THE GEOLOGY OF POWELL, CHRISTOFFERSEN AND MICHELSEN ISLANDS, SOUTH ORKNEY ISLANDS

By JANET W. THOMSON

ABSTRACT. Powell Island, the third largest of the South Orkney Islands, is composed of low-grade regionally metamorphosed *para*schists (greenschist facies) which are apparently overlain by the much contorted and dynamically metamorphosed Greywacke–Shale Formation and the younger, gently dipping Powell Island Conglomerate. The junction between the two sedimentary formations is probably an unconformity but only faulted contacts have been observed in the field. The age of the metamorphic rocks is not known but the Greywacke–Shale Formation is possibly of Carboniferous age and the Powell Island Conglomerate, which also crops out on Michelsen and Christoffersen Islands, has been tentatively assigned to the Jurassic or Cretaceous. A brief geological outline of Fredriksen, Bruce, Saddle, Weddell and Laurie Islands is also given.

POWELL ISLAND (lat. 60°41′S., long. 45°03′W.) is situated between Coronation and Laurie Islands, the two principal members of the South Orkney Islands, and it is separated from them by Washington Strait to the east and Lewthwaite Strait on the west (Fig. 1). Michelsen

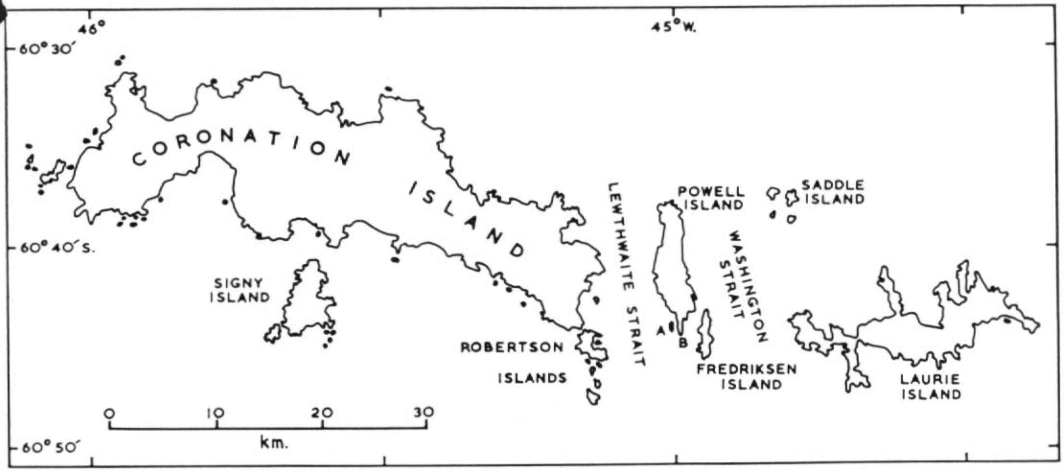


Fig. 1. Sketch map of the South Orkney Islands; localities A and B are Christoffersen and Michelsen Islands, respectively.

Island (lat. 60°45′S., long. 45°02′W.), which lies south of Powell Island, is connected to it by a narrow low-lying isthmus, whereas Christoffersen Island (lat. 60°45′S., long 45°03′W.) is completely separated from the adjacent mainland.

Although Powell Island was observed for the first time in December 1821, when Captain G. Powell and Captain N. Palmer discovered the South Orkney Islands, Michelsen and Christoffersen Islands were not charted until Captain P. Sørlle made a running survey of the group during 1912–13. The first geological specimens from Powell and Michelsen Islands were collected by members of R.R.S. *Discovery II* in January 1933 and the petrography of these rocks was subsequently described by Tilley (1935). However, the results of more recent rock collections (Table I) and geological surveys made by British Antarctic Survey personnel have hitherto remained undescribed or unpublished (Hoskins, 1960).

PHYSIOGRAPHY

The general physiography of the South Orkney Islands has been described by Pirie (1913, unpublished), Holtedahl (1929), John (1934) and Marr (1935), but little attention was given to either Powell Island or the two smaller islands until A. K. Hoskins and K. D. Holmes visited

TABLE I. COLLECTIONS OF ROCK SPECIMENS FROM POWELL, CHRISTOFFERSEN AND MICHELSEN ISLANDS

Date	*Collector*	*Station numbers*	*Remarks*
1933	Discovery Investigations	1089	Specimens described by Tilley (1935)
January 1957	D. H. Matthews	H.1333–1336, 1338, 1341	Powell Island and Whale Skerries
December 1957	A. K. Hoskins	H.1700–1708	Powell and Michelsen Islands; visited Christoffersen Island
1964–65	K. D. Holmes	H.2106–2121	Powell and Michelsen Islands

them during 1957 and 1964–65, respectively. Both of these men were only in the area for a short time and their observations were necessarily limited, but Hoskins was able to investigate the southern part of Powell Island, Michelsen Island and Christoffersen Island, and Holmes covered most of the accessible ground on Powell and Michelsen Islands.

Topography

Powell, Michelsen and Christoffersen Islands are all elongated north–south, transverse to the overall west–east or west-north-west to east-south-east trend of the South Orkney Islands. Powell Island, which is the largest of the three, is approximately 11 km. in length and 3 km. wide. From the highest point (approximately 594 m.), which is in the north of the island, the mountains decrease in height towards John Peaks (414·8 and 374·8 m.) and again farther south to the considerably lower Christoffersen Island (95·7 m.) and Michelsen Island (38·1 m.) (Fig. 2). This topographic pattern is similar to that of Coronation and Laurie Islands, where the steep cliffs and high altitudes of the northern coasts are replaced by gentle slopes and lower relief in the south.

Fig. 2. View of the southern part of Powell Island with Michelsen Island (foreground) and the low-lying rocks of Christoffersen Island (centre). Ellefsen Harbour lies between Christoffersen and Michelsen Islands, and the snow-covered mountains in the background are John Peaks. (Drawn from a photograph (John, 1934, pl. 9).)

Both Hoskins (1960, p. 2) and Holmes (unpublished field notes) recognized several physiographic units on Powell Island. These are:

i. A shelf of piedmont ice on the eastern side of the island. This is approximately 300 m. in height adjacent to the mountain ridges in the west, dropping eastward to the sea where it forms ice cliffs approximately 30 m. high (cf. Figs. 3 and 10).

Fig. 3. Panorama of the ridge north of the John Peaks ridge, Powell Island, viewed from the north. Cape Disappointment is on the far right, the snow-capped mountain (centre background) is John Peaks and Fredriksen Island is just visible in the left background beyond the ice piedmont. (Photograph by K. D. Holmes.)

ii. Two prominent ridges are present on the western side of the island. The southern one, trending north-north-east to south-south-west and containing the twin summits of John Peaks (Fig. 2), is 2·4 km. in length and it is separated from the ridge to the north by a small glacier. The narrow northern ridge (Figs. 3 and 4), which is 4 km. long and trends approximately north-north-west to south-south-east, falls away steeply to the ice piedmont on the east and to the fringing glaciers on the west and north (Fig. 5); a spur of this ridge terminates at station H.1333.

iii. Farther north, a dome-shaped hill rises above the ice piedmont to a height of approximately 560 m. and beyond this the island narrows into a high steep ridge (Fig. 6; Marr, 1935, pl. XXII, fig. 3), 2·4 km. in length, which culminates in Cape Faraday.

In addition to these, the numerous above-water rocks and islets lying off the west coast of Powell Island (e.g. Whale Skerries) and the relatively small number present off the east coast (Hydrographic Department, 1961, p. 250) are indicative of the physiographic differences between the two sides of the island.

Powell Island's alpine topography has reached a mature stage of the glaciation cycle (Hoskins, 1960, p. 2) and the glaciers between the ridges (arêtes) represent poorly developed examples of the transverse ridges and trough glaciers described by Holtedahl (1929, p. 94–97) and Marr (1935, p. 364). Two contrasting forms of glaciated topography can be seen in the John Peaks ridge where the southern and western faces are triangular with sharp rock corners, and the northern and eastern faces are heavily glaciated slopes which drop smoothly but steeply to the ice piedmont (Fig. 2); Hoskins (1960, p. 2) considered that the steep western face of the ridge is an eroded fault plane. A bluff-like peninsula south-west of John Peaks (Marr, 1935, pl. XXII, fig. 2) is composed of "greywacke" but Hoskins (1960, p. 9) was unable to correlate any one physiographic form with a particular rock type, e.g. conglomerate forms both the angular and irregular crags of John Peaks and the low rounded hills of Christoffersen and Michelsen Islands (Fig. 2). Two natural harbours, Falkland and Ellefsen Harbours, have been eroded in the conglomerate of southern Powell Island (Fig. 2; Marr, 1935, pl. XIV, fig. 2).

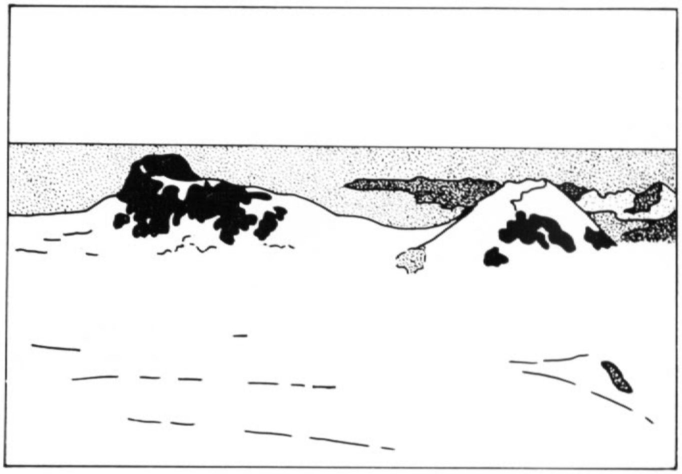


Fig. 4. View of the ridge north of the John Peaks ridge, taken from the north-east; the Robertson Islands are in the background and cloud partially obscures the right-hand side of the picture. (Drawn from a photograph by K. D. Holmes.)

Fig. 5. View of the northern west coast of Powell Island from the northern summit of the ridge shown in Fig. 4. Note the dome-shaped hill (far right) and the small west–east-trending ridge (station H.2117) on the left beyond the westward-flowing glacier (foreground). (Photograph by K. D. Holmes.)

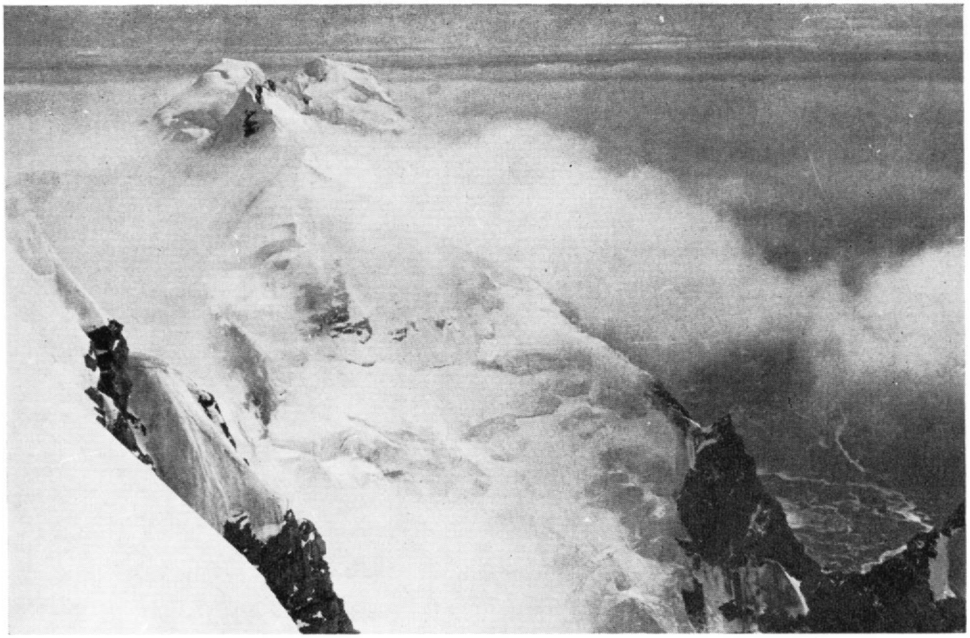


Fig. 6. View of the high steep ridge at the northern end of Powell Island from the south. (Photograph by K. D. Holmes.)

In profile Christoffersen Island resembles a large *roche moutonnée* and it is possible that its present shape is due to the erosive action of ice (Hoskins, 1960, p. 3). The dip slopes on the island reflect the structure of the southward-dipping Powell Island Conglomerate but Hoskins could find no obvious structural weaknesses to account for the cirque-like valley on the west coast of the island. Michelsen Island is topographically similar to the ground on the eastern side of Falkland Harbour and it is only separated from it by a narrow isthmus which is awash at high tide. Its topography is characterized by small groups of hillocks (the highest of these (38·1 m.) occurs in the north of the island) separated from one another by a beach-like feature about 10 m. in width. These "beaches" trend approximately west–east and Hoskins (1960, p. 3) believed that they were the result of erosion and deposition along fault lines.

