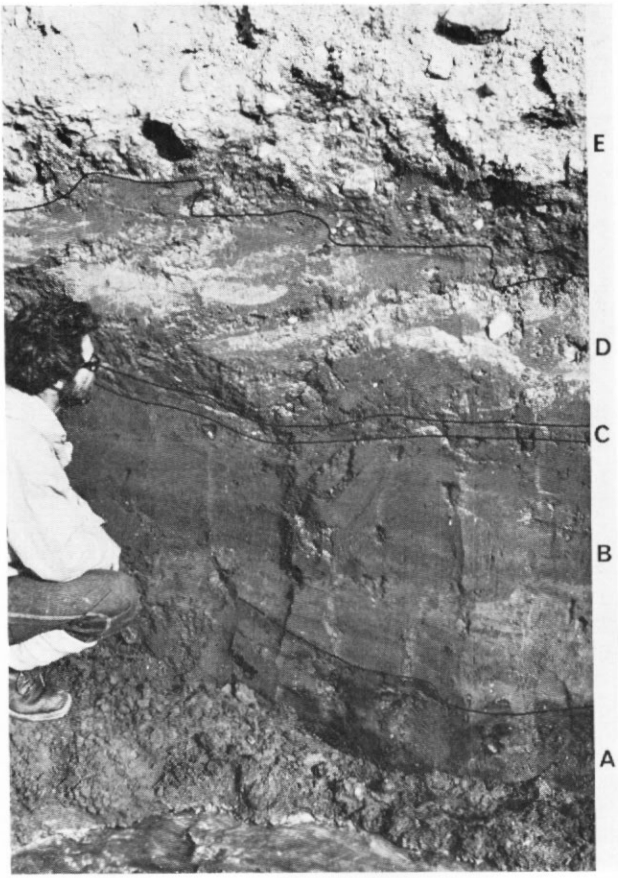

Fig. 38. Till resting on marine deposits at Potter Cove, King George Island.
- A. Shell-bearing silty layer.
- B. Shell-bearing sandy layer 0·6 m. thick.
- C. 5–8 cm. band of iron staining coinciding with seaweed fragments.
- D. Grey beach sand in lenses.
- E. Till with striated stones in reddish sandy matrix.

This section indicates a re-advance of the Potter Cove glacier over marine deposits.

On the south shore distinct moraines are less obvious but a series of transects revealed beaches falling from 5·5 m. in the west to 3·4 m. near the present glacier.

The glacier retreat was at first rapid but it has slowed down in more recent times. An extreme example is "MacKellar Glacier" where, out of a total retreat of 2 km. since 6 m. times it has retreated only 250 m. since the building of a beach at 5·5 m. In other troughs, a 3·4 m. beach occurs close to the glacier front, indicating relatively little glacier retreat at a period when sea-level fell sufficiently far to build the present 1·8 m. beach. For example, in Yankee Harbour the glacier has retreated only *c.* 200 m. since 3·6 m. times out of a total of nearly 1·5 km. since 6 m. times, and in Potter Cove a 4·3 m. beach is only *c.* 150 m. from the ice, whereas the total retreat since 6 m. times has been 1·5 km. There is a similar association where ice domes and weak outlet glaciers terminate on the present seashore. The truncation of lateral moraines immediately adjacent to the ice by the 3–4 m. beach shows that the ice has not withdrawn laterally to any great extent since 3–4 m. times. However, the same moraines show that since 3–4 m. times the ice has thinned by several metres.

There is little indication of present-day trends. The glacier snout positions may be static, for a comparison of the positions of various outlet glacier snouts on aerial photographs taken in 1956–57 with positions in 1965–66 shows no appreciable change in 10 years. Contemporary sea-level movements are less obvious. The extensiveness of the present-day beach could be interpreted as evidence of a stillstand, but the general lack of a prominent beach ridge on the present shore, as opposed to a mere beach flat, may suggest that relative sea-level is falling. The recent build-up of the Tartar Island–Round Point tombolo may also be interpreted in a similar way. This tombolo may not have been able to form until the fall of sea-level presented a rock floor sufficiently shallow for longshore drift material to accumulate.

In summary, it appears that the progressive fall of sea-level relative to the land in the South Shetland Islands has been accompanied by an equivalent withdrawal of the ice caps and associated glaciers. The first peninsulas were exposed during *c.* 54 m. times. There followed a period of overall glacier retreat while sea-level fell to at least 17–20 m. Then a rapid phase of deglaciation, during which the ice front withdrew behind its present-day position in places, was immediately followed by the building of a major beach at *c.* 18·5 m. Probably this represents a transgression. Following a period of further fall in relative sea-level a major beach at *c.* 6 m., possibly representing a transgression, correlates with a widespread valley-glacier re-advance. Further rapid retreat of the glacier snouts to near their present positions was accompanied by a further fall in relative sea-level. While present-day sea-level movements are not known, the glacier snouts have remained static for at least 10 years.

Mode of uplift of undisturbed beach deposits

Since the period of raised beach formation coincides with a phase of deglaciation, it is reasonable to suggest that the elevation of the beaches is due to isostatic recovery initiated by the decrease in weight of overlying ice. However, eustatic movements of sea-level have confused the picture to some extent and it is difficult to determine the significance of any beach purely in terms of isostatic or eustatic movements. Probably, the initial phases of isostatic recovery were rapid, for it is notable that the beach remnants between *c.* 18·5 and 54 m. afford no evidence of significant stillstands. Although this could reflect the paucity of evidence at these altitudes, it is reasonable to suggest that overall isostatic recovery in the South Shetland Islands was initially rapid and similar to trends in other glacierized lands, for example, in East Greenland (Washburn and Stuiver, 1962), Vestspitsbergen (Blake, 1961) and Arctic Canada (Farrand, 1962).

There is more evidence with respect to the 18·5 m. beach where it appears that the building of the beach was broadly contemporaneous with or immediately followed a major acceleration in the process of deglaciation. At such a stage it would be expected that the land was rising isostatically, probably rather rapidly. The evidence of a major stillstand or transgression in 18·5 m. times seems to demand a rapidly rising eustatic surge in sea-level. The existence of such surges even in areas of isostatic uplift has long been accepted. For example, such a view is widely held in Scandinavia following the work of Tanner (1930) and in most instances it can be regarded as proven (Fairbridge, 1961). Furthermore, this view has been increasingly supported by glaciological work which recognizes the possibility that ice may surge forward catastrophically from time to time (Wilson, 1964, 1966; Weertman, 1966). If glacier surges take place on major ice sheets, as in the Antarctic, the effect will be for sea-level to rise abruptly (Hollin, 1964, 1965).

