THE GEOLOGY OF NORTH-WESTERN SOUTH GEORGIA: IV. STRUCTURAL GEOLOGY

By R. A. S. Clayton

Abstract. Structural mapping of the area bounded by the Bay of Isles, King Haakon Bay and Wilson Harbour has led to the recognition of three phases of folding. The first folds (F1) are asymmetrical with steep southerly dipping axial surfaces and gentle westerly plunging hinges. The first cleavage is intense in all lithologies, occurring as a slaty cleavage in the mudstones and a fracture cleavage in the volcanic greywackes.

Minor F2 folds are slightly asymmetric open structures with a gentle westerly plunge. The hinge surfaces of the minor folds dip steeply to the north and, although large-scale F2 folds have not been observed in the field, their presence is inferred both from stereographic analysis and from systematic changes in the attitude of the first cleavage.

F3 folds are characteristically monoclinal with north-north-easterly trending hinges and sub-vertical hinge surfaces. Although a corresponding crenulation cleavage has not been observed, the F3 folds generally occur in association with well-developed kink banding, which is axial planar to the major structures.

The formation of the F1 folds and the superimposed F2 structures is attributed to a northerly directed compressive stress.

The sub-Antarctic island of South Georgia lies approximately 2,000 km. east of Cape Horn (between lat. 54° and 55°S., and long. 36° and 38°W.) and is the largest island on the north Scotia Ridge. The structural geology of the intensely deformed Cumberland Bay Formation at the north-western end of South Georgia was investigated during the austral summer seasons of 1972–73 and 1973–74 as part of a broad geological survey of the island.

The first detailed account of the structural geology of South Georgia was given by Trendall (1953), who described a single phase of folding in the Cumberland Bay-type rocks between Grytviken and Fortuna Bay. He suggested that the rocks were overfolded from the south-south-west, individual folds plunging at 10–20° to the west-north-west. This work was supplemented by a more comprehensive report (Trendall, 1959), in which he noted that on tracing the well-developed cleavage north-westward from Cumberland East Bay its intensity diminished and the inclination steepened. These changes were accompanied by a swing in the strike of the cleavage to east–west and a gradual decrease in the westerly fold plunge to less than 10° in the Right Whale Bay area.

Skidmore (1972) confirmed Trendall's findings by suggesting that the structure of the Cumberland Bay rocks had resulted from a single fold episode which gave rise to a series of asymmetrical folds with moderate to steep south-westerly dipping axial planes.

Geological mapping in the Bay of Isles and Cheapman Bay–Wilson Harbour areas of South Georgia has revealed three phases of folding. East–west trending F1 folds (Fig. 1) predominate throughout this area, being re-folded in the area between Elephant Cove and Nilse Hullet by the north-north-east trending F3 monoclines (Figs. 1 and 2). F2 folds also trend east–west but are much smaller and occur in zones on the limbs of the F1 folds.

The folds in their typical development show the following geometries:

F1. Asymmetric folds (Fig. 3) with a shallow plunge in a westerly or west-north-west direction. Folds are open to closed with a southerly axial-planar dip of approximately 45° (Figs. 3–5). Where F3 re-folding is intense, the westerly F1 plunge increases by up to 40°.

F2. Slightly asymmetric open folds with a gentle westerly plunge. Wave-lengths of the minor folds rarely exceed 2 m. and hinge surfaces dip steeply to the north. Large-scale F2 folds were not observed in the field but their presence is inferred from stereographic analysis.