Glaciology

Northern Powell Island, with its heavy highland ice and suspended cliff glaciers (Marr, 1935, pl. XXII, fig. 3) contrasts strongly with the light glacierization of the southern part of the island and with the practically ice-free Michelsen Island. Nevertheless, the ice piedmont on the eastern side of Powell Island is a continuous feature from the north to the south of the island. Rocky headlands occasionally break through this ice cover as steep sea cliffs 90–120 m. in height but bergschrunds and rock cliffs are relatively rare marginal features of the ice piedmont and the ice slope from the ridges to the glacier is usually an uninterrupted one. In places the ice piedmont flows westward over cols between the main ridges to feed short, steep and broad glaciers clinging to the western slopes of the ridges; although these glaciers resemble shallow cirque glaciers (Hoskins, 1960, p. 5), they are supplied by ice from the cols above. The ice piedmont is nourished by ice from the almost permanently snow-covered eastern slopes of the ridges and by direct precipitation (Hoskins, 1960, p. 5).

Moraines have been recorded only in the southern part of Powell Island (Hoskins, 1960, p. 5) and at one locality (H.1333) on its western coast (Matthews, 1956, p. 3). The moraines near Falkland Harbour are irregularly distributed over the southern part of the ice piedmont and they are composed entirely of conglomerate boulders which were probably derived from the conglomerates of John Peaks; the largest boulder measured 3 m. by 2·4 m. by 1·8 m. Conglomerate boulders predominate in the west coast moraine but a few boulders of plant-bearing grey sandstones (cf. Fig. 14a) were also recorded. Sub-rounded boulders of conglomerate (0·45–1·8 m. in diameter), which occur on the top of Christoffersen Island and the peninsula west of Falkland Harbour, are regarded as evidence of a greater glacial extension in the past (Hoskins, 1960, p. 7).

Sea-level changes

"The South Orkneys present the features of a dissected upland, whose main outlines probably owe their origin to glacial action when the land stood at a higher level, although the present-day rock features are largely the result of sub-aerial weathering, and the rock-shattering action of frost.

"More recent depression of the land has left exposed merely the top of a carved and fretted mountain ridge, whose main axis extends in an east to west direction for a distance of about seventy-two geographical miles measured from Cape Dundas, the easternmost point of Laurie Island, to the western extremity of Coronation Island." (Pirie, 1913, p. 837)

Holtedahl (1929, p. 101) also assumed that the present topography of the South Orkney Islands could only be explained by a "previous higher stand of the land" and Marr (1935, p. 363) reiterated this by assuming a heavier and more extensive glaciation in the past.

Pirie (1913, p. 837) recorded a recent fall in sea-level of 4·5 m. for Laurie Island, based on the evidence of raised beaches, rock notches and raised sea caves, and he also noted a marine platform at approximately 30 m. above sea-level (Pirie, unpublished, p. 9). Hoskins (1960, p. 3) recorded a conspicuous rocky shelf 6–7 m. in height around the shores of Christoffersen Island and on the western side of the peninsula west of Falkland Harbour. He also observed that a 6–7 m. rise in sea-level would submerge most of the "beaches" present on Michelsen Island and the low ridges or beaches of the peninsula to the north; a rise of 1·5 m. would flood the true beach on this peninsula and it would cover the small 1 m. high cliff which separates the beach from the low rocky terrain to the north-west. Hoskins was unable to find any evidence of a marine platform at 30 m. on Powell, Christoffersen and Michelsen Islands.

General Geology

Powell Island is composed of both metamorphic rocks and sediments belonging to two age groups (Fig. 7a and b); the younger of these sedimentary sequences has yielded a small collection of fossil plants. At least two phases of folding and faulting have affected the older rocks but the overall structure of the island is not fully known at present.

Stratigraphy

The stratigraphy of Powell Island is summarized in Table II. It differs slightly from those successions given previously for the whole of the South Orkney Islands (Matthews, 1959; Adie, 1964; Matthews and Maling, 1967) as it indicates that the Powell Island Conglomerate could be Jurassic in age, on the basis of palaeobotanical evidence (p. 158). However, earlier workers assigned the lithologically similar Spence Harbour Conglomerate of Coronation Island to the (?) Cretaceous or Upper Cretaceous (on the evidence of fossil invertebrate remains) and a Cretaceous age for the Powell Island Conglomerate is also possible.

Table II. The stratigraphy of Powell Island

(?) **Cretaceous** or (?) **Jurassic**	Powell Island Conglomerate
(?) **Carboniferous**	Greywacke–Shale Formation
(?)	Metamorphic complex

The connection between the metamorphic complex and the Greywacke–Shale Formation*

* Originally called the Greywacke–Shale Series, this has been re-named the Greywacke–Shale Formation because it is a well-defined lithostratigraphic unit which has no obvious chronostratigraphic significance (cf. American Commission on Stratigraphic Nomenclature, 1961, article 9f, p. 651).

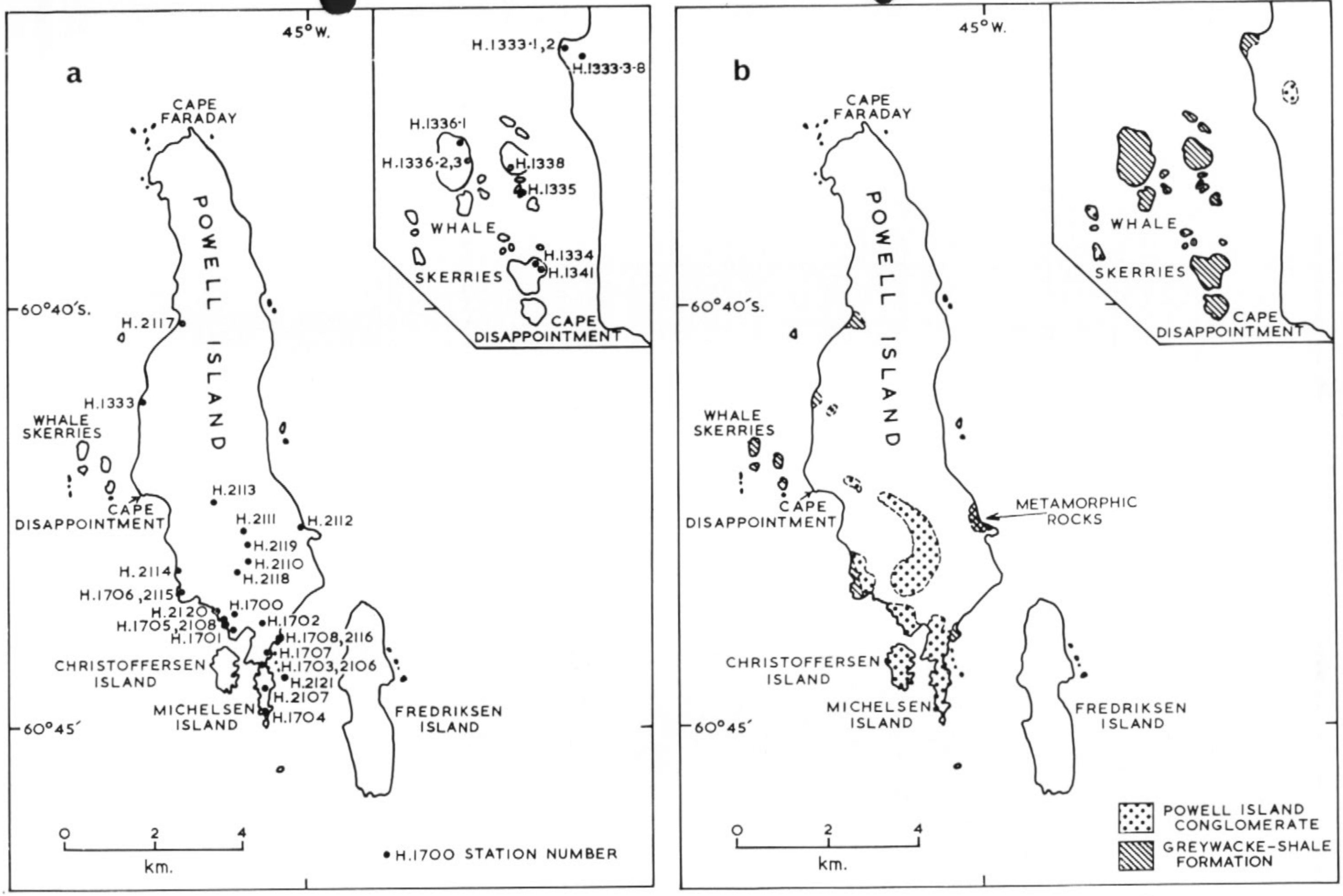


Fig. 7. Sketch map of Powell, Michelsen and Christoffersen Islands, showing the approximate positions of the geological stations (a) and the general geology (b). The sketch map of Whale Skerries (inset) is taken from a field map byD. H. Matthews.

is not known, although the two sequences could grade into one another; metamorphic rocks have been collected at the base of the sea cliffs near station H.2117 (Fig. 7a) (personal communication from I. W. D. Dalziel) and phyllitic mudstones, which in the hand specimen are obviously members of the Greywacke–Shale Formation, crop out approximately 270 m. above, at the top of these cliffs (H.2117). The Greywacke–Shale Formation has been tentatively correlated with the Carboniferous Trinity Peninsula Series of Graham Land (Adie, 1957) but its relationship with the Powell Island Conglomerate is still problematical because all of the observed contacts are faulted ones. However, comparative petrographic studies of the sediments from both sequences have shown that the Powell Island Conglomerate is certainly younger than the Greywacke–Shale Formation and it is assumed that the two are separated by an unconformity.

Owing to the extremely disrupted nature of the Greywacke–Shale Formation, it has been impossible to obtain an estimate of the thickness of these sediments. Similarly, the lack of well-defined bedding and the absence of marker horizons in the Powell Island Conglomerate have hindered in stratigraphical investigations and the determination of its thickness; sandy partings in the conglomerate are only a few metres thick and they have too limited a lateral extent to be of any stratigraphical use. Nevertheless, Hoskins (1960, p. 8) has estimated that, allowing for structural complications, the conglomerate is at least 610 m. thick because a vertical thickness of 366 m. of undisturbed conglomerate is exposed on the west face of John Peaks and 396 m. are believed to be present on Christoffersen Island. Observations by K. D. Holmes in the John Peaks area confirm the presence of at least 305 m. of conglomerate.

Structure

According to Dalziel (1971), the structure of the Powell Island metamorphic rocks is dominated by asymmetric folds which plunge gently to the south and re-fold small isoclinal folds. Previous rather limited observations by Holmes (1965) had shown that the thinly laminated schists at station H.2112 were intensely micro-folded about horizontal axes. The Greywacke–Shale Formation is considerably disturbed and the rocks are infolded with each other but the few measurements available indicate that the general structural trend varies from north–south to north-north-west–south-south-east. Strongly folded tough black mudstones and siltstones, with fold axes trending 340–350° mag., crop out on the cliff top at station H.2117 (Fig. 5), and at the same locality the coarser-grained siliceous sediments form pods and rolls, possibly small boudins, separated from one another by shaly material; similar pods or nodules of sandstone have been observed at station H.1708 (Hoskins, 1960, p. 8) and stations H.2114 and 2115.

The Powell Island Conglomerate was deposited after the period of violent upheaval which folded the Greywacke–Shale Formation but it has probably been affected by major forces aligned approximately north–south (Hoskins, 1960, p. 12). Only one small anticline, on Michelsen Island (Fig. 8), has been observed but variations in dip directions on southern Michelsen Island suggest that more minor folds may be present. In the southern part of Powell Island and on Christoffersen Island, the conglomeratic sequence dips gently to the south-south-west at approximately 30°, although anomalous dips have been recorded in the vicinity of faults. The junction between the Greywacke–Shale Formation and the Powell Island Conglomerate has not been seen in the field but its inferred position has been placed at 304 m. in the north of Powell Island, at 183 m. in the area of the John Peaks ridge (opposite station H.2112) and below sea-level in the extreme south of the island (unpublished field notes of K. D. Holmes). This assumes that faulting has been of a very small order.