The 6 m. beach probably reflects a different association between sea-level movements and isostatic recovery. It has been shown to coincide with a temporary glacier re-advance during a phase of overall glacier retreat. It is tempting to relate the two occurrences and to suggest that the re-advance of the glaciers was sufficient to slow down or even reverse the process of isostatic recovery to such an extent that it was equalled or overtaken by eustatic movements. Such a view may be criticized on the grounds that it implies the Earth's crust is remarkably sensitive to relatively minor variations in the mass of the overlying glaciers. However, there are several instances where a similar mechanism has been invoked to explain a major stillstand as in the Great Lakes region (Flint, 1957), north and west Iceland (Thorarinsson, 1951), Greenland (Jonsson, 1957; Sugden and John, 1965) and in the Forth Valley in Scotland (Sissons and Smith, 1965).

One problem concerns the speculation that both the 18·5 and 6 m. beaches are tilted, but in opposite directions. In general, the 18·5 m. beach remnants are up to 3 m. higher on western Livingston Island than on King George Island. In the case of the 6 m. beach, remnants on western Livingston Island are 1–2 m. lower than on King George Island. The presence of two beaches at different altitudes tilting in opposite directions may be related to the contrasts in the topography of the islands. Western Livingston Island is an extensive low-lying area, while eastern Livingston, Greenwich and King George Islands are higher in altitude. The first phase of thinning or retreat of the ice which initiated isostatic recovery may have been more complete in areas with low-lying accumulation zones such as western Livingston Island than in the higher more mountainous areas farther east. Isostatic recovery was possibly delayed by the amounts of ice persisting on islands such as King George Island, and this could explain the generally lower altitude of remnants of the 18·5 m. beach in these areas. Following a brief glacial re-advance in 6 m. times, the subsequent retreat of the ice fronts and thinning of the ice caps was rapid and may have had a greater effect on isostatic recovery in areas still bearing extensive glaciers than in those with only a thin or non-existent ice cover. This may account for the generally higher altitudes of the 6 m. beach remnants on King George Island compared with those on western Livingston Island beyond the ice limit. A similar effect on the pattern of isostatic recovery in areas of contrasting ice cover has been noted on west Baffin Island in the Canadian Arctic (Andrews, 1966).

However, when considering any implications, it cannot be emphasized too strongly that these postulated tilts are highly tentative. In the first place, the total amplitude of the tilt is little more than the altitudinal range of 2 m. on one beach ridge on west Keller Peninsula. Secondly, there is not necessarily any significance in the fact that the tilts are parallel to the long axis of the island group, as shown in Fig. 26.

Thus it seems that the fresh beach ridges in the South Shetland Islands reflect the complicated interplay between the extent of glaciation from place to place, the effects of isostatic recovery and eustatic movements of sea-level. Isostatic uplift was probably most rapid during the initial stages of deglaciation and has subsequently been influenced by the amount of ice still remaining on the various islands. Almost certainly a re-advance of the glaciers was sufficient to check uplift and it may have actually reversed the process in 6 m. times. In contrast, the 18·5 m. beach probably reflects an eustatic rise in sea-level of sufficient scale to have dominated isostatic movements.

Significance of the South Shetland Islands Evidence

Landscape evolution

Examination of the distinctive landform groups in the previous sections has provided clues to a complex story of landscape development. Although any reconstruction must be very tentative, it is possible to piece together the evidence in order to propose a simplified sequence of events (Table II).

Pre-glacial events

The earliest events which affected the landscape of the South Shetland Islands are recorded in the stratigraphic column rather than in the islands' morphology. The Basement Complex of the islands and the Carboniferous and Jurassic rocks of King George and Livingston Islands form an elongated core on the flanks of which Tertiary volcanic rocks were extruded. Faulting and crustal deformation occurred at various stages in the geological evolution and the influence of tectonics on the siting of the major centres of volcanic activity may have been responsible for the broad sub-division of the area into uplands and lowlands. During the Tertiary the islands were the scene of phases of volcanic activity and marine inundation. There were outpourings of lava and ash eruptions from volcanic centres, some of which are now preserved in the landscape as volcanic plugs such as Three Brothers Hill and Flat Top Peninsula. The climate appears to have been warmer than at present, since the vegetation record points to a wooded environment (Orlando, 1964; Barton, 1965).*

* This is also indicated by a hitherto unrecorded locality on Dee Island, where fossilized tree trunks and branches are embedded in tuffs.

TABLE II. TENTATIVE RECONSTRUCTION OF LANDSCAPE EVOLUTION IN THE SOUTH SHETLAND ISLANDS

Age		Events	Sea-level relative to the present*	Climate
QUATERNARY	Recent	Glacier retreat; beaches below 6 m.	Falling with fluctuations	Becoming warmer with fluctuations
		Re-advance stage; 6 m. beach (transgression?)		
		Rapid deglaciation; 18·5 m. transgression		
		Onset of deglaciation; beaches up to 54 m.	Higher	
	Pleistocene	**Local glaciation**; expansion of local island ice caps	?	Glacial
		Non-glacial interval; beaches up to 275 m.; retrimming or cutting of minor platforms	At least +275 m.	Becoming cooler?
		Deglaciation; abundance of melt water		Warmer
		Major north-west glaciation(s)	? Lower	Glacial ↑ Onset of glaciation
		Lower platforms cut (Uplift ↑)	At least up to 120 m.	
TERTIARY	Pliocene	Higher surfaces cut; some volcanic activity (Uplift ↑)	Higher fluctuations	Becoming cooler
	Miocene, Oligocene, Eocene	Volcanic activity; basic outlines of islands formed	Fluctuations	Subtropical

* No account is taken of eustatic, isotatic and tectonic movements.

The surfaces and platforms extending from *c.* 275 m. to below sea-level represent stillstands during a time when the South Shetland Islands first emerged from the sea. The geological relationships of the *Pecten* conglomerate at Lions Rump suggest that this probably took place at some stage in the Plio-Pleistocene. Probably the surfaces above 120 m. represent the remnants of original subaerial landscapes developed over a considerable period of time close to sea-level. During uplift they were modified by subaerial erosion, and during sea-level fluctuations some may even have been retrimmed by the sea. The well-developed platforms below 120 m. reflect phases of marine planation at 85–102, 27–50, 11–17 m., close to present sea-level, and at a variety of depths beneath present sea-level. The sequence of cutting is difficult to establish, because in view of the apparent great age of the coastline in the island group, the submarine surfaces may be the oldest. However, above sea-level it appears that as a rule the highest features are the oldest and the lowest ones are the youngest. Apparently, most of the platforms were cut before the north-western glaciation, although it is possible that one or two relatively minor fresh features such as the 11–17 m. platform and low-lying platforms in the glacial troughs were formed later. There is no evidence to indicate that any of the platforms are post-glacial, as suggested by previous workers. They are basically ancient features, some of which may even pre-date the most recent coastal deformation or tilting in the area.