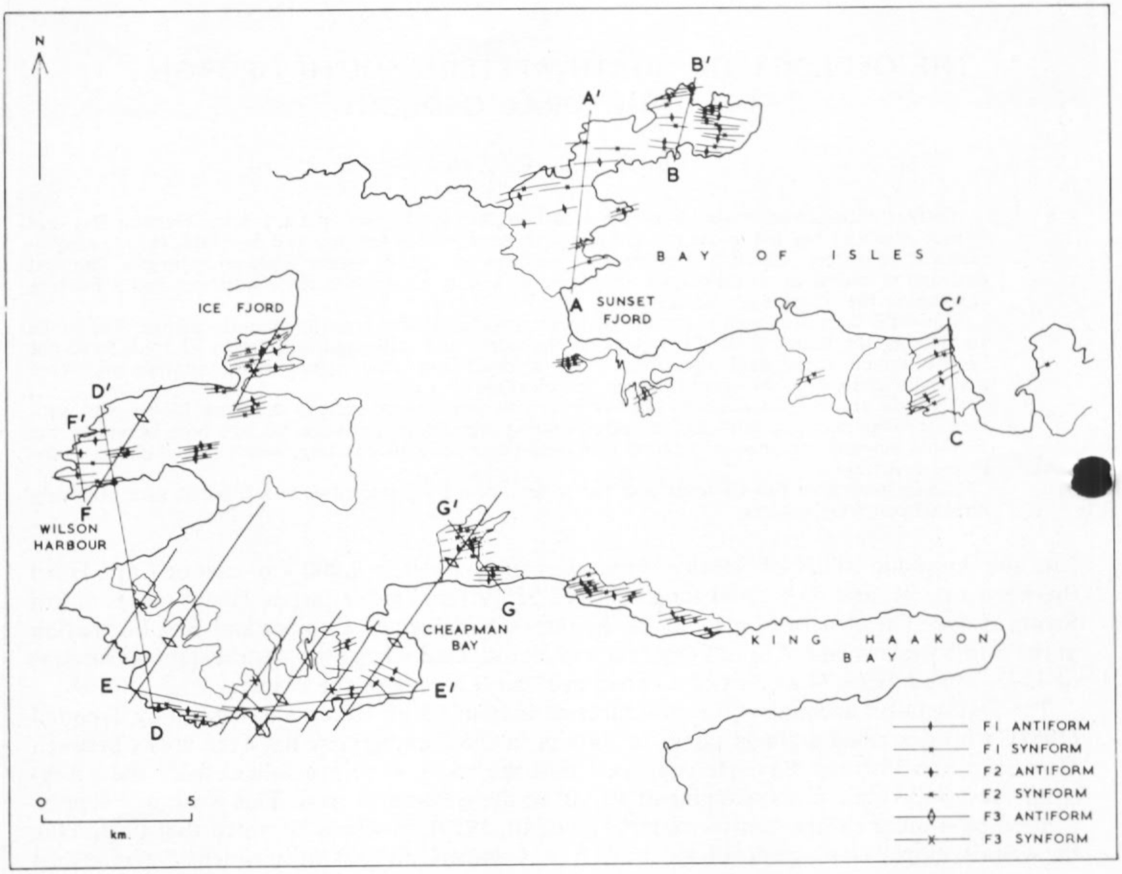

Fig. 1. Sketch map of part of north-western South Georgia showing the trend of major folds.

F3. Open to gentle monoclinal folds (Fig. 4) with a moderate south-westerly plunge. Axial planes dip steeply to the south-east. The larger structures have wave-lengths well in excess of 1 km.

Trend maps for bedding, cleavage and lineations summarize the structural data (Figs. 6–12). Bedding, cleavage and lineation data have been plotted stereographically for the eight topographically delineated sub-areas shown in Fig. 2.

F1 Folding

F1 fold hinges trend predominantly east–west, swinging to west-north-west in some areas as a result of F3 re-folding (Fig. 13). The majority of F1 folds are parallel but similar and occasional chevron folds have been observed. Folding changes in style and wave-length from the north towards the south coast of the island, individual folds becoming more upright with an increased wave-length and less distinct asymmetry (Figs. 3–5). The inclination of the southerly dipping axial surfaces changes correspondingly from moderate to steep (Figs. 3 and 4). F1 folds are generally close in the north with a sub-horizontal plunge. Towards the south coast, folding becomes open and the hinge plunge varies, increasing to moderate in areas where F3