Near-vertical dip faults displace Greywacke–Shale Formation sediments on the Whale Skerries (unpublished field notes of D. H. Matthews) but faulting definitely prior to the deposition of the Powell Island Conglomerate is unknown. Major faults, trending approximately north–south, separate the outcrops of the two sedimentary sequences on the coast west of John Peaks, near stations H.1706 and 2115, and on the south-east coast of Powell Island, at stations H.1708 and 2116 (Fig. 9). A well-defined fault scarp about 6 m. in height occurs near stations H.1706 and 2115, and it is bounded to the east, on the down-thrown side of the fault, by a 5 m. wide breccia zone. To the west of this major fault, near station H.2114,

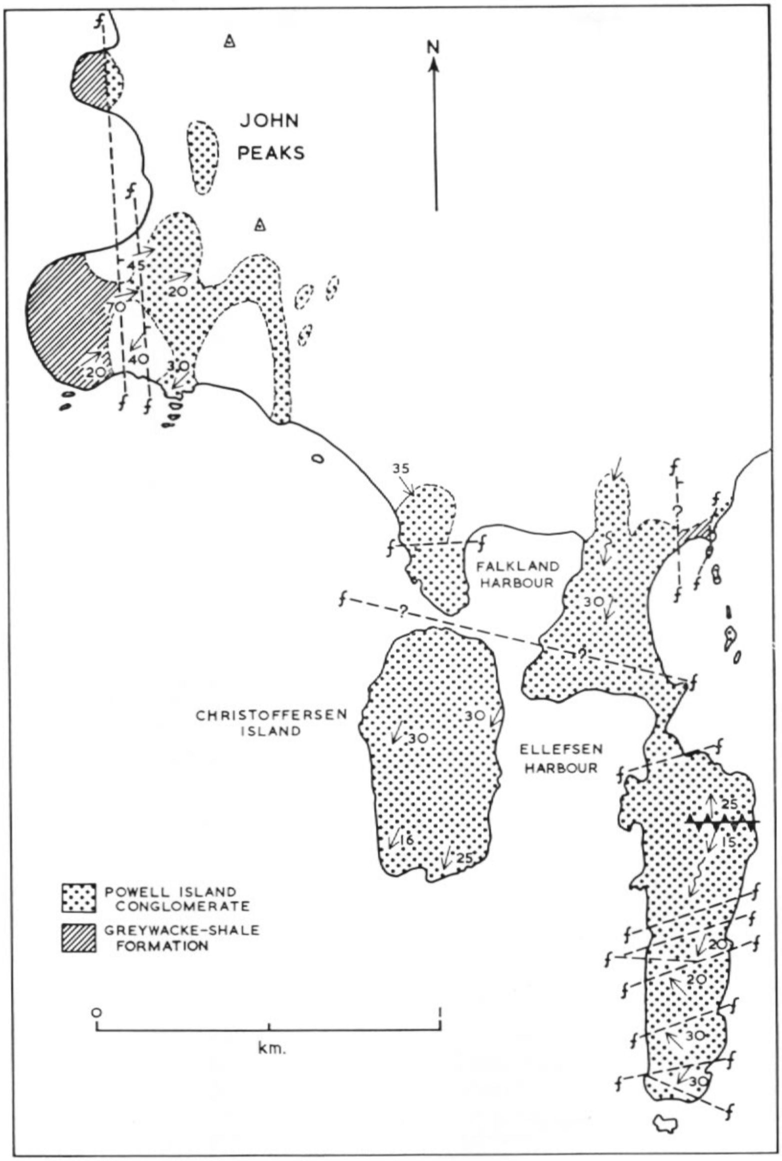


Fig. 8. Geological sketch map of the southern part of Powell Island, Christoffersen and Michelsen Islands, showing the distribution of rock types and the general structure of the area. (Partly from Hoskins, 1960, fig. 5.)

K. D. Holmes observed a small outcrop of a conglomerate containing well-rounded cobbles (up to 25 cm. in diameter) of greywacke–shale type sediments. Its origin is unknown but it is obviously not a fault breccia because of the roundness and size equality of the cobbles; it is apparently too coarse to be one of the greywacke-conglomerates Pirie (unpublished) observed on Laurie Island.

Lewthwaite and Washington Straits, which trend approximately north–south, are probably the sites of major faults similar to those already described. Several minor faults, particularly on Michelsen Island (Fig. 8), have been inferred by Hoskins (1960).

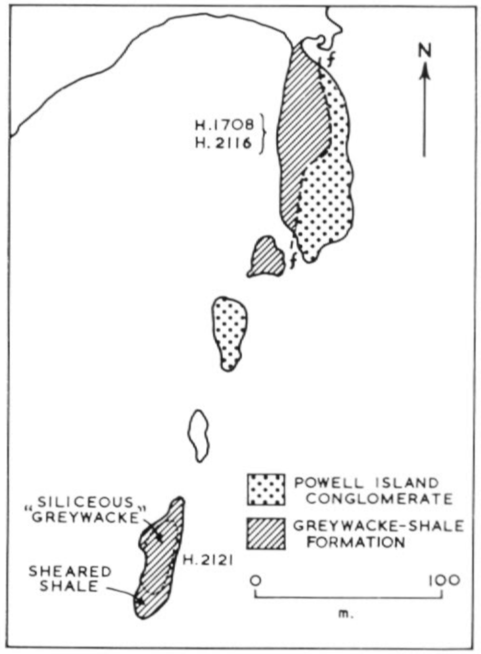


Fig. 9. Sketch map showing the faulted contact between the Greywacke–Shale Formation and the Powell Island Conglomerate in south-eastern Powell Island. (From a field map by K. D. Holmes.)

Disharmonic micro-folds have been recorded in the contorted schists from station H.2112 and the laminated phyllitic siltstone (semi-schist) collected at station H.2117. The approximate scale of the folds is given below, using the descriptive terms suggested by Matthews (1958):

Short limb height	= 3·5 mm.
Long limb height	= 6·0 mm.
Axial-plane separation (short limb)	= 5·0 mm.
Axial-plane separation (long limb)	= 7·0 mm.

Metamorphic Complex

Regionally metamorphosed schists were first recorded by K. D. Holmes on the east coast of Powell Island (H.2112; Fig. 10) but subsequent investigations by I. W. D. Dalziel (personal communication, 1971) have shown that the metamorphic rocks (phyllites and chlorite-schists) are more widespread. It is now known that they crop out at several localities around the northern coast of the island and form the entire cliffs near Cape Faraday.

The specimens collected at station H.2112 are thinly laminated, uncontorted quartzo-feldspathic schists (Fig. 11a) and strongly contorted, more gneissose ones (Fig. 11b). The uncontorted schists forming the 100 m. high sea cliffs at station H.2112 are extremely fine-grained (0·05–0·1 mm.), dark grey rocks with a greenish sheen and, although they lack biotite, they are similar in appearance to the thinly laminated quartz-albite-biotite-muscovite-schists of Coronation Island (Thomson, in press; Fig. 11c). They comprise quartzo-feldspathic laminae of fine-grained quartz and some plagioclase alternating with thin discontinuous laminae of muscovite, chlorite, epidote and occasional albite porphyroblasts (? An_9) 0·2–0·4 mm. in length; the porphyroblastic plagioclase is rarely twinned and it includes small crystals of quartz and muscovite. Relatively large crystals of sphene, epidote (0·2 mm. in length), apatite, allanite and actinolite ($\gamma : c = 11°$) are sporadically distributed in the schists and there are rare relict grains of chequer-board albite and perthite. The presence of these relict grains could

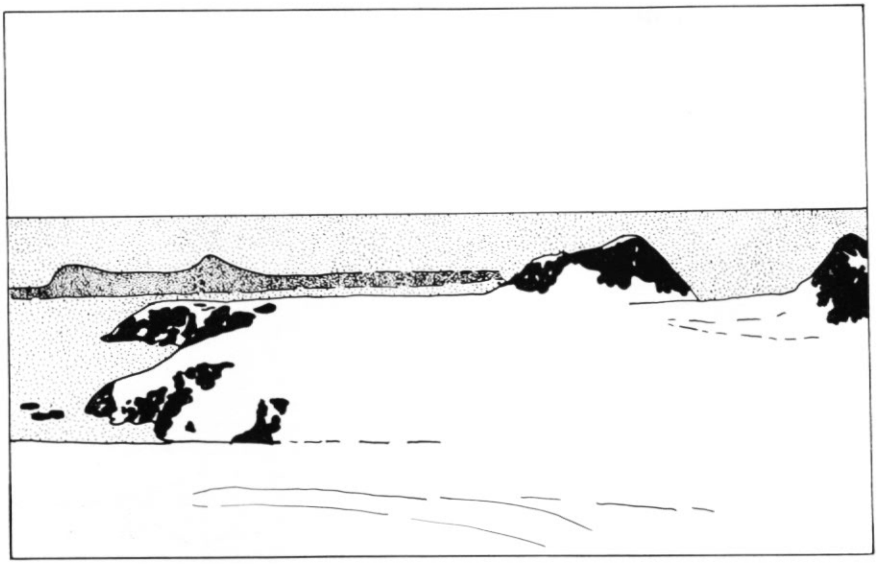


Fig. 10. View of the southern east coast of Powell Island showing the locality from which the schists (H.2112.1–4) were collected and the position of the ice piedmont; John Peaks are to the right of centre and Fredriksen Island is in the background. (Drawn from a photograph by K. D. Holmes.)

suggest that the schists were originally sandstones comparable, perhaps, to those of the Greywacke–Shale Formation.

The strongly contorted schists which crop out 100–200 m. inland from the cliff top at station H.2112 are characterized by abundant feldspar and thicker quartzo-feldspathic laminae. They are similar to some of the micro-folded schists on Coronation Island (Fig. 11d), having acute-angled micro-folds which in thin section are enhanced by mimetic crystallization of muscovite (indicating that metamorphic recrystallization was a post-kinematic phenomenon) and streaks and trails of graphite. Rare (?) detrital clouded plagioclase crystals, recrystallized to a water-clear variety of (?) albite, a few minute crystals of greenish brown tourmaline and a little haematite or rutile have also been observed in thin section, and secondary calcite and quartz veining are present in both this and the uncontorted type of schist; cubes of iron pyrites have also been recorded at the schist outcrops.

Both types of schist belong to the quartz-albite-muscovite-chlorite sub-facies of the greenschist facies (Turner and Verhoogen, 1960, p. 533–37) and they are therefore of a slightly lower metamorphic grade than most of the schists forming the metamorphic complex of Coronation Island (Thomson, in press) and Signy Island (Thomson, 1968).

Petrology of the Greywacke–Shale Formation

Those sandstones which form a large part of the Greywacke–Shale Formation have previously been referred to as greywackes (Pirie, 1905, unpublished; Matthews, 1959; Hoskins, 1960), probably because of their high matrix* content (Table III). Unfortunately, it has not been possible to distinguish between detrital matrix and the matrix formed by the alteration and break-down of the coarser mineral and lithic debris, and the percentages shown in Table III are probably not, therefore, a true representation of the original detrital content of the sandstones. However, using Folk's (1954, p. 354, 1959, p. 110) and van Andel's (1958, p. 746) classifications, which are based on the mineral composition of the silt–sand–gravel

* Matrix includes all grains smaller than 0·03 mm. and all secondary minerals, e.g. sericite, chlorite and recrystallized quartz, which obscured the original mineral or lithic fragments. Secondary veins of quartz and calcite and the heavy minerals have been placed in the category "others" in Table III.

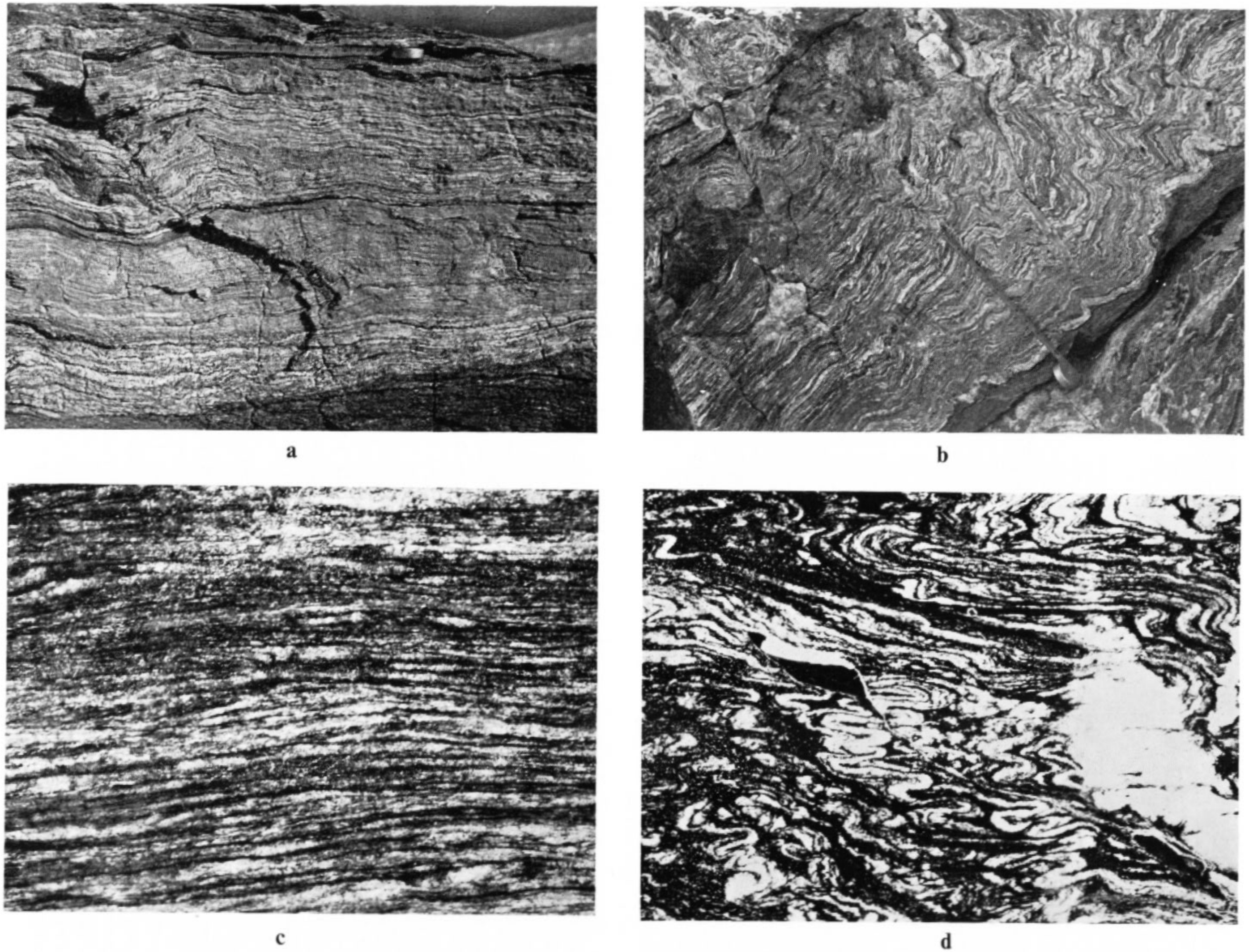


Fig. 11. a. Thinly laminated and generally uncontorted quartz-muscovite-chlorite-schists forming the cliffs on the east coast of Powell Island; the scale is 30·5 cm. in length. (Photograph by K. D. Holmes.)

b. Strongly contorted quartz-muscovite-chlorite-schists at an outcrop slightly west of the locality shown in Fig. 11a; the scale is 30·5 cm. in length. (Photograph by K. D. Holmes.)

c. A thinly laminated and uncontorted quartz-albite-biotite-muscovite-schist from Coronation Island (H.554.1; ×2·5).

d. A strongly contorted and quartz-veined graphitic quartz-mica-schist from Coronation Island (H.194.2; ×1·25).