Glacial events

It is not certain when glaciation commenced in the South Shetland Islands, for no datable tillites have been discovered. The identifiable glaciations almost certainly post-date the cutting of the major platforms and thus probably did not commence until some time in the Pleistocene. There are difficulties in deciding how many glacial oscillations there have been in the islands, but there is evidence of at least two distinct glacial phases. At the onset of glaciation there may have been local ice caps on the islands, but it seems that by the time of the glacial maximum a major ice cap had developed with its axis on the submerged platform north of the South Shetland Islands (Fig. 16). The dominant direction of ice movement was transverse to the island group—from the north-west into Bransfield Strait. It is not known whether this main glaciation comprised one or more phases. All that can be said is that there has been profound modification of the platforms by at least one glaciation from the north-west.

The dissolution of the main ice cap may well have been rapid, since the complex melt-water channels of Fildes Peninsula and elsewhere indicate the presence of large volumes of melt water similar to those accompanying the wastage of ice sheets in northern temperate latitudes. Although this evidence suggests a warm climatic interval, its nature is difficult to interpret. It may have been either a full interglacial or simply an interstadial. The residual beaches, which were deposited at some stage after the main glaciation, imply that sea-level was high and that little ice could have existed on the islands at the time. However, it is not certain whether this necessarily implies a climate warmer than that of today.

Following the deposition of the residual beaches, the ice cover expanded again, possibly accompanied by a rapid fall of sea-level. There appears to have been a local expansion of the island ice caps with radial outflow across the peninsulas, which were previously ice-free, and into pre-existing troughs. There was little modification of the landscape, except for the destruction of most of the residual beaches and the deposition of fresh till. The glaciation was probably neither extensive nor prolonged, for the survival of some residual beaches indicates a relatively ineffective ice cover.

Recent events

When the ice of this local glaciation began to waste, sea-level may have been over 54 m. higher relative to the land. At first, few coastal points were exposed to attack by the sea but as isostatic recovery proceeded small beaches were formed on scattered points at a variety of altitudes below *c.* 54 m. Continued deglacierization led to the exposure of still more points to the sea and it seems that throughout this period there may have been a relatively simple relationship between ice wastage and isostatic recovery.

There is no evidence for a recent marine transgression in the South Shetland Islands until the time of the 18·5 m. beach. At this stage there was probably a rapid eustatic rise in sea-level resulting in the development of beach ridges at many coastal localities in the island group. The ice cover of the islands during 18·5 m. times was probably no more extensive than that of today and in some localities it was less extensive.

Following this transgression, a gradual retreat of the ice edge was accompanied by the formation of beaches at even more localities as sea-level fell. At the same time there was modification of higher beach deposits by periglacial processes. When sea-level was below *c.* 6 m. there was a marked re-advance of valley glaciers which over-rode older marine deposits, as at Potter Cove. There was probably an associated transgression of the sea initiated by a pause in isostatic recovery, during which beaches were built up throughout the South Shetland Islands at *c.* 6 m.

The subsequent glacier withdrawal was at first rapid but then more gradual. At the same time the sea fell to approximately its present-day level. Since the building of beaches at *c.* 3 m. there has been little glacier retreat, and today the glacier snouts and ice margins appear to be in a state of equilibrium. Present-day littoral processes are active everywhere and have built some notable beach forms in recent years.

Wider correlations

The evidence from the South Shetland Islands has been considered thus far largely in isolation, in order to construct a reasonable hypothesis of landscape formation. However, the sequence of events proposed here is of only limited value unless it is placed in a wider context by a comparison with events elsewhere. In particular, it is helpful to consider work in other parts of Antarctica and in southern Latin America.

Surfaces and platforms

It seems logical to assume that there is some correlation between the surfaces and platforms of the South Shetland Islands and those in adjacent parts of Antarctica. Linton (1963, 1964) and King (1964) have described some of the characteristics of the uplifted Antarctic Peninsula surface at an altitude of 460–1,830 m. The former writer gave excellent illustrations of the pre-glacial landscape, and he estimated that local relief on the uplifted surface must have been about 450 m. The fringing islands of the Antarctic Peninsula have also received some attention: King (1964) referred to the high-level plateau with residuals rising to 2,440 m. on Alexander Island, while Dewar (1967) described "planed surfaces" at 1,500–1,800, 730–990 m. and below sea-level on Adelaide Island. At the northern tip of the Antarctic Peninsula, Nelson (1966) referred to "erosional steps" at *c.* 152 m. on James Ross Island, and Bibby (1965) to "levels", "flats" and "platforms" at several altitudes on the James Ross Island group. Adie (1964*b*) referred to platforms at a variety of altitudes in the South Orkney Islands and elsewhere, and the writers have observed fine platforms on South Georgia. For example, they occur in the Jason Island–Busen Point area, and at Morse Point and Right Whale Bay.

There is little obvious correlation between the absolute altitudes of the platforms and surfaces in the South Shetland Islands and those in adjacent parts of Antarctica. While occasional platforms such as the one at *c.* 150 m. occur on both sides of Bransfield Strait, it is perhaps more significant that prominent South Shetland Islands platforms, such as the one at 27–50 m., do not appear to have obvious correlatives in adjacent parts of Antarctica.

Glaciation

Evidence has been cited for a more extensive cover of ice at a time when an ice mass of considerable proportions lay north-west of the South Shetland Islands. This evidence is paralleled in many parts of Antarctica for it has long been realized that in the past the Antarctic ice sheet was thicker and more extensive than at present (Gould, 1940; Nichols, 1953; Swithinbank, 1959; Mercer, 1962; Van Autenboer, 1964; Trail, 1964; Voronov, 1964; Worsfold, 1967; Denton and Armstrong, 1968). Indeed there is sufficient evidence for Hollin (1962) and Voronov (1965) to have attempted estimates of the extra amount of ice in Antarctica during its maximum extent.

There is evidence that the phase of more extensive glaciation in the South Shetland Islands was responsible for the bulk of glacial erosion and that it was separated from the subsequent minor glaciation by a phase when almost no ice could have existed in the islands. This evidence of two distinct phases of glaciation is compatible with that elsewhere in Antarctica and in South America. Much has been written on the subject of multiple glaciation in the McMurdo Sound area of Antarctica and at least four phases of glaciation have been recognized (Péwé, 1958, 1960; Nichols, 1961; Angino and others, 1962; Bull, 1962; Bull and others, 1962). However, there seems to have been a loose usage of the terms "glacial" and "interglacial", and it is difficult to evaluate the relative significance of the various phases. Possibly, the later stages represent relatively minor fluctuations (Black and Berg, 1964). Moreover, Calkin (1964*a*, *b*) has suggested that there is good evidence for only two glaciations. During the earlier major glaciation the west–east troughs of Victoria Land were cut by major outlet glaciers pouring from the main Antarctic ice sheet. Subsequent less extensive glaciation was responsible for a succession of moraines in the troughs. It is the latter moraines that have previously been attributed to full glaciations (Péwé, 1960). Calkin's interpretation of the sequence of events in McMurdo Sound is in close agreement with the South Shetland Islands evidence.

Across Drake Passage there is widespread evidence for a similar pattern of glaciation in Fuego–Patagonia. On the eastern side of the Andes there are clear signs of an extensive weathered till and a fresh till of more restricted distribution. Where both tills occur in the same vertical section, they are often separated from each other by peat layers, suggesting the occurrence of a major glaciation separated by an interglacial from a smaller glaciation (Feruglio, 1944–45; Ljungner, 1949; Auer, 1951, 1960; Flint, 1957). This is comparable to the South Shetland Islands evidence. But in no area is there clear evidence that the earlier extensive glaciation was necessarily represented by only one maximum. It could equally well represent several separate phases of glaciation with similar characteristics which are difficult to recognize at this stage.

Although two distinct phases of glaciation can be recognized in Antarctica and South America, it is more difficult to correlate the interval between them. This reflects the ambiguity of some of the evidence not only in the South Shetland Islands but also elsewhere. In eastern Antarctica, in the McMurdo Sound area, a number of "interglacial" features have been recognized (Nichols, 1965); but many of these could be associated with the minor fluctuations of the last major phase of glaciation, and some may not even be as old as this (Gibson, 1962). Elsewhere in Antarctica there is evidence for a warmer period which may be comparable to the South Shetland Islands interval. Smith (1967) has described a labyrinth of anastomosing rock channels in Wright Valley cut many metres into solid dolerite. These channels have no systematic gradient and there are often basins 76 m. deep. Their pattern is remarkably similar to the rock channels on Fildes Peninsula and it seems that only melt-water activity could have been responsible for their excavation. From his studies on the roundness and size of particles in sands and gravels in Victoria Valley, Cailleux (1962) concluded that at one stage in the Quaternary there was more abundant melt water than today. Both of these findings seem to indicate a warmer climatic fluctuation. In addition, Schytt (1961) argued for a warmer, wetter climatic fluctuation at least in the margins of Antarctica, when much of the widespread relict patterned ground was formed.

It is difficult to find a basis for comparison of the South Shetland Islands non-glacial interval with any phase in Fuego–Patagonia. At first it might be tempting to relate it to the major interglacial in Fuego–Patagonia, but there are inconsistencies. For example, the South American evidence points to a long period of weathering separating the two glaciations. In the South Shetland Islands there is no evidence of a comparable period of weathering; in fact, the freshness of the beaches suggests the opposite conclusion. Clearly there is no basis for such a correlation at this stage.

Although the two phases of glaciation recognized in the South Shetland Islands have parallels in other parts of Antarctica and Fuego–Patagonia, the absence of positive correlations makes it impossible to give even approximate ages to either.

Raised beaches and associated glacier fluctuations

There is more detailed evidence of events subsequent to the maximum of the last glaciation both in the South Shetland Islands and adjacent landmasses. Raised beaches have been recognized widely in the Antarctic Peninsula area. Bibby (1965) has described beaches up to 24 m. on James Ross Island, while Fleming (1940) and Nichols (1947) recorded beaches up to 21–24 m. in the Marguerite Bay area. Nichols (1960) recorded occasional higher beaches, including one at 33·5 m. on Red Rock Ridge, the highest in the Marguerite Bay area. The writers visited Marguerite Bay briefly and undertook three rapid abney-level transects on Jenny, Neny and Stonington Islands. Although these can provide no more than an approximate basis for a comparison, it is notable that they show a striking similarity with the main features of the South Shetland Islands beaches. A beach at *c.* 6·7 m. marks a significant break in freshness between those beaches above and those below this altitude. On eastern Neny Island, where it forms the break of slope between a lower terrace and a slope eroded into higher beach deposits, it is identical in form and altitude to many features related to the major 5–7·5 m. beach in the South Shetland Islands. On western Jenny Island there is a further significant beach at 18 m. A field record for this area is as follows: "The 18 m. ridge is the best developed in the series and has a 1 m. backslope . . . There is a marked contrast between the beaches below and above 18 m.; above there is less rounding, more lichen cover and more shattering." Such a description would fit many beaches at 17–20 m. in the South Shetland Islands. On Stonington Island, beaches were recorded up to an altitude of *c.* 15 m. as described by Fraser (1965). Their position only a few metres from the active snout of Northeast Glacier resembles the situation on Fildes Peninsula, where an 18 m. ridge extends right up to the ice edge. On Neny and Jenny Islands, beaches which would be described as undisturbed beach ridges in the South Shetland Islands occur up to heights of *c.* 23 m. (masked by snow and scree) and 24·5 m., respectively. Above this, at least up to 58 m. on Jenny Island, is an interesting deposit of beach material incorporated in a solifluction fan, but its significance was not clear during the authors' hurried visit.

The correlation between the tentative observations in Marguerite Bay and those in the South Shetland Islands is remarkable, especially on the beaches below *c.* 18 m. Although there is far too little evidence to be other than tentative, it seems possible that the beaches in the two areas represent a similar pattern of deglaciation and isostatic response.

The further afield one goes the less obvious is the correlation between beaches. Summaries of beach altitudes around the coasts of Antarctica have been given by Nichols (1960, 1964) and Yevteyev (1962) but the latter's list also seems to include platforms. Generally, it appears that beach deposits occur up to an altitude of *c.* 30 m. on sites around much of the coast of Antarctica, although possible beaches occur at higher levels (Nichols, 1960). The highest studied by Nichols (1964) (at Dunlop Island, Marble Point and Cape Roberts) are at *c.* 20·5 m. and represent the marine limit at these points. All of these beaches post-date the youngest glaciation recognized in Wright Valley. On Kronprins Olav Kyst the highest recorded elevated shoreline post-dating the recent ice witdrawal occurs at 20 m. on the Ongul Islands and Langhovde, and at 30 m. on Shinnan iwa (Meguro and others, 1964). Although there are few grounds for comparison at this stage, it seems likely that the undisturbed raised beaches in the South Shetland Islands are comparable to those below *c.* 30 m. around the coast of continental Antarctica. Probably all of these beaches represent isostatic recovery accompanying a phase of overall deglaciation, at least round the periphery of Antarctica.

Little can be said regarding a comparison of the South Shetland Islands beaches with those of Fuego–Patagonia. Auer (1960) recognized beaches at 25, 22, 18, 15, 9 and 6 m. Their order of altitude is broadly comparable to that of the South Shetland Islands but this could be sheer coincidence.

As yet it has not been possible to date sufficient organic material found in the lower beaches of the South Shetland Islands to obtain a reliable estimate of their age, and thus of related glacier movements. However, in due course it is planned to supplement this paper with ^{14}C age determinations. In the meantime it is useful to consider ^{14}C dates elsewhere which might give a broad idea of beach ages. Cameron and Goldthwait (1961) have given a ^{14}C date of 6,040$\pm$250 yr. B.P. for algae in a lake on a 23 m. terrace in the Windmill Islands. Nichols (1964) found a seal carcass embedded in a 13·5 m. beach in McMurdo Sound and this was dated at 4,600$\pm$200 yr. B.P. Tentatively, he considered that the highest beaches in the area are *c.* 7,000 yr. old. This is broadly confirmed by Black and Berg (1964) who considered, on the basis of dating by patterned ground, that general deglaciation occurred in Victoria Land perhaps less than 10,000 yr. ago.