TABLE III. MODAL ANALYSES OF SANDSTONES FROM THE GREYWACKE–SHALE FORMATION

	H.1333.1	H.1334.1C	H.1334.3B	H.1335.1	H.1336.1A	H.1336.2	H.1706.2	H.2114.1	H.2114.4	H.2115.1	H.2116.1	H.2121.1
Quartz	15	9	14	17	12	12	14	14	18	10	22	33
Feldspar	6	4	8	3	3	7	3	4	5	8	27	21
Metamorphic rocks	–	*	*	*	1	1	*	*	1	*	*	–
Igneous rocks	*	1	7	1	3	3	4	2	10	3	2	2
Sedimentary rocks	*	–	*	*	*	1	*	*	1	–	–	–
Chert	–	*	2	1	2	*	3	1	2	*	–	–
Others	16	24	4	7	3	2	17	4	1	2	5	3
Matrix	63	62	65	71	76	74	59	75	62	77	44	41

* Less than 0·5 per cent present.

H.1333.1	Point on central west coast of Powell Island, north-east of Whale Skerries.
H.1334.1C and 3B, 1335.1, 1336.1A and 2	Whale Skerries, off central west coast of Powell Island.
H.1706.2 and 2115.1	Rock promontory south-west of John Peaks, Powell Island.
H.2114.1 and 4	Headland north of station H.1706.
H.2116.1	South-east coast of Powell Island.
H.2121.1	Small island south of station H.2116.

fraction and disregard chemical cements, clay minerals, micaceous material finer than 0·03 mm., heavy minerals, etc., the sandstones from the Greywacke–Shale Formation are mostly arkoses or sub-arkoses (Fig. 12a and b) and few plot as greywackes. The multiple origins of the matrix in a sandstone have an important bearing on the meaning of the term "greywacke" (Klein, 1963, p. 571) and to prevent further confusion about the implications of this term, those rocks composed of sand-sized grains will be referred to as sandstones in the following petrographical descriptions.

Petrography

Outcrops of the Greywacke–Shale Formation have been observed only on those islands to the east of Coronation Island, namely Powell, Fredriksen, Saddle, Weddell and Laurie Islands. The outcrops on Powell Island are very scattered (Figs. 7b and 8) and correlation between these various outcrops is impossible because of the undistinctive lithology of the sediments, the lack of fossils and their extremely disrupted nature. There are no known outcrops of these sediments on either Michelsen or Christoffersen Islands, although Tilley (1935, p. 385) stated that, on Michelsen Island, the conglomerates [the Powell Island Conglomerate] "are said to rest on a band of greywacke". Unfortunately, detailed field information is not available but from a study of the thin sections described by him, it seems likely that this greywacke band is one of the many sandy partings within the Powell Island Conglomerate.

Lithologically, the sediments are rhythmically bedded medium- and fine-grained sandstones, siltstones, mudstones and shales (Hoskins, 1960, p. 9), all of which have been affected by dynamic metamorphism during folding. D. H. Matthews recorded a limestone intercalated with sheared greywacke on one of the islets of the Whale Skerries (H.1334) and a sheared calcareous grit at station H.1336 but only sandstones were collected from these geological stations.

The *sandstones* have been arbitrarily divided into those with a muddy matrix and those with a siliceous one but in the hand specimen they are all massive medium-grained rocks, usually with a greenish grey colour and a characteristic angular, blocky or sub-conchoidal fracture (H.2116.1 and 2121.1). All of the sandstone specimens are cut by thin veinlets of quartz and calcite, and field data indicate that iron pyrites is also common. Small dark streaks noticed in a few of the rocks are probably biotite or chlorite flakes rather than organic remains.

In thin section both the muddy and siliceous sandstones are characterized by either a chlorite-sericite matrix or a siliceous, partially cataclastic one, the minute flakes of chlorite and sericite in the former showing varying degrees of parallel alignment in different specimens of sandstone. The muddy sandstones (Fig. 13a) are poorly sorted deposits with sub-rounded or lenticular lithic debris and smaller, more angular and irregular mineral fragments. The lithic material was derived mostly from an igneous source (represented by granitic and rhyolitic fragments) and there is little sedimentary or metamorphic detritus present; slivers of sericite-phyllite, similar to the penecontemporaneous "shale" specimens collected from the Whale Skerries (cf. p. 153), were regarded as sedimentary rock fragments, whilst pieces of fine-grained quartz-mica-schist were recorded as metamorphic debris. Sub-rounded fragments of chert are apparently common (Table III) but some of them could be misidentified fine-grained, non-porphyritic rhyolite. The commonest mineral fragments are individual quartz crystals with an undulose extinction, a few of the larger ones being embayed by the matrix. Polycrystalline quartz aggregates and single crystals of quartz with hair-like inclusions of (?) rutile are uncommon. Most of the feldspar crystal fragments are partially sericitized or saussuritized plagioclase but there are also several unaltered crystals of twinned plagioclase (An_{9-12}). Heavy minerals are represented by epidote, sphene, allanite, tourmaline, garnet and iron ore, whereas flakes of muscovite (0·3 mm. in length) and both granular and irregular crystals of epidote are probably authigenic minerals.

The siliceous sandstones (Fig. 13b) have a greater range in grain-size (0·1–1·0 mm.) than the muddy sandstones, due partly to the mechanical granulation of the sand-sized clasts. The matrix is composed of recrystallized microcrystalline quartz, rare brownish coloured glassy mylonitic bands and small angular fragments of quartz and feldspar (0·1 mm.). Larger fragments of quartz (mostly individual crystals with an undulose extinction) and feldspar

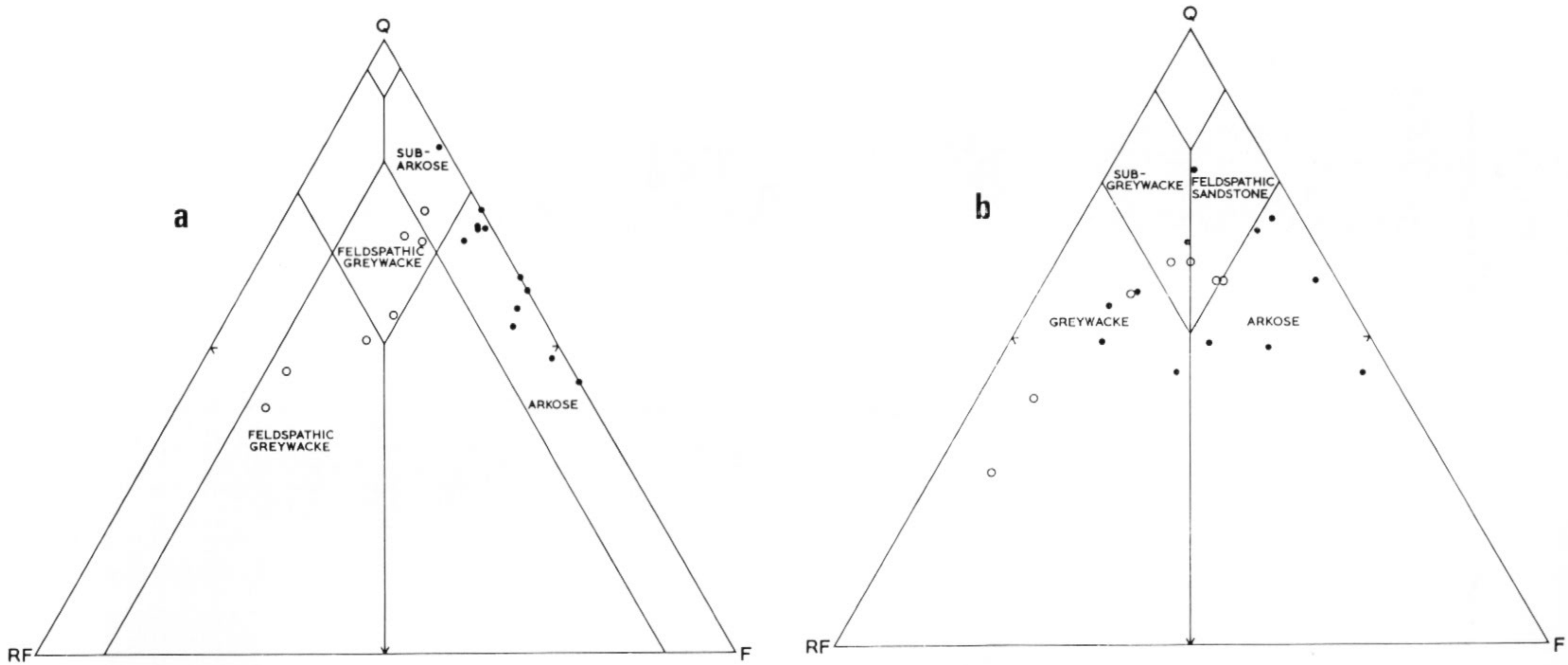


Fig. 12. Triangular diagrams showing the classification of sandstones; Greywacke–Shale Formation (solid circles), sandstones from partings in the Powell Island Conglomerate (open circles).

a. Q quartz + chert, F total feldspar + igneous rock fragments, RF metamorphic rock fragments + mica + metaquartzite. Field limits after Folk (1954).
b. Q quartz, F total feldspar, RF rock fragments + chert. Field limits after van Andel (1958).

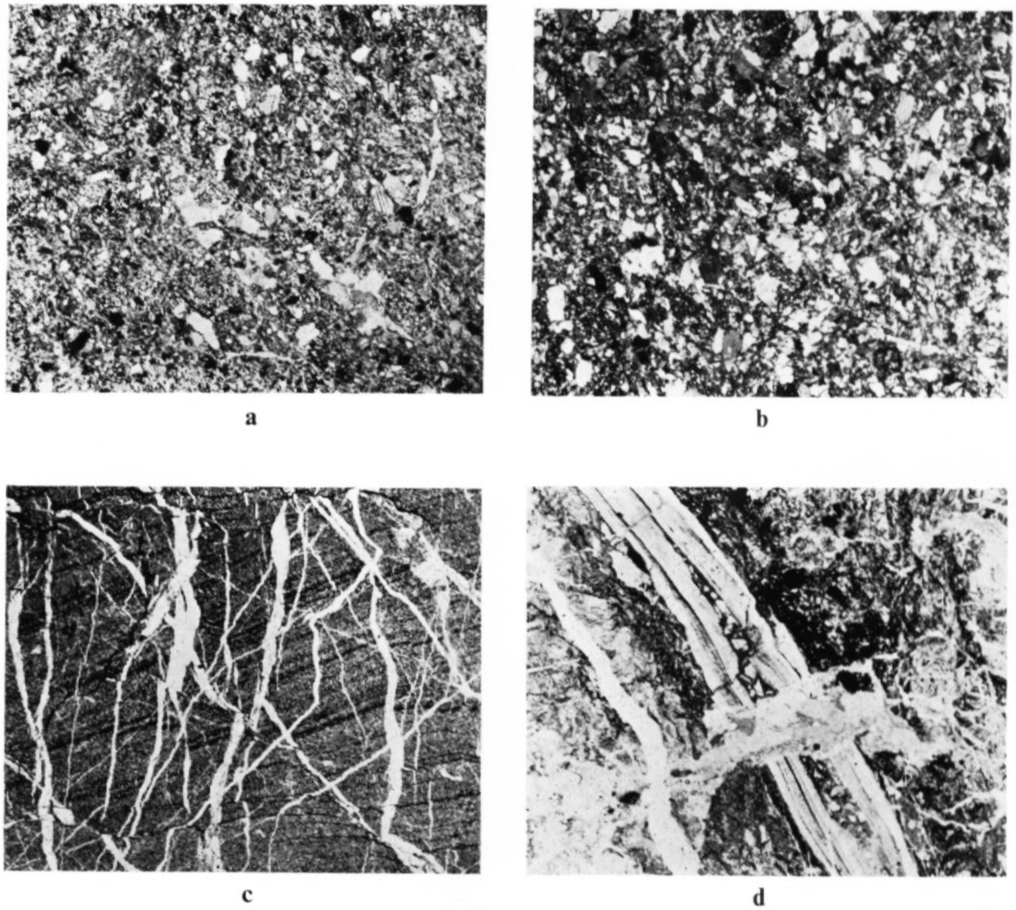


Fig. 13. a. A slightly sheared muddy sandstone from the Greywacke–Shale Formation. The matrix comprises minute flakes of chlorite and sericite in parallel alignment, and elongated patches of secondary calcite (twinned) enhance this directional feature; southern west coast of Powell Island (H.2114.1; X-nicols; ×6).

b. One of the siliceous sandstones from the Greywacke–Shale Formation. Note the generally larger grain-size of the crystal fragments and the smaller quantity of matrix than in Fig. 13a; small island off the southern east coast of Powell Island (H.2121.1; X-nicols; ×6).

c. A network of quartz veins emplaced along shear planes in a thinly bedded siltstone. A few of the veins have themselves been displaced by a later phase of shearing; south-western Powell Island (H.1706.1; ordinary light; ×4).

d. A laminated glassy band formed at the contact between an altered (?) volcanic rock (right) and a disrupted silty shale (left). Subsequent calcite veining cuts across the contact; east coast of Fredriksen Island (H.1346.4; ordinary light; ×6).

form the predominant detrital material since lithic debris is rare. The majority of the feldspar fragments are partially sericitized, polysynthetically twinned plagioclase crystals (An_{10-11}) but there are several fragments of vein- and patch-microperthite and one or two crystals of microcline, myrmekite and chequer-board albite. Scattered flakes of mica and chlorite, and crystals of garnet, allanite and tourmaline represent the accessory detrital minerals, whereas granular concentrations of sphene and epidote and small flakes of muscovite are considered to be authigenic minerals. Lithic debris is represented by occasional pieces of chert, penecontemporaneous siltstones and phyllites and a few fragments of glassy volcanic rocks.