This pattern is generally in agreement with that of Fuego–Patagonia. On the basis of previous correlations and ^{14}C dates on peat and interdigitated volcanic ash layers, Auer (1956, 1958, 1960) considered that the deglaciation chronology is similar to Europe and he has accepted a date of *c.* 9,000 yr. B.P. as the start of post-glacial conditions. A similar conclusion has been reached by Mercer (1965), who radiocarbon dated recent moraines in southern Patagonia. He noted glacier advances dated at 3,600 and *c.* 2,300 yr. B.P., and correlated the latter with the sub-Atlantic re-advances in New Zealand, West Greenland, Sweden, Iceland and the European Alps.

It seems likely that the fresh beach ridges in the South Shetland Islands which have accompanied recent deglaciation are of a broadly comparable age to those elsewhere in Antarctica and South America. Probably the majority of them formed during the last 10,000 yr., although the higher ones may be slightly older. There is no reliable way of dating either the eustatic 18·5 m. transgression or the glacier re-advance associated with the stillstand of *c.* 6 m. until ^{14}C dates are available. According to Fairbridge (1961), rapid eustatic rises in sea-level occurred *c*. 10,000, 8,600, 5,300 and 3,800 yr. B.P. Any of these surges might account for the 18·5 m. beach but it is more likely to belong to one of the middle surges. The glacial advance of 6 m. times may correlate with one of the Patagonian re-advances of 3,600 or 2,300 yr. B.P.; perhaps it is even more recent.

Some implications and problems

It would be misleading to conclude a paper on the interpretation of the landscape of the South Shetland Islands without acknowledging the many problems and implications which have emerged. Of these, the following seem to merit particular mention.

Pecten conglomerate. The dating of the surfaces in the South Shetland Islands depends largely on the correct interpretation of the Pliocene *Pecten* conglomerate at Lions Rump, for the cutting of the surface across a sequence of volcanic rocks interbedded with the conglomerate defines a maximum age for the surfaces as Pliocene. However, certain crucial questions remain to be answered. Is the conglomerate truly interbedded with the volcanic rocks? If so, what is the relationship of the *Pecten*-bearing sandstone found in moraines at a higher altitude? Furthermore, what is the relationship, if any, between the Lions Rump conglomerate and the marine conglomerates that occur on platforms on Byers Peninsula and e Island?

Horizontality of platforms below 120 m. The platforms below 120 m. in the South Shetland Islands are remarkably horizontal throughout the island group over a distance of *c*. 250 km. This degree of horizontality might appear to confirm the hypothesis that the platforms were cut by eustatic fluctuations in sea-level. According to this hypothesis, high Pleistocene sea-levels related to interglacial stages might have cut the platforms during periods of stillstands. However, no evidence has been found in support of such a view and the indications that the platforms pre-date the glaciations discovered would seem to preclude this possibility. In spite of their horizontality, the elevation of the platforms has been attributed largely to tectonic uplift. In this context it is interesting to note Cooke's (1965) views on the horizontal shorelines at or below 110 m. between Carriyal Bajo and La Serena in Chile. He has suggested that, if a platform series lies on a coastline parallel to an axis of tectonic uplift, it is theoretically possible for horizontal platforms to be raised without any longitudinal warping as long as the coastline forms part of a relatively stable block. If tectonic uplift in the South Shetland Islands paralleled the island group's structural axis, the platforms may have been elevated without warping. Clearly, there are arguments for both of these interpretations and it will probably be found that both processes played a part in the explanation of the height and horizontality of the South Shetland Islands platforms.

Selectivity of glacial erosion. The remarkable feature of the South Shetland Islands landscape is the preservation of landforms which pre-date both phases of glaciation for which there is evidence. Almost everywhere there are flights of surfaces and platforms, some bearing fragile stacks which have survived a major glaciation from the north-west as well as smaller local glaciations. Glacial erosion appears to have been highly selective; evidence of major transformation of the landscape seems to be limited to the serrated mountains of eastern Livingston and Greenwich Islands, and the various troughs cut into the flanks of the South Shetland Islands block. Even these troughs have apparently been incised into already existing depressions.

Nature of the interval represented by residual beaches. It has been suggested that the residual beaches represent a non-glacial interval between two phases of glaciation. It is impossible to infer whether they reflect a minor climatic fluctuation on the periphery of Antarctica or a full interglacial. Furthermore, the possible role of tectonics in explaining their altitude is unknown. Clearly, more detailed and extensive evidence is required to explain the true significance of these high beaches.

Horizontality of the raised beaches. The undisturbed raised beaches in the South Shetland Islands are here attributed to isostatic recovery accompanying or following deglaciation. In spite of possible slight tilts, the impression is that the elevation of the beaches has been remarkably uniform throughout the island group over a distance of *c*. 250 km. If the tentative conclusions drawn from the few Marguerite Bay beaches visited are correct, the recent elevation has been uniform in two localities 700 km. apart. Even if one suggests that the amount of ice throughout the areas visited was formerly similar, it seems a remarkable coincidence that the extent of isostatic response to deglacierization in widely separated regions has been identical. This is especially so in view of the evidence suggesting that relatively minor fluctuations in the mass of overlying ice can influence the rate and amount of isostatic uplift. Indeed, the occurrence of similarly horizontal shorelines in Tierra del Fuego and Patagonia has been used by Auer (1960) to rule out the possibility of isostatic recovery. Although the authors would not go so far, they admit that on this matter, as on many others, they remain puzzled.

ACKNOWLEDGEMENTS

The work on which this paper is based was undertaken while we were in the employ of the British Antarctic Survey in 1965–66. We are grateful to the Survey for supporting the project both in the planning stages and in the field. We are especially indebted to Dr. R. J. Adie for his encouragement and help throughout the course of the work, and to Professor F. W. Shotton for making available the facilities of the Department of Geology, University of Birmingham. Captain D. H. Turnbull (R.R.S. *Shackleton*), Captain T. Woodfield (R.R.S. *John Biscoe*) and Captain K. Sandford (H.M.S. *Protector*), and respective crew members are warmly thanked for their energetic logistic support in the field.

Many other people have assisted in innumerable ways and to all we offer our sincere thanks. In particular, we thank the following: Professor K. M. Clayton, Dr. N. Stephens and Dr. C. M. Clapperton for reading early drafts of the text and for making many constructive comments; Professor D. L. Linton and Dr. C. W. M. Swithinbank for helpful discussion at all stages; and Professor K. Walton and Professor W. B. Fisher for use of facilities at the Department of Geography, University of Aberdeen and the Department of Geography, University of Durham, respectively.

MS. received 9 July 1968

REFERENCES

ADIE, R. J. 1953. New evidence of sea-level changes in the Falkland Islands. *Falkland Islands Dependencies Survey Scientific Reports*, No. 9, 8 pp.

———. 1964*a*. Geological history. (*In* PRIESTLEY, R. E., ADIE, R. J. *and* G. DE Q. ROBIN, *ed. Antarctic research*. London, Butterworth and Co. (Publishers) Ltd., 118–62.)

———. 1964*b*. Sea-level changes in the Scotia arc and Graham Land. (*In* ADIE, R. J., *ed. Antarctic geology*. Amsterdam, North-Holland Publishing Company, 27–32.)

ANDERSSON, J. G. 1906. On the geology of Graham Land. *Bull. geol. Instn Univ. Upsala*, **7**, 19–71.

ANDREWS, J. T. 1966. Pattern of coastal uplift and deglacierization, west Baffin Island, N.W.T. *Geogrl Bull., Ottawa*, **8**, No. 2, 174–93.

ANGINO, E. E., TURNER, M. D. *and* E. J. ZELLER. 1962. Reconnaissance geology of Lower Taylor Valley, Victoria Land, Antarctica. *Geol. Soc. Am. Bull.*, **73**, No. 12, 1553–61.

AUER, V. 1951. Preliminary results of studies on the Quaternary geology of Argentine. *Suomal. Tiedeakat. Toim.*, Ser. A.III, No. 25, 12 pp.

———. 1956. The Pleistocene of Fuego–Patagonia. Part I: The ice and interglacial ages. *Suomal. Tiedeakat. Toim.*, Ser. A.III, No. 45, 226 pp.

———. 1958. The Pleistocene of Fuego–Patagonia. Part II: The history of the flora and vegetation. *Suomal. Tiedeakat. Toim.*, Ser. A.III, No. 50, 239 pp.

———. 1960. The Quaternary history of Fuego–Patagonia. *Proc. R. Soc.*, Ser. B, **152**, 507–16.

AUTENBOER, T. VAN. 1964. The geomorphology and glacial geology of the Sør-Rondane, Dronning Maud Land. (*In* ADIE, R. J., *ed. Antarctic geology*. Amsterdam, North-Holland Publishing Company, 81–103.)

BARTON, C. M. 1965. The geology of the South Shetland Islands: III. The stratigraphy of King George Island. *British Antarctic Survey Scientific Reports*, No. 44, 33 pp.

BIBBY, J. S. 1961. The geology of Ezcurra Inlet and Point Thomas, Admiralty Bay, King George Island, South Shetland Islands. *Falkland Islands Dependencies Survey Preliminary Geological Report*, No. 8, 10 pp. [Unpublished.]

———. 1965. Some observations on sea-level changes in the James Ross Island group. *British Antarctic Survey Bulletin*, No. 6, 67–75.

BLACK, R. F. *and* T. E. BERG. 1964. Glacier fluctuations recorded by patterned ground, Victoria Land. (*In* ADIE, R. J., *ed. Antarctic geology*. Amsterdam, North-Holland Publishing Company, 107–22.)

BLAKE, W. 1961. Radiocarbon dating of raised beaches in Nordaustlandet, Spitsbergen. (*In* RAASCH, G. O., *ed. Geology of the Arctic. Proceedings of the first international symposium on Arctic geology, Calgary, 1960*. Toronto, University of Toronto Press, Vol. 1, 133–45.)

Bryan, R. B. 1965. Observations on snow accumulation patterns at Adelaide Island. *British Antarctic Survey Bulletin*, No. 6, 51–62.

Bull, C. 1962. Quaternary glaciations in southern Victoria Land, Antarctica. *J. Glaciol.*, **4**, No. 32, 240–41.

———., McKelvey, B. C. *and* P. N. Webb. 1962. Quaternary glaciations in southern Victoria Land, Antarctica. *J. Glaciol.*, **4**, No. 31, 63–78.

Cailleux, A. 1962. Étude de géologie au détroit de McMurdo (Antarctique). *Comité National Française Recherches Antarctiques*, No. 1, 41 pp.

Calkin, P. E. 1964*a*. Geomorphology and glacial geology of the Victoria Valley system, southern Victoria Land, Antarctica. *Rep. Inst. polar Stud. Ohio State Univ.*, No. 10, 66 pp.

———. 1964*b*. Glacial geology of the Mount Gran area, southern Victoria Land, Antarctica. *Geol. Soc. Am. Bull.*, **75**, No. 10, 1031–36.

Cameron, R. L. *and* R. P. Goldthwait. 1961. The US–IGY contribution to Antarctic glaciology. *Gen. Assembly int. Un. Geod. Geophys., Helsinki, 1960. Colloque sur la glaciologie antarctique*, 7–13.

Cooke, R. 1965. High stands of Quaternary sea level along the Chilean coast. Part 3. Evidence of changing sea level between lat. 28° and 30°S. during Quaternary time. (*In* Fuenzalida, H. *and others*. *Spec. Pap. geol. Soc. Am.*, No. 84, 482–89.)

Dalziel, I. W. D. 1969. Structural studies in the Scotia arc: Livingston Island. *Antarct. Jnl U.S.*, **4**, No. 4, 137.

Davies, J. L. 1964. A morphogenic approach to world shorelines. *Z. Geomorph.*, **8** (sonderheft), 127*–42*.

Denton, G. H. *and* R. L. Armstrong. 1968. Glacial geology and chronology of the McMurdo Sound region. *Antarct. Jnl U.S.*, **3**, No. 4, 99–101.

Dewar, G. J. 1967. Some aspects of the topography and glacierization of Adelaide Island. *British Antarctic Survey Bulletin*, No. 11, 37–47.

Fairbridge, R. W. 1961. Eustatic changes in sea level. (*In* Ahrens, L. H., Press, F., Rankama, K. *and* S. K. Runcorn, *ed. Physics and chemistry of the Earth*, **4**. London, Oxford, New York, Paris, Pergamon Press, 99–185.)

Farrand, W. R. 1962. Postglacial uplift in North America. *Am. J. Sci.*, **260**, No. 3, 181–99.

Ferrar, J. E. 1962. The raised beaches of the Noel Hill peninsula, King George Island, South Shetland Islands. *British Antarctic Survey Preliminary Geological Report*, No. 13, 12 pp. [Unpublished.]

Feruglio, E. 1944–45. Estudios geológicos y glaciológicos en la region del Lago Argentina (Patagonia). *Bol. Acad. nac. Cienc. Cordoba*, **37**, 1–208.

Fleming, W. L. S. 1940. Relic glacial forms on the western seaboard of Graham Land. *Geogrl J.*, **96**, No. 2, 93–100.

Flemming, N. C. 1965. Form and relation to present sea level of Pleistocene marine erosion features. *J. Geol.*, **73**, No. 5, 799–811.

Flint, R. F. 1957. *Glacial and Pleistocene geology*. New York, John Wiley and Sons.

Fraser, A. G. 1965. The petrology of Stonington and Trepassey Islands, Marguerite Bay. *British Antarctic Survey Scientific Reports*, No. 52, 51 pp.