The *siltstones* and finer-grained sandstones are tough massive, dark grey rocks which, like the coarser sandstones, are commonly infolded with the mudstones or enveloped by a veneer of black shale. Shearing and even brecciation of the less ductile sediments have been recorded at a few localities (H.2116) and fissure-like cavities, probably formed during shearing, are present in many specimens. The *mudstones* are normally dull black, massive rocks but when sheared they have developed a slight fissility and shiny slickensided surfaces. Thin alternating laminations of siltstone and mudstone or shale were observed only in specimens H.1706.1 and 1341.2 and in the slightly metamorphosed specimens from station H.2117. A fine network of quartz and calcite veins is a common feature of all the fine-grained sediments (Fig. 13c).

In thin section the sandstones and siltstones are compositionally the fine-grained equivalents (silt-size to 0·2 mm. in grain-size) of the medium-grained sandstones, although they lack lithic fragments. Most of them resemble the siliceous type of sandstone with closely packed, irregular grains of strained quartz and partially sericitized plagioclase embedded in a crushed, fine-grained quartz matrix. Pockets of fine-grained muddy material have been observed in specimen H.2116.2 and concentrations of heavy minerals such as sphene, epidote, (tourmaline, garnet and allanite), and small detrital flakes of muscovite and biotite define a crude bedding in one or two specimens.

Black phyllitic "*shales*" occur on one of the Whale Skerries, at station H.1341. In specimen H.1341.2 they are interbedded with thin horizons of siltstone and in thin section these appear as alternating discontinuous thin laminae (0·1–2·0 mm. in thickness) of phyllitic, dark clay-rich material with minute flakes of chlorite and sericite in preferred orientation, and lighter-coloured silty horizons.

Metamorphism

During a period of extensive folding the Greywacke–Shale Formation of Powell Island was subjected to a phase of essentially dynamic metamorphism which affected the argillaceous sediments more than the arenaceous ones. The shales and finer-grained sediments (H.2117.2) were metamorphosed to phyllitic rocks rich in sericite and chlorite but the sandstones have retained their original clastic structure, showing only the effects of incipient mechanical and chemical reconstitution. In the muddy sandstones the matrix has recrystallized to a mass of microcrystalline quartz and minute sub-parallel flakes of chlorite and sericite, the micaceous minerals sometimes forming thin but definite mineral segregations within the matrix (H.1333.1). All of the crystal and lithic fragments in the sandstones are marginally corroded and the lenticular form of the larger clasts is due to shearing along poorly defined and discontinuous planes in the argillaceous matrix; tiny sub-parallel chlorite flakes have crystallized in the pressure shadows of these augen-shaped detrital fragments. The siliceous sandstone specimens were collected from the vicinity of large faults and their present cataclastic texture is probably due to tectonic brecciation and mylonitization superimposed on the earlier metamorphism induced by folding.

None of the sediments contains any of the critical minerals of the zeolite facies (Coombs and others, 1959) but many of them show a degree of reconstitution similar to that observed in the metamorphosed greywacke sequence of the Te Anau Series, New Zealand (Turner, 1935). However, the New Zealand sediments are progressively metamorphosed to phyllites and ultimately schists, whereas on Powell Island there is no conclusive field evidence for the Greywacke–Shale Formation metasediments grading into the schists of the metamorphic complex.

The age of the orogeny and consequent metamorphism of the Greywacke–Shale Formation must be post-Carboniferous (the tentative age assigned to these sediments) but earlier than the deposition of the relatively undeformed (?) Jurassic or Cretaceous Powell Island Conglomerate. Since K-Ar age determinations on quartz-mica-schists from Signy and Coronation Islands (Miller, 1960; Rex, in press) indicate that there was a period of deformation during Upper Triassic to Lower Jurassic times (based on Kulp's (1961) geological time scale), it is probable that the folding and metamorphism of the Greywacke–Shale Formation were also of that age.

Provenance

A detailed provenance for the Greywacke–Shale Formation cannot be deduced from these altered rocks but it is clear that granitic ones, together with acid volcanic rocks and some subordinate metamorphic rocks formed the source area. Granitic rocks are represented by fairly coarse-grained composite aggregates of quartz and feldspar and by single crystal grains of alkali-feldspar, chequer-board albite, unaltered plagioclase and strained quartz (perhaps from gneisses or sheared older intrusive rocks). Volcanic rock fragments are slightly more abundant than plutonic ones and they are represented by porphyritic and non-porphyritic spherulitic rhyolite, a little andesite and possibly by the crystal fragments of altered feldspar. Fine-grained quartz-mica-schists, metaquartzites and crystal fragments of garnet, epidote and amphibole (very rare) were derived from a metamorphic source, whilst chert and siltstone fragments and (?) phyllites ("shales") are believed to have come from penecontemporaneous sediments.

Petrology of the Powell Island Conglomerate

The Powell Island Conglomerate crops out in the central southern part of Powell Island and on Christoffersen and Michelsen Islands (Figs. 7b and 8). It forms the two main topographic ridges on Powell Island, namely the John Peaks ridge and the one to the north of it, and it is also exposed in the relatively low ground south of John Peaks and around Falkland Harbour. Another conglomerate sequence, the Spence Harbour Conglomerate, unconformably overlies metamorphic rocks at the eastern end of Coronation Island and in the Robertson Islands group, and it differs from the Powell Island Conglomerate in the abundance of clasts derived from a metamorphic source and the unusual occurrence of calcareous grit clasts bearing invertebrate fossils. It is not known whether these two conglomerates are contemporaneous formations (cf. p. 160), since no identifiable plant remains have been found in the Spence Harbour Conglomerate but they are both structurally and lithologically similar and they both overlie disturbed and metamorphosed rocks.

Neither the base nor the top of the Powell Island Conglomerate has been seen and the only recorded contacts between this formation and the underlying, tectonically disturbed Greywacke–Shale Formation are faulted ones. It should be noted that the band of greywacke which was supposed to underlie the conglomerate on Michelsen Island (Tilley, 1935, p. 385) is now believed to be a sub-greywacke parting in the conglomerate (Hoskins, 1960, footnote to p. 8).

Petrography

The Powell Island Conglomerate is a sequence of massive thick conglomerate beds separated by thin impersistent sandstone, siltstone and shale partings which are rarely more than 1 m. in thickness. Many of the finer-grained sediments are carbonaceous, but well-defined plant fragments of a (?) Lower Jurassic age (personal communication from H. A. Orlando) have been recorded only at stations H.2110 and 2119. Boulders of grey plant-bearing sandstones (Fig. 14a) observed at station H.1333 were assigned to the "Derived Series" (cf. p. 165) by Matthews (1959, p. 434) because he had not seen any similar rocks *in situ* on Powell Island. However, A. K. Hoskins subsequently collected a large branch- or root-like fragment (H.1700.3) from a coarse sandstone parting in the Powell Island Conglomerate and K. D. Holmes collected a large slab of micaceous sandstone with plant remains (Fig. 14b) from the moraine on Matthews Island (rocks *in situ* nearby were identical); D. H. Matthews noted that pebbles of a similar sandstone occur on a raised beach on Fredriksen Island.

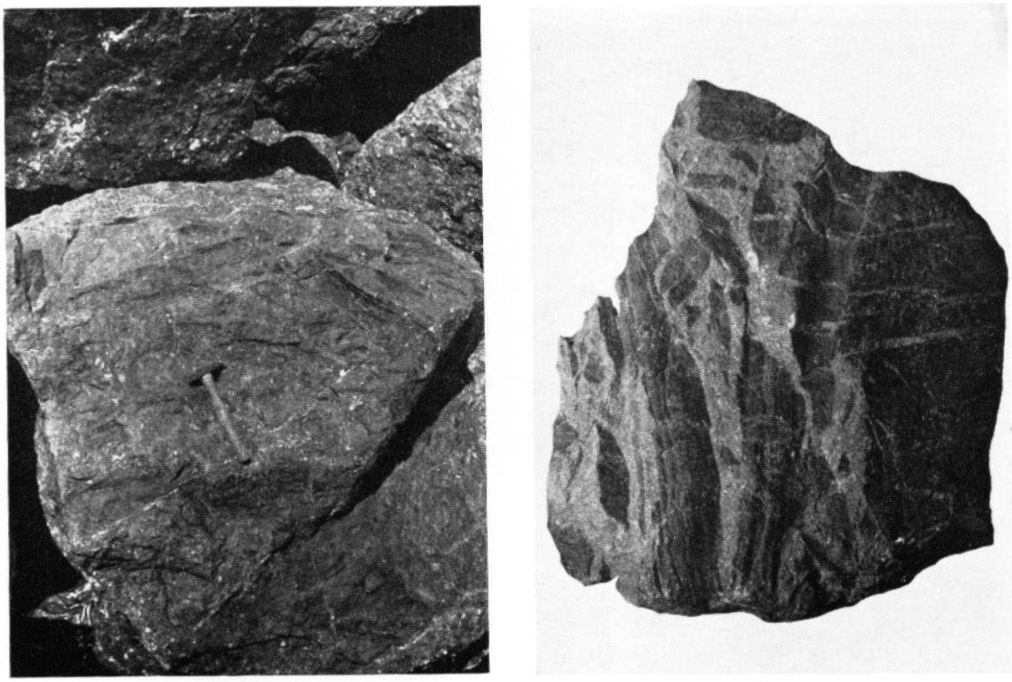
The *conglomerates* (Fig. 15a) are typically of pebble or cobble grade, with closely packed clasts (25–75 mm. in diameter) embedded in a grey gritty sandstone matrix (0·5–1·0 mm. to 1·0–5·0 mm. in grain-size). Coarse cobble conglomerates with clasts up to 17·7 cm. in diameter have been recorded at stations H.1701 and 1704 (Hoskins, 1960, p. 8), while granule-conglomerates (Pettijohn, 1957, p. 19) with only a small number of relatively large fragments were collected from stations H.2106 and 2108 (Fig. 15b). Bedding in the conglomerate is usually indistinct (Fig. 16) but the preferred orientation of the pebbles and the presence of sandy partings in the sequence give a general indication of the depositional layering. Slight

TABLE IV. TYPES OF LITHIC CLASTS PRESENT IN THE POWELL ISLAND CONGLOMERATE

Specimen number	H.1333.3A‡‖	H.1333.3C‡‖	H.1333.10‡‖	H.1333.4D†‡	H.1700.1	H.2106.1†	H.2107.1	H.2108.1	H.2113.1‖	H.2118.1§	H.2118.2§	H.2118.3§	H.2118.4§	H.2120.1	H.2120.5	H.2120.8	H.2120.10
"Greywacke"	*	*	*	*	*	*	*	*	*	*	*	–	*	*	*	*	*
Phyllite	–	–	*	*	–	*	*	*	*	–	*	*	*	*	–	–	*
Mudstone	*	*	–	–	*	*	*	*	*	*	*	*	–	–	*	*	*
Siltstone	–	–	–	–	*	*	*	*	*	*	*	*	–	*	*	*	–
Laminated metasiltstone	–	–	–	–	–	*	*	–	*	–	–	–	–	*	–	*	–
Vein quartz	–	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Quartz-mica-schist	–	–	–	*	–	–	*	*	*	*	–	*	*	*	*	*	*
Micaceous quartzite	–	–	–	*	*	*	–	*	*	–	–	*	–	*	–	–	*
Micaceous siltstone	–	–	–	–	–	–	–	–	–	–	–	–	–	*	–	–	–
Orange-brown or buff sandstone	*	*	*	–	–	–	–	*	*	–	*	*	–	*	–	–	–
Grey sandstone	–	–	–	–	?	*	*	*	–	?	–	–	–	–	*	*	*
Brown shale	*	*	*	*	–	–	*	–	*	–	–	–	–	–	–	*	*
Wood	–	–	–	–	*	–	–	–	–	–	–	–	–	–	–	*	*
Diameter of largest clast (in mm.)	45	50	63	15	23	25	55	10	56	40	50	25	33	100	93	45	26
General size range of diameter of clasts (in mm.)	15–25	10–15	10–25	5–10	1–10	3–10	6–25	4–10	5–15	10–25	15–25	5–15	5–15	10–20	10–25	25–30	5–15

* Present.
† Contains a trace of jasper.
‡ Specimens collected from the moraine.
§ Micaceous haematite in matrix.
‖ Limonitized specimens.