Fuenzalida, H., Cooke, R., Paskoff, R., Segerstrom, K. *and* W. Weischet. 1965. High stands of Quaternary sea level along the Chilean coast. (*In* Wright, H. E. *and* D. G. Frey, *ed*. International studies on the Quaternary. Papers prepared on the occasion of VII Congress of the International Association for Quaternary Research, Boulder, Colorado, 1965. *Spec. Pap. geol. Soc. Am.*, No. 84, 473–96.)

Gibson, G. W. 1962. Geological investigations in southern Victoria Land, Antarctica. Pt. 8. Evaporite salts in the Victoria Valley region. *N.Z. Jl Geol. Geophys.*, **5**, No. 3, 361–74.

Gjessing, J. 1960. Isavsmeltningstidens drenering, dens forløp og formdannende virkning i Nordre Atnedalen. Med sammenlignende studier fra Nordre Gudbrandsdalen og Nordre Østerdalen. *Skr. norske geogr. Selsk., Ad Novas*, Nr. 3, 492 pp.

Gould, L. M. 1940. The glacial geology of the Pacific Antarctic. *Proc. 6th Pacif. Sci. Congr., 1939*, **2**, 723–40.

Griffiths, D. H., Riddihough, R. P., Cameron, H. A. D. *and* P. Kennett. 1964. Geophysical investigation of the Scotia arc. *British Antarctic Survey Scientific Reports*, No. 46, 43 pp.

Hattersley-Smith, G. 1949. King George Island glaciological report for 1948–49. [Unpublished.]

Hawkes, D. D. 1961. The geology of the South Shetland Islands: I. The petrology of King George Island. *Falkland Islands Dependencies Survey Scientific Reports*, No. 26, 28 pp.

Hobbs, G. J. 1959. The geology of Livingston Island. *Falkland Islands Dependencies Survey Preliminary Geological Report*, No. 3, 17 pp. [Unpublished.]

———. 1962. *The geology of Livingston Island, South Shetland Islands, west Antarctica*. M.Sc. thesis, University of Birmingham, 116 pp. [Unpublished.]

———. 1968. The geology of the South Shetland Islands: IV. The geology of Livingston Island. *British Antarctic Survey Scientific Reports*, No. 47, 34 pp.

Hollin, J. T. 1962. On the glacial history of Antarctica. *J. Glaciol.*, **4**, No. 32, 173–95.

———. 1964. Origin of ice ages: an ice shelf theory for Pleistocene glaciation. *Nature, Lond.*, **202**, No. 4937, 1099–100.

———. 1965. Wilson's theory of ice ages. *Nature, Lond.*, **208**, No. 5005, 12–16.

Holtedahl, O. 1929. On the geology and physiography of some Antarctic and sub-Antarctic islands. *Scient. Results Norw. Antarct. Exped.*, No. 3, 172 pp.

Jonsson, J. 1957. The Hoffellssandur—a glacial outwash plain. Part III. Notes on changes of sea-level in Iceland. *Geogr. Annlr*, **39**, Nos. 2–3, 143–212.

Kapitsa, A. P. 1964. Dependence of the form of the east Antarctic ice cap upon bottom topography and character of ice flow. (*In Soviet Antarctic Expedition Information Bulletin*, *Vol. I*. Amsterdam, London, New York, Elsevier Publishing Company, 25–29. [No. 1, 1958.])

KING, C. A. M. 1963. Some problems concerning marine planation and the formation of erosion surfaces. *Trans. Inst. Br. Geogr.*, No. 33, 29–43.

KING, L. 1964. Pre-glacial geomorphology of Alexander Island. (*In* ADIE, R. J., *ed. Antarctic geology*. Amsterdam, North-Holland Publishing Company, 53–64.)

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

LAMB, H. H. 1964. Circulation of the atmosphere. (*In* PRIESTLEY, R. E., ADIE, R. J. *and* G. DE Q. ROBIN, *ed. Antarctic research*. London, Butterworth and Co. (Publishers) Ltd., 265–77.)

LINTON, D. L. 1957. Radiating valleys in glaciated lands. *Tijdschr. K. ned. aardrijksk. Genoot.*, **74**, No. 3, 297–313.

———. 1963. Some contrasts in landscapes in British Antarctic Territory. *Geogrl J.*, **129**, Pt. 3, 274–82.

———. 1964. Landscape evolution. (*In* PRIESTLEY, R. E., ADIE, R. J. *and* G. DE Q. ROBIN, *ed. Antarctic research*. London, Butterworth and Co. (Publishers) Ltd., 85–99.)

LJUNGNER, E. 1949. East–west balance of the Quaternary ice caps in Patagonia and Scandinavia. *Bull. geol. Instn Univ. Upsala*, **33**, 11–96.

MEGURO, H., YOSHIDA, Y., UCHIO, T., KIGOSHI, K. *and* K. SUGAWARA. 1964. Quaternary marine sediments and their geological dates with reference to the geomorphology of Kronprins Olav Kyst. (*In* ADIE, R. J., *ed. Antarctic geology*. Amsterdam, North-Holland Publishing Company, 73–79.)

MERCER, J. H. 1962. Glacier variations in the Antarctic. *Glaciol. Notes*, No. 11, 5–29.

———. 1965. Glacier variations in southern Patagonia. *Geogrl Rev.*, **55**, No. 3, 390–413.

NELSON, P. H. H. 1966. The James Ross Island Volcanic Group of north-east Graham Land. *British Antarctic Survey Scientific Reports*, No. 54, 62 pp.

NICHOLS, R. L. 1947. Elevated beaches of Marguerite Bay, Antarctica. *Bull. geol. Soc. Am.*, **58**, No. 12, 12[illegible]

———. 1953. *Geomorphology of Marguerite Bay, Palmer Peninsula, Antarctica*. Washington, D.C., Department of the Navy, Office of Naval Research. [Ronne Antarctic Research Expedition, Technical Report, No. 12.]

———. 1960. Geomorphology of the Marguerite Bay area, Palmer Peninsula, Antarctica. *Bull. geol. Soc. Am.*, **71**, No. 10, 1421–50.

———. 1961. Multiple glaciation in the Wright Valley, McMurdo Sound, Antarctica. *Abstracts of Symposium Papers, Tenth Pacif. Sci. Congr., Honolulu*, 317.

———. 1964. Present status of Antarctic glacial geology. (*In* ADIE, R. J., *ed. Antarctic geology*. Amsterdam, North-Holland Publishing Company, 123–35.)

———. 1965. Antarctic interglacial features. *J. Glaciol.*, **5**, No. 40, 433–49.

ORLANDO, H. A. 1964. The fossil flora of the surroundings of Ardley Peninsula [Ardley Island], 25 de Mayo Island [King George Island], South Shetland Islands. (*In* ADIE, R. J., *ed. Antarctic geology*. Amsterdam, North-Holland Publishing Company, 629-36.)