H.1333.3–4 Point on central west coast of Powell Island, north-east of Whale Skerries.
H.1700.1 Northern end of peninsula on west side of Falkland Harbour, Powell Island.
H.2106.1 Northern Michelsen Island.
H.2107.1 Central Michelsen Island.
H.2108.1 North-western coast of peninsula on west side of Falkland Harbour, Powell Island.
H.2113.1 North-western flank of northern John Peaks ridge, Powell Island.
H.2118.1–4 Northern summit of John Peaks, Powell Island.
H.2120.1–10 North-western coast of peninsula on west side of Falkland Harbour, Powell Island.



a b

Fig. 14. a. Boulder of a plant-bearing micaceous sandstone in the moraine at the west coast of Powell Island. (Photograph by D. H. Matthews.)
b. Plant-bearing micaceous sandstone boulder collected from the moraine of southern Matthews Island (H.2101.1; ×0·25).

grading of the deposits is shown by a decrease in the size and the abundance of cobbles from the bottom to the top of a bed (Hoskins, 1960).

The pebbles and cobbles are usually well rounded to sub-rounded, whereas the majority of the smaller clasts are sub-rounded to sub-angular. Table IV shows the lithic types present as clasts in the conglomerates and, although only a limited number of specimens was available for study in the laboratory, it appears that vein-quartz and sandstone pebbles are the most abundant, while clasts of low-grade metamorphic rocks and intraconglomeratic shales and siltstones are less common; a few fragments of fine-grained, altered volcanic rocks are present in the conglomerates collected at Discovery Investigations station No. 1089 (slide Nos. 35998 (Powell Island), and 36004 and 36005 (Michelsen Island)). The sandstone clasts are generally the largest and most equidimensional ones, the fragments of phyllite, schist and intraconglomeratic shales and siltstones occurring as relatively small thin slivers. However, well-rounded oval clasts of brown shale have been observed in the limonitized conglomerates from station H.1333. Small fragments of crushed indeterminate wood were noted in only a few of the conglomerates (Table IV).

The characteristic grey colour of the Powell Island Conglomerate is sometimes modified by a brown limonitic pellicle round the clasts (H.1700.1) and in other examples by the local effects of weathering and mineralization. At station H.2118 the matrix of an otherwise normal pebble conglomerate contains small flaky aggregates of red micaceous haematite. On weathering, the haematite alters to an earthy red substance which has stained the adjacent clasts of the conglomerate and also a sandstone parting (H.2118.5) in the vicinity. Boulders of a pebble conglomerate with an orange-brown sandy matrix have been collected from the moraine and beach at station H.1333 on the west coast of Powell Island. Unfortunately, no specimens of this type have been observed *in situ* but identical orange-brown sandstones (buff-coloured

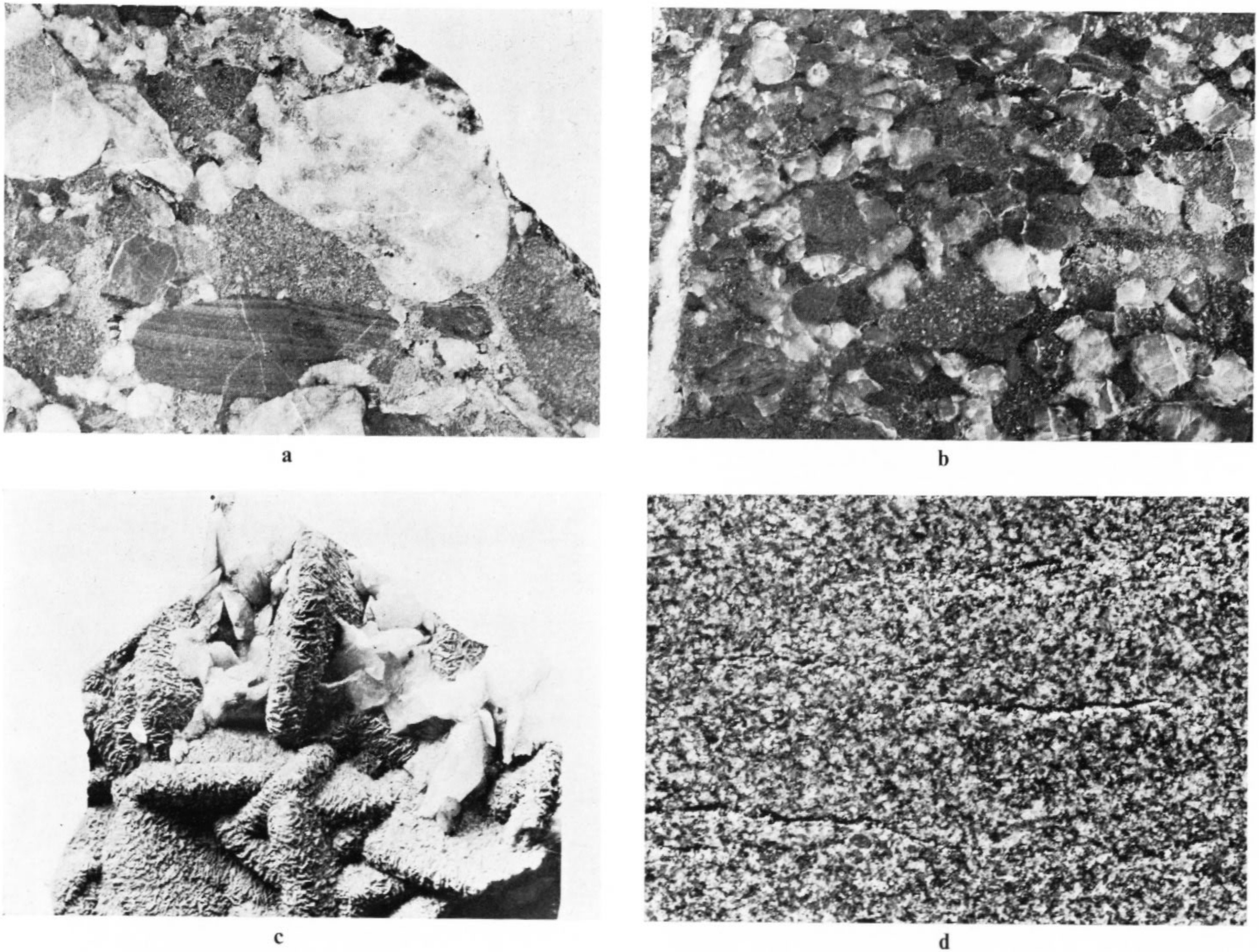


Fig. 15. a. A typical specimen of the Powell Island Conglomerate with pebbles of vein quartz (white), sandstone (light grey) and laminated siltstone (dark grey); central Michelsen Island (H.2107.1; ×1·5).

b. A granule-conglomerate from the Powell Island Conglomerate sequence; western south coast of Powell Island (H.2108.1; ×2).

c. A mineral vein showing calcite rhombohedra grown on rhombohedral siderite; northern John Peaks ridge, Powell Island (H.2113.5; ×1·25).

d. A coarse-grained sandstone from a lens within the Powell Island Conglomerate sequence; northern John Peaks ridge, Powell Island (H.2113.3; ×1·75).

Fig. 16. Bedding indicated by pebbly horizons in the Powell Island Conglomerate; Powell Island. (Photograph by K. D. Holmes.)

when fresh) form clasts in the conglomerate at station H.2113 (H.2113.1 and 4). The orange-brown colour of the sandstone is due to extensive limonitization and, since even the clasts of the conglomerate are pervaded by limonite, it is probable that this orange-brown variety is a locally limonitized example of the typical grey conglomerate; apart from well-rounded brown shale fragments, the clasts are the same as those occurring in the normal Powell Island Conglomerate (Table IV). Although slight limonitization has occurred in the sandstone partings at station H.2113 and a calcite-siderite vein has also been noted here (Fig. 15c), the present position of the moraine specimens (H.1333.3A-G and 1333.10) suggests that this limonitized conglomerate was probably originally situated in the range to the north of the John Peaks ridge. Holmes (1965) noted a (?) sideritic pebble-conglomerate in this northern ridge but no specimens were collected. Orange-brown sandstone clasts also occur in a (?) fault-brecciated conglomerate specimen (H.1703.1) collected from much farther south, where an isthmus connects Powell and Michelsen Islands.

At several localities the conglomerate beds are separated by thin partings of sandstone, siltstone or shale. The junction between the finer-grained sediments and the conglomerate is usually sharp but the partings have a variable thickness and an inconsistent lateral extent, e.g. at station H.1701 Hoskins (1960, p. 9) observed a sandstone band approximately 45 cm. thick which thinned laterally to nothing within 5–6 m.. and at station H.1704 penecontemporaneous erosion of a sandstone has reduced its height from 0·9 to 0·3 m. within a lateral distance of 3 m. The greatest thickness of sandstones noted by Hoskins (1960, p. 9) occurs at station H.1707, where two sandstone partings 3 m. in thickness are separated by approximately 1 m. of conglomerate. No current bedding has been recorded in the sandstones.

A few of the partings have yielded a fossil flora: indeterminate plant remains (mainly fragmental stems and pinnules) were collected by A. K. Hoskins from a 35 cm. thick parting in the conglomerate at station H.1705 and he also collected a large branch- or root-like fragment from a coarse sandstone parting at station H.1700. A better-preserved flora was discovered by K. D. Holmes in black, slightly micaceous mudstone and siltstone partings in the conglomerate of the John Peaks ridge (H.2110.1–6 and 2119.1–15). These specimens (a varied collection of broken fronds, stems and pinnules) were examined by H. A. Orlando, who likened them to the Hope Bay flora of Trinity Peninsula which he regards as Lower Jurassic in age (personal communication). Shiny black streaks present in a coarse sandstone from Michelsen Island (H.2107.2) and a dark grey sandstone (H.1333.8) collected from the moraine on the west coast of Powell Island could also be of vegetable origin.

The *sandstones* (Fig. 15d) are mid-grey in colour and sometimes slightly micaceous, having a grain-size which varies from 0·1–0·3 mm. to 1–2 mm. In thin section they can be distinguished from the sandstones of the Greywacke–Shale Formation by their greater quantity of shaly and schistose lithic material, the common presence of detrital biotite, the inclusion of altered "greywacke–shale" type fragments and their general lack of cataclasis or alteration. Moderate to poor sorting of the sandstones and the abundance of detrital biotite imply a textural immaturity but the rounded to sub-angular shape of some of the crystal fragments (probably re-worked detritus of the Greywacke–Shale Formation) suggests a greater textural maturity. Modal analyses of the sandstones are given in Table V and their classification, according to Folk (1954) and van Andel (1958), is shown in Fig. 12a and b.

TABLE V. MODAL ANALYSES OF SANDSTONES FROM PARTINGS IN THE POWELL ISLAND CONGLOMERATE

	H.1700.2	H.1702.1	H.2107.2	H.2107.3	H.2111.1	H.2113.2	H.2113.3
Quartz	24	42	33	41	32	42	52
Plagioclase	5	9	6	14	13	12	10
Alkali-feldspar	1	2	1	3	1	1	2
Mica	4	6	6	11	10	4	*
Chlorite	1	–	*	*	1	*	*
Heavy minerals	*	1	*	1	1	*	*
Metamorphic rocks	23	2	23	5	7	3	6
Igneous rocks	1	1	3	1	*	1	3
Sedimentary rocks	30	12	17	6	2	9	18
Chert	*	1	*	–	–	*	1
Matrix	11	24	11	18	33	28	8

* Less than 0·5 per cent present.

H.1700.2	Northern end of peninsula on west side of Falkland Harbour, Powell Island.
H.1702.1	North-east of Falkland Harbour, Powell Island.
H.2107.2 and 3	Central Michelsen Island.
H.2111.1	Eastern flanks of the John Peaks ridge, Powell Island.
H.2113.2 and 3	North-western flank of northern John Peaks ridge, Powell Island.

Bedding of the sandstones is indicated in thin section by the crude preferred orientation of the shaly and schistose lithic fragments, many of the slivers being partially distorted by the impact of adjacent quartz grains, whilst some are squeezed between other lithic and crystal fragments (Fig. 17). Sediments usually form the most abundant lithic debris but metamorphic rock fragments predominate in specimens H.2107.2 and 2111.1, and small clasts of volcanic

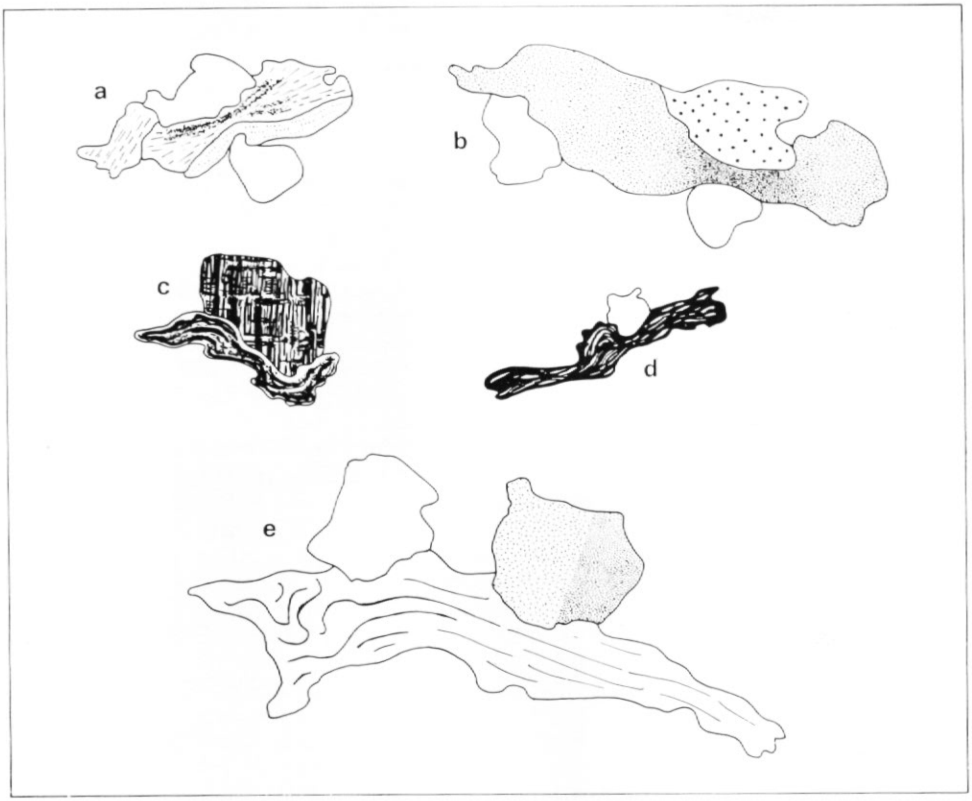


Fig. 17. Irregularities in mica, siltstone or schist fragments in intra-conglomeratic sandstones caused by contact with quartz or feldspar crystals. All drawings are ×80.

a. Biotite (shaded and speckled with (?) graphite) and muscovite (aligned stipple) flakes impinged upon by quartz grains (clear); in both micas the cleavage is bent accordingly; Michelsen Island (H.2107.3).
b. Siltstone (fine stipple) fragment squeezed between a sandstone fragment (coarse stipple) and a quartz grain (clear); Michelsen Island (H.2107.2).
c. Microcline crystal (twinned) causing distortion of a graphitic quartz-mica-schist fragment; Michelsen Island (H.2107.3).
d. Quartz crystal (clear) impinging on a graphite-schist fragment; central Powell Island (H.2113.2).
e. Quartz (clear) and twinned feldspar (stippled) crystals causing irregularities in a fragment of quartz-mica-schist; southern Powell Island (H.1700.2).

rocks, although uncommon, occur in every specimen studied. Crystal fragments of quartz (often cracked) and partially sericitized plagioclase (An_{7-11}) are common, whereas fragments of vein- and patch-perthites, microcline and granophyric and myrmekitic quartz-feldspar intergrowths are relatively rare. Large flakes of orange-brown biotite are slightly bleached and they have suffered from post-depositional kinking and straining; some chloritized biotite is also present. Heavy minerals such as epidote, garnet, sphene, zircon and apatite are abundant but hornblende is extremely rare and iron ore, usually leucoxenized, is uncommon.

Limonite is a constant feature of all the sandstones but it is particularly important in the finer-grained ones where it replaces both lithic and mineral detritus (H.2113.2). In the medium- and coarse-grained sandstones it forms either sporadic small, interstitial patches of yellowish brown material (H.2107.3) or a thin film coating the clasts (H.2107.2). Patches of secondary calcite are uncommon.

The *siltstones* and *mudstones* are thickly laminated, dark grey or black rocks with a poor fissility and a scattering of mica flakes on the bedding planes. The siltstones are generally more micaceous than the mudstones (a pronounced depositional alignment of the muscovite and biotite flakes is visible in thin section) but both rocks contain plant fronds and other fragmental plant debris. There is only one micaceous silt-shale specimen (H.1704.1A) in the collection.

Depositional environment and provenance

The Powell Island Conglomerate represents the accumulation of deposits in a shallow marine or fluviatile environment. The roundness of most of the cobbles and pebbles in the conglomerates is indicative of erosion by water and, from the rock types forming the cobbles, it is clear that the source area was situated locally. Fluviatile or estuarine deposition of the sandstone bands was favoured by Hoskins (1960, p. 9), since lenses of pebbles occur in them, whereas plant-bearing horizons in the conglomeratic sequence indicate a proximity to land.

The majority of the clasts in the Powell Island Conglomerate can be correlated with the metamorphic and sedimentary rocks recorded *in situ* on Powell Island and the Whale Skerries. Although the general absence of garnetiferous schist clasts and the paucity of garnet crystal fragments in the intra-conglomeratic sandstones indicates that little material was derived from the west, i.e. from the metamorphic rocks of Signy and Coronation Islands, there is some evidence that debris was derived both from the north and the south. Phyllitic rocks and schists present as clasts in the conglomerates from the south coast of Powell Island are similar to rocks observed *in situ* at geological stations farther north (H.1341, 2112 and 2117), whereas volcanic fragments apparently increase in number on passing south-eastward from Powell Island to Michelsen and Fredriksen Islands, implying perhaps that there was a south-easterly volcanic source area. Tilley (1935, p. 385) indicated a southerly derivation of the conglomerates by noting that they increased in grain-size towards the south but Hoskins (1960, p. 11) was unable to corroborate this.

Hoskins (1960, p. 11) maintained that 50 per cent of the cobbles in the Powell Island Conglomerate were derived from the "Basement Complex", presumably referring to the schists of Signy and Coronation Islands as the basement. However, some of the cobbles which he included in the "Basement Complex" are regarded by the author as members of the metamorphosed Greywacke–Shale Formation, e.g. a phyllite (H.1704.4) and a semi-schist (H.1701.2). The source of the vein-quartz and quartzite pebbles is not known because veins of quartz in the Greywacke–Shale Formation of Laurie and Powell Islands and in the schists of Signy and Coronation Islands are not usually very wide, whereas some of the quartz pebbles in the conglomerate are fairly large; there is no record of quartzites on Powell Island and very few occur on Coronation Island. Pebbles of vein quartz and volcanic rocks apparently form only 20 per cent of the conglomerate and the rest of the detritus was derived from the metamorphic complex, the Greywacke-Shale Formation and intra-conglomeratic sediments.

Correlation with the Spence Harbour Conglomerate

The Spence Harbour Conglomerate, which overlies the metamorphic complex of the South Orkney Islands, has been recorded at the eastern end of Coronation Island and in the Robertson Islands (Fig. 18). The relationship between the Spence Harbour Conglomerate and the metamorphic complex rocks is an enigmatic one, since at Gibbon Bay approximately 2 m. of fossiliferous sheared black shale separate the two formations (Matthews, 1959, p. 435) and in the vicinity of Fulmar Crags and at Whale Bay a dark grey to black conglomerate or breccia occurs between the typical light grey conglomerate and a sequence of brecciated schists (unpublished report of D. H. Matthews; Thomson, in press). Further contacts between the conglomerate and the schists are known on Matthews Island and a small island to the south of it (Thomson, 1971) but these are obscured by snow and scree and they are not readily accessible. However, at least 90 per cent of the clasts in the conglomerate are derived from metamorphic rocks and it is clear that the Spence Harbour Conglomerate is younger than the metamorphic complex.

Although the Spence Harbour Conglomerate is lithologically similar to the Powell Island Conglomerate, there are minor differences between the two. Boulders up to 2·4 m. in diameter have been recorded in the former, whereas the largest fragment in the Powell Island Conglo-

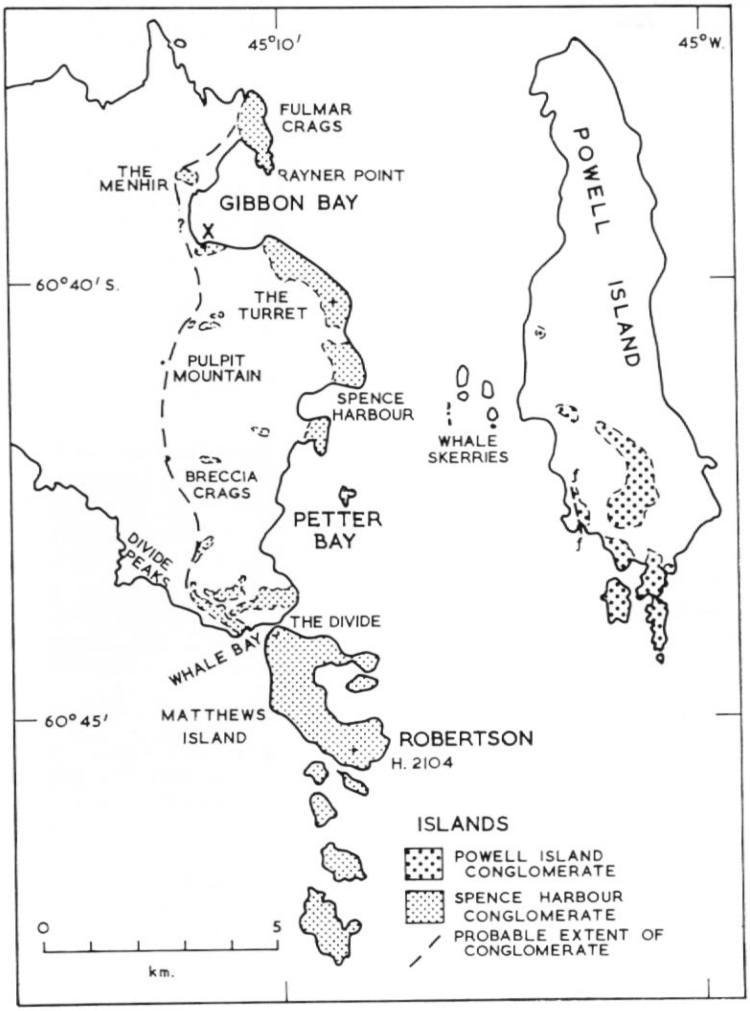


Fig. 18. Sketch map of eastern Coronation Island showing the outcrops and probable extent of the Spence Harbour Conglomerate; the distribution of the Powell Island Conglomerate on Powell Island is shown for comparison. Locality X is the collecting site for the Gibbon Bay Shale.

merate measures 17·7 cm. in diameter. On the south side of Petter Bay, the thin sandstone bands separating the crudely bedded conglomerates become thicker and more common, and on the Gibbon Bay coast north of The Turret these reach a maximum of 3·5 m. (unpublished report of D. H. Matthews). A 24 m. thick sequence of micaceous sandstones and siltstones lying between the conglomerates on Matthews Island (Thomson, 1971, fig. 6) represents the thickest development of fine-grained sediments in either of the South Orkney Islands conglomerates. Ripple-marked sandstones have been observed in the vicinity of Divide Peaks, Coronation Island, and on the ridge to the south of the highest peak of Matthews Island but none has been recorded in the Powell Island Conglomerate; there is no record of current bedding in the sandstones from either of the conglomerates.

Fossil evidence, by which a direct correlation of the conglomerates could be made, is lacking and, although an identifiable Lower Jurassic flora has been collected on Powell Island (personal communication from H. A. Orlando), there are no similar collections from Coronation or Matthews Islands. Nevertheless, indeterminate plant remains have been observed at several localities on Coronation Island and large stems or branches (Fig. 14b) similar to one specimen from Powell Island (H.1700.3) occur in the Matthews Island sandstones. No faunal remains have been found in the Powell Island Conglomerate and only a poorly preserved invertebrate fauna occurs in or beneath the Spence Harbour Conglomerate. For example, the 2 m. thick Gibbon Bay Shale has yielded a fauna which is possibly Upper Cretaceous in age (Matthews, 1959, p. 435) although it may be older, and at Rayner Point there are a few calcareous grit boulders in the conglomerate (similar to calcareous grit pebbles included in the Gibbon Bay Shale) which also contain a poorly preserved fauna of Cretaceous affinities; these boulders have been assigned to the "Derived Series" by Matthews (1959, p. 434). On Matthews Island, micaceous sandstones with a calcareous cement occur at station H.2104 and moraine specimens derived from this locality have yielded a few fragmentary ammonites and a small number of poorly preserved bivalves; the ammonites are possibly Cretaceous in age (personal communication from M. R. A. Thomson). The fossil evidence therefore gives rise to conflicting opinions with regard to the age of the conglomerates and, until direct evidence becomes available, the two conglomerates should be regarded as separate formations.

Comparison of Powell Island with the Other Islands of the South Orkney Islands

Powell Island separates the unmetamorphosed Greywacke–Shale Formation of Laurie and Fredriksen Islands (Fig. 1) from the metamorphic complex of Coronation and Signy Islands and it conveniently divides the South Orkney Islands into an eastern group and a western one. Those islands east of Powell Island have been visited infrequently and no detailed geological survey of them has been undertaken but the geology of Signy and Coronation Islands is well known (Matthews and Maling, 1967; Thomson, 1968, in press), and the petrography of the Larsen and Inaccessible Islands has been studied in detail (West, 1968).

Islands east of Powell Island

The islands east of Powell Island (Fig. 19) are the principal areas of outcrop for the relatively unmetamorphosed Greywacke–Shale Formation. (?) Volcanic rocks occur within the Greywacke–Shale Formation on Fredriksen Island and there are possibly Mesozoic conglomerates on both Fredriksen and Laurie Islands.