PÉWÉ, T. L. 1958. Quaternary glaciation: McMurdo Sound region. *IGY Bull.*, No. 14, 1–3. [*Trans. Am. geophys. Un.*, **39**, No. 4, 787–89.]

———. 1960. Multiple glaciation in the McMurdo Sound region, Antarctica—a progress report. *J. Geol.*, **68**, No. 5, 498–514.

PRICE, R. J. 1963. A glacial meltwater drainage system in Peeblesshire, Scotland. *Scott. geogr. Mag.*, **79**, No. 3, 133–41.

REICHELT, G. 1961. Über Schotterformen und Rundungsgradanalyse als Feldmethode. *Petermanns geogr. Mitt.*, **105**, No. 1, 15–24.

ROBIN, G. DE Q. 1962. The ice of the Antarctic. *Scient. Am.*, **207**, No. 3, 132–42, 144, 146.

———. 1964. Glaciology. *Endeavour*, **23**, No. 89, 102–07.

———. *and* R. J. ADIE. 1964. The ice cover. (*In* PRIESTLEY, R. E., ADIE, R. J. *and* G. DE Q. ROBIN, *ed. Antarctic research*. London, Butterworth and Co. (Publishers) Ltd., 100–17.)

RUNDLE, A. S. 1967. Studies of the Anvers Island ice cap, 1965–1966. *Antarct. Jnl U.S.*, **2**, No. 5, 183–84.

SADLER, I. 1968. Observations on the ice caps of Galíndez and Skua Islands, Argentine Islands, 1960–66. *British Antarctic Survey Bulletin*, No. 17, 21–49.

SCHAUER, O. C. *and* N. H. FOURCADE. 1964. Geological–petrographical study of the western end of 25 de Mayo Island [King George Island], South Shetland Islands. (*In* ADIE, R. J., *ed. Antarctic geology*. Amsterdam, North-Holland Publishing Company, 487–91.)

SCHYTT, V. 1961. Glaciology. II. Blue ice-fields, moraine features and glacier fluctuations. *Norw.-Br.-Swed. Antarct. Exped., Scient. Results*, **4E**, 181–204.

SISSONS, J. B. 1960. Some aspects of glacial drainage channels in Britain. Part I. *Scott. geogr. Mag.*, **76**, No. 3, 131–46.

———. 1961. Some aspects of glacial drainage channels in Britain. Part II. *Scott. geogr. Mag.*, **77**, No. 1, 15–36.

———. 1966. Relative sea-level changes between 10,300 and 8,300 B.P. in part of the Carse of Stirling. *Trans. Inst. Br. Geogr.*, No. 39, 19–29.

———. *and* D. E. SMITH. 1965. Raised shorelines associated with the Perth readvance in the Forth Valley and their relation to glacial isostasy. *Trans. R. Soc. Edinb.*, **66**, No. 8, 143–68.

SMITH, H. T. U. 1967. Scabland topography in Victoria Land, Antarctica. (*In* WATSON, J. W., *ed. Congress Proceedings of 20th International Geographical Congress (1964)*. London, Thomas Nelson and Sons Ltd., Sect. IIIb, 150.)

SOLLID, J. L. 1963–64. Isavsmeltingsforløpet langs hovedvasskillet mellom Hjerkinn og Kvikneskogen. *Norsk geogr. Tidsskr.*, **19**, Nos. 1–2, 51–76.

SUGDEN, D. E. *and* B. S. JOHN. 1965. The raised marine features of Kjove Land, East Greenland. *Geogrl J.*, **131**, Pt. 2, 235–47.

SWITHINBANK, C. 1959. Glaciology. I. The morphology of the inland ice sheet and nunatak areas of western Dronning Maud Land. *Norw.-Br.-Swed. Antarct. Exped., Scient. Results*, **3D**, 97–117.

TANNER, V. 1930. Studier över Kvartärsystemet i Fennoskandias nordliga delar: IV. Om nivåförändringarna och grunddragen av den geografiska utvecklingen efter istiden; Ishavsfinland samt om homotaxin av Fennoskandias Kvartära marina avlagringar. *Bull. Commn géol. Finl.*, **14**, No. 88, 594 pp.

THORARINSSON, S. 1951. Laxárgljúfur and Laxárhraun (a tephrochronological study). *Geogr. Annlr*, **33**, 1–89.

TRAIL, D. S. 1964. The glacial geology of the Prince Charles Mountains. (*In* ADIE, R. J., *ed. Antarctic geology*. Amsterdam, North-Holland Publishing Company, 143–51.)

TRICART, J. *and* R. SCHAEFFER. 1950. L'indice d'émoussé des galets, moyen d'étude des systèmes d'érosion. *Revue Géomorph. dyn.*, **1**, 151-79.

USHAKOV, S. A. *and* G. E. LAZAREV. 1964. Concerning the isostatic equilibrium of Antarctica. (*In Soviet Antarctic Expedition Information Bulletin, Vol. II*. Amsterdam, London, New York, Elsevier Publishing Company, 9–13. [No. 11, 1959.])

VORONOV, P. S. 1964. Geomorphology of east Antarctica. (*In Soviet Antarctic Expedition Information Bulletin. Vol. I*. Amsterdam, London, New York, Elsevier Publishing Company, 20–24. [No. 1, 1958.])

————. 1965. Attempt at a reconstruction of the Antarctic ice cap of the epoch of the Earth's maximum glaciation. (*In Soviet Antarctic Expedition Information Bulletin, Vol. III*. Amsterdam, London, New York, Elsevier Publishing Company, 88–93. [No. 23, 1960.])

————. *and* S. A. USHAKOV. 1965. Some problems in studying isostatic processes in Antarctica. (*In Soviet Antarctic Expedition Information Bulletin, Vol. III*. Amsterdam, London, New York, Elsevier Publishing Company, 351–54. [No. 30, 1961.])

WASHBURN, A. L. *and* M. STUIVER. 1962. Radiocarbon-dated postglacial delevelling in northeast Greenland and its implications. *Arctic*, **15**, No. 1, 66–73.

WEERTMAN, J. 1966. Effect of a basal water layer on the dimensions of ice sheets. *J. Glaciol.*, **6**, No. 44, 191–207.

WILSON, A. T. 1964. Origin of ice ages: an ice shelf theory for Pleistocene glaciation. *Nature, Lond.*, **201**, No. 4915, 147–49.

————. 1966. Variation in solar insolation to the South Polar region as a trigger which induces instability in the Antarctic ice sheet. *Nature, Lond.*, **210**, No. 5035, 477–78.

WORSFOLD, R. J. 1967. Physiography and glacial geomorphology of Heimefrontfjella, Dronning Maud Land. *British Antarctic Survey Bulletin*, No. 11, 49–57.

YEVTEYEV, S. A. 1962. Marine terraces along the Antarctic coast. (*In Soviet Antarctic Expedition Information Bulletin, Vol. IV, No. 2*. Washington, D.C., American Geophysical Union, 73–76. [No. 33, 1962.])