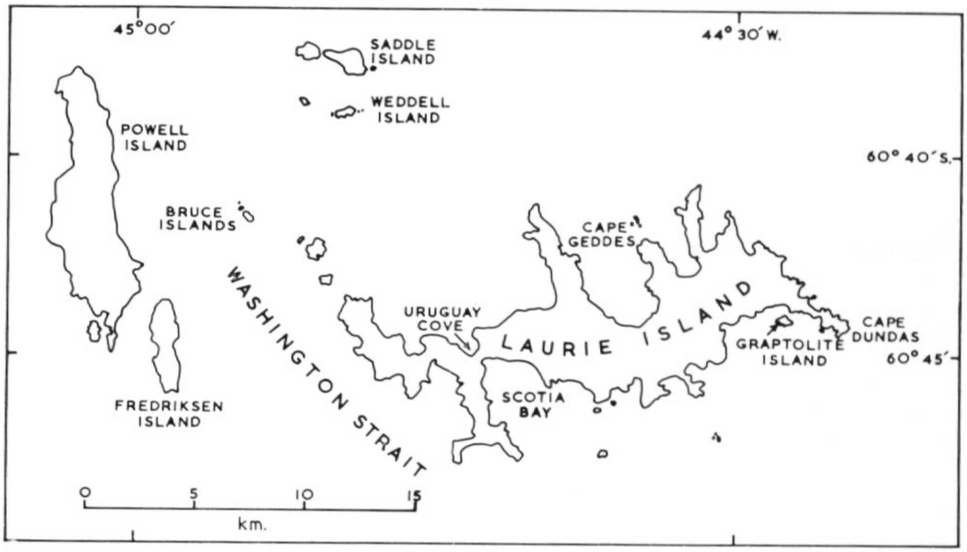


Fig. 19. Sketch map of Powell, Fredriksen and Laurie Islands; only the place-names mentioned in the text are shown.

Fredriksen Island, which is a small narrow island 0·8 km. south-east of Powell Island, is elongated north–south and it has a well-defined central ridge extending the whole of its length (Marr, 1935, pl. XXII, fig. 1). The present cursory examination of the island is based on a small rock collection from two localities on the west coast (Discovery Investigations station 1090; Tilley, 1935, fig. 1) and the few specimens collected from the east coast by D. H. Matthews (January 1957; H.1343.1–1346.4) and D. W. Matthews (January 1965; H.2209.1). Highly folded dark sandstones and black phyllitic shales are present on both the east and west coasts ("greywacke" pods in the shale and a dip of 40° to the south were recorded in the Greywacke–Shale Formation of the east coast) and there may be conglomerate on the summit of the central ridge in the middle of the island (unpublished field notes of D. H. Matthews). Although in thin section the sandstones and the finer-grained sediments are very similar to those of the Powell Island Greywacke–Shale Formation, both in detrital content and general appearance they have been less affected by dynamic metamorphism. Both quartzo-feldspathic and muddy sandstones are represented and several of them contain small streaks of (?) carbonaceous material; depositionally aligned detrital biotite is an important mineral in a few of the muddy sandstones. The shales have a slightly shiny crumpled surface similar to that of the phyllites from the Whale Skerries (specimen H.1345.1 is a paper shale interbedded with a thin horizon of siltstone), and a shale collected from the west coast (Discovery Investigations station 1090, slide No. 36016) has an opaque brown matrix of (?) carbonaceous material.

A greenish sill-like feature, previously referred to as a (?) serpentinitic sheet (Thomson, 1968, p. 24), is exposed in the sandstone cliffs of the east coast (unpublished field notes of D. H. Matthews and D. W. Matthews); the "sill" is in sharp contact with the country rock but it is infolded with it and has many slickensided surfaces. In the hand specimen, the rock is massive, fine-grained and light greyish green in colour, and it is cut by a complex of quartz, epidote and calcite veins (H.1346.2 and 2209.1). In thin section it comprises a confused mass of radiating plumose aggregates of crudely twinned plagioclase (An_6), streaks of chlorite, granular epidote and sphene, and patches of quartz. No definite structures could be discerned under the microscope but the overall appearance of the "greenstone" is more typical of a lava than a serpentinite.

The sharp contact between the "greenstone" and the country rock (a thinly laminated black shale) is seen in a small specimen (H.1346.4) collected from the beach below the main sill-like outcrop. It is marked by a laminated glassy band (Fig. 13d), possibly representing the chilled base of a lava or the chilled margin of a minor intrusion but the shale in contact with the glass is extremely disrupted and the glass could be of tectonic origin (i.e. a pseudotachylyte). A cobble (H.1346.3) collected from the beach at this locality is a massive, fine-grained, dark red rock which in thin section is similar to the "greenstone" specimens, differing from them only in the widespread occurrence of dendritic haematite. It is interesting to note here that massive dark red haematitized rocks occur also on Joinville Island (Elliot, 1967, p. 29).

Only one pebble-conglomerate specimen has been collected from Fredriksen Island (Discovery Investigations station 1090, slide No. 36019) but it has been tentatively correlated with the Powell Island Conglomerate. The clasts are predominantly volcanic rocks, the largest of these being a pebble of spherulitic rhyolite 1·7 cm. in diameter; smaller fragments (1–2 mm. in diameter) of rhyolite and other fine-grained volcanics, graphitic quartz-mica-schists, quartzose schists, vein quartz and biotite-rich sandstones are also present.

The *Bruce Islands*, a small group of islands north-west of Fredriksen Island (Fig. 19), are composed of massive greenish rocks intercalated with black beds (unpublished field notes of D. H. Matthews); the greenish rocks here could be either sandstones or igneous sheets.

Saddle and Weddell Islands are also relatively unknown. The first landing on Weddell Island was made in 1838 under the direction of Captain Dumont d'Urville and he recorded greyish limestone and phyllitic shales with a north-north-west to south-south-east trend and a dip greater than 60°. Pirie (unpublished, p. 2) visited Saddle Island briefly and he compared the "hard, grey-green greywacke" to the sandstones from Laurie Island; no rocks other than "greywacke" were observed on the island and neither bedding nor cleavage was visible. Although no specimens were available for examination in the laboratory, it is assumed that the rocks from these islands belong to the Greywacke–Shale Formation.

Laurie Island is the second largest of the South Orkney Islands and it is also the easternmost one. The first geological survey of the island was carried out by the Scottish National Antarctic Expedition during 1902–04 (Pirie, 1905, 1906, unpublished) and the rock specimens collected by Pirie were described by Holtedahl (1929) and Stewart (1937). Further rock collections were made by members of R.R.S. *Discovery II* in January 1933 (Tilley, 1935) and February 1937, and additional specimens were collected by R. J. Adie in 1947 (Adie, 1958); the results of recent structural investigations of the island have been outlined by Dalziel (1971).

Sediments of the Greywacke–Shale Formation are present at most of the known localities on Laurie Island, and from Pirie's (1905, unpublished) description of the rocks, together with a re-examination of the later collections, it appears that many of the sandstones and siltstones are similar to those of either Fredriksen or Powell Islands. However, veins of prehnite and quartz are common in the Laurie Island specimens and the sandstones are only slightly altered in comparison with those of Powell Island, i.e. their sedimentary texture has not been completely obscured by folding and shearing. Nevertheless, Holtedahl (1929, p. 99) noticed in a few of Pirie's specimens that the rocks had undergone "considerable mechanical deformation, with crushing or breaking of mineral and rock fragments" and a "greywacke showing gneissic banding and folding" on the east side of Uruguay Cove (Pirie, unpublished, p. 4) could be an outcrop of low-grade schists comparable to those on Powell Island.

Pirie (1905, 1906) discovered three fossils in the shales of Graptolite Island and these were identified as the stipes of *Pleurograptus* and two fragments of a crustacean carapace. On the basis of this fossil evidence he concluded that the Greywacke–Shale Formation was Ordovician in age but Wilckens (1933, p. 327) dismissed the fossils as inorganic structures and refuted the early Palaeozoic age assigned to the sediments, agreeing with Tyrrell (1930, p. 53) that the sediments from the South Orkney Islands were similar to the "greywackes" of South Georgia. Cordini (1955, p. 273–77, fig. 82) described a more recent collection of fossils from Graptolite Island, amongst which were fragments of [?] *Dicellograptus* and [?] *Conularia*, together with a few fragmentary plants, and he also mentioned that fossils similar to those of Graptolite Island have been seen at Cape Dundas, Laurie Island. Cordini believed that these fossils confirmed the Ordovician age of the Greywacke–Shale Formation but a subsequent re-examination of Pirie's specimens from Graptolite Island has shown that their graptolitic affinities are extremely doubtful and they could "equally well be identified as plant fragments and assigned to the Carboniferous" (Adie, 1957, p. 22). However, the Laurie Island sediments are still considered as early Palaeozoic in age by some authors (e.g. Cordini, 1959, p. 154, 157; King and Downard, 1964).

Dalziel (1971, p. 124) doubted the presence of any late Mesozoic conglomerates on Laurie Island but there is, nevertheless, some evidence for a younger sequence of rocks on the island. Two granule-conglomerate specimens collected at Cape Geddes by R. J. Adie and two more from the west side of Scotia Bay (Discovery Investigations station 1959, slide Nos. 38838 and 38890) are similar to the granule-conglomerates of Powell Island, although they contain a much higher percentage of matrix (rich in detrital biotite) and the lithic fragments are predominantly volcanic. A few of the sandstones (CG.4 and 7) are similar to the sandy matrix of the granule-conglomerates and they appear to be much fresher than the sandstones of the Greywacke–Shale Formation; they are rich in detrital biotite and cracked quartz crystals and the small amount of lithic detritus in them (generally volcanic) is well rounded, suggesting that it is second-cycle debris. These sediments possibly represent, therefore, a younger sequence of conglomerates resting on the contorted Greywacke–Shale Formation of Laurie Island (cf. "Laurie Island Conglomerate" of Matthews and Maling (1967, p. 2)) but the author has not had the opportunity to verify this suggestion in the field.

Islands west of Powell Island

Rocks of the South Orkney Islands metamorphic complex crop out on all the islands west of Powell Island but the Mesozoic Spence Harbour Conglomerate, which overlies the metamorphic rocks, is present only at the eastern end of Coronation Island and in the Robertson Islands. The geology and petrography of the metamorphic rocks (low- and medium-grade regionally metamorphosed *para*schists) have been described in considerable detail

(Tilley, 1935; Matthews and Maling, 1967; Thomson, 1968, 1971, in press; West, 1968), those on Coronation Island belonging to the greenschist, albite-epidote-amphibolite and amphibolite facies of Fyfe and Turner (1966). The Larsen Island schists also belong to the greenschist facies, whereas those farther west in the Inaccessible Islands fall within the albite-epidote-amphibolite and the amphibolite facies (West, 1968). The abundance of marbles and amphibolites in the metamorphic complex of Signy Island (Matthews and Maling, 1967; Thomson, 1968) distinguishes it from the metamorphic sequence of Coronation Island and it is possible that the original sedimentary rocks of the two islands were of differing facies.

Conclusions

Although the low-grade regionally metamorphosed rocks of Powell Island are apparently overlain by the much contorted and altered sandstones and shales of the Greywacke–Shale Formation, the relationship between the two formations has not been satisfactorily observed in the field. The relative and absolute ages of the metamorphic rocks are not therefore known but the Greywacke–Shale Formation has been compared with the Carboniferous Trinity Peninsula Series of Graham Land (Adie, 1957) and the younger Powell Island Conglomerate has been tentatively assigned to either the Lower Jurassic (on palaeobotanical evidence) or the Cretaceous; it is not known whether the Powell Island Conglomerate is separated from the underlying Greywacke–Shale Formation by a thrust or an unconformity. The Powell Island Conglomerate has been compared with the Spence Harbour Conglomerate but there is insufficient fossil evidence to support a direct correlation of the two. Similarly, there is no direct proof that the conglomerates of Fredriksen Island, and possibly those of Laurie Island, are an easterly extension of the Powell Island Conglomerate. The age of the "greenstone" recorded in the Greywacke–Shale Formation on Fredriksen Island is not clear from the known field data and it could represent either an altered lava flow or a minor intrusion.

The "Derived Series" of Matthews (1959, p. 434) has not been included in the stratigraphical scheme of Powell Island for a number of reasons. Matthews originally erected this "series" to accommodate a group of rocks of unusual lithologies which he had observed as boulders in the Spence Harbour Conglomerate and in the moraine on Powell Island, apparently assuming that they were all of Jurassic age. He defined the rocks of the "Derived Series" as:

"(a) Calcareous grits with brachiopods, lamellibranchs, belemnites, and plants of Mesozoic, probably Jurassic, age.
(b) Current-bedded sandstones with plants.
(c) Felsite, spherulitic felsite and rhyolite (Tilley, 1935, p. 386)."

However, plant-bearing sandstones (category (b)) have been found *in situ* within the Powell Island Conglomerate and also within the (?) Cretaceous Spence Harbour Conglomerate of Matthews Island, and the fossiliferous calcareous grit boulders (category (a)) occur in the Gibbon Bay Shale which underlies the Spence Harbour Conglomerate at one locality on Coronation Island. Therefore, caterory (b) could be appreciably younger than category (a) and it should not be included in the same stratigraphical "series". Furthermore, acid volcanic detritus (category (c)) is abundant in the granule-conglomerates and sandstones collected at Cape Geddes and Scotia Bay, Laurie Island; until it is known whether these belong to the Greywacke–Shale Formation or a younger sedimentary sequence, the validity of referring the volcanic detritus to the *Jurassic* "Derived Series" is disputable.

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