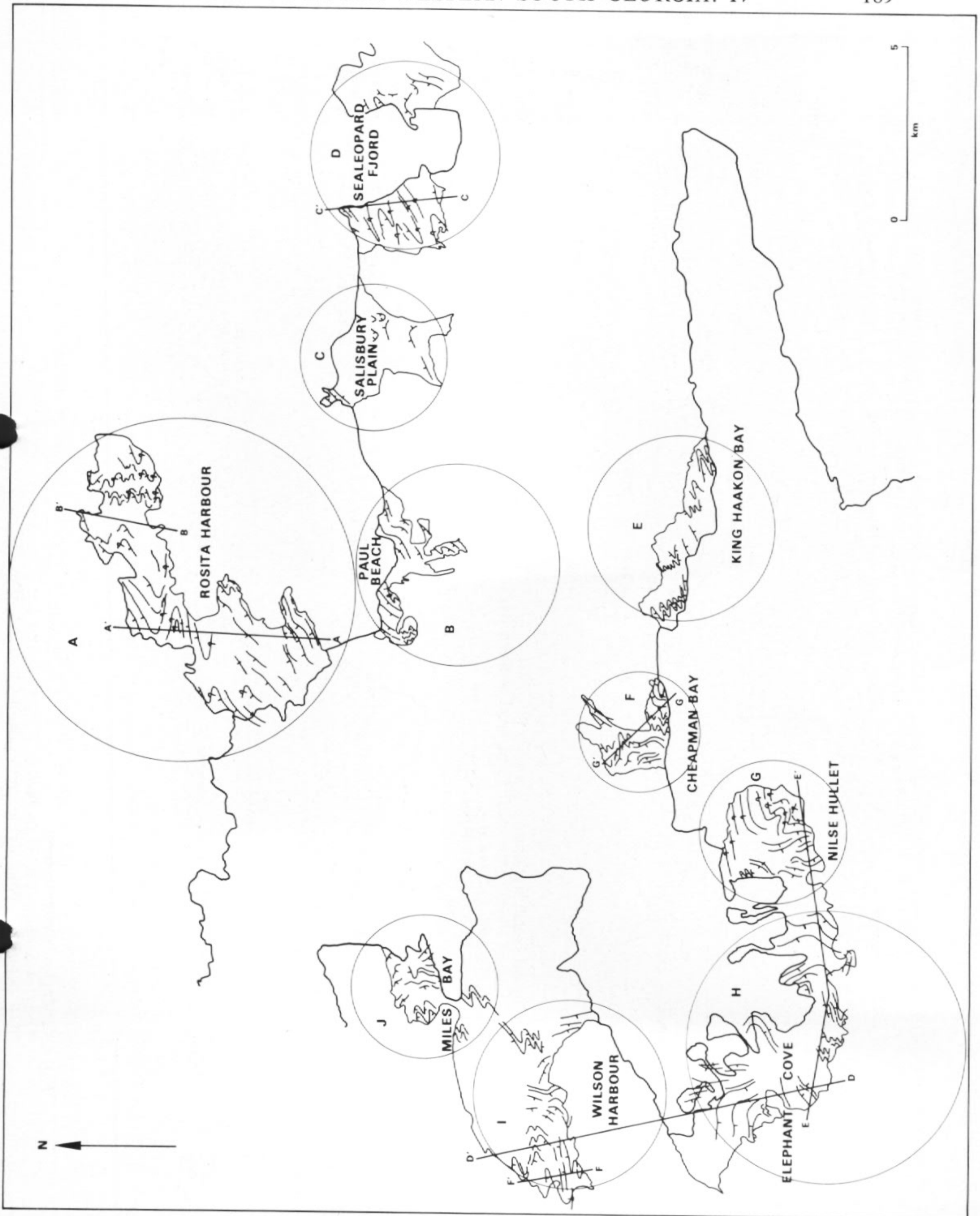

Fig. 2. Bedding trend map of part of north-western South Georgia. Circles define topographically delineated areas chosen for stereographic analysis.

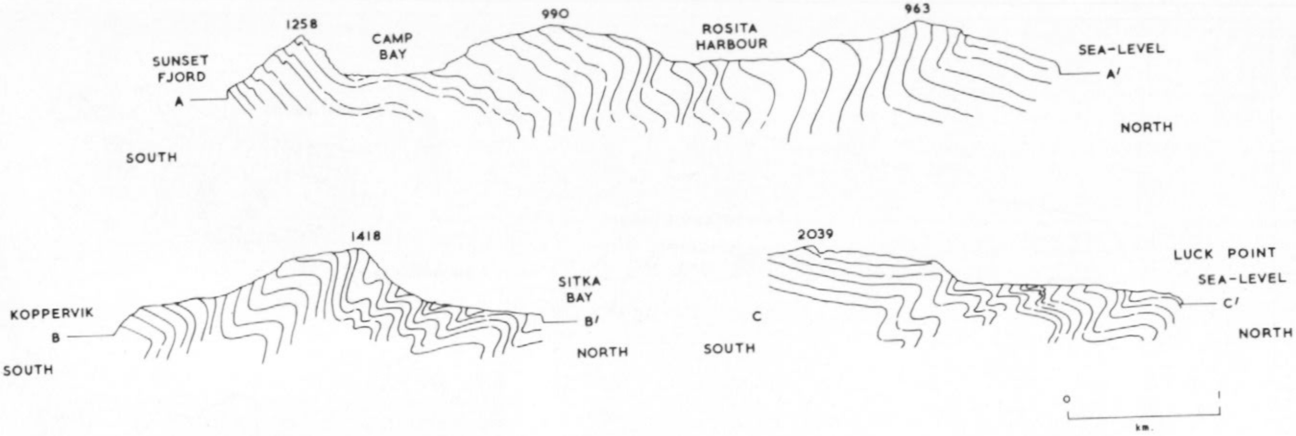

Fig. 3. Geological sketch sections.
A–A′ Sunset Fjord to the coast 5 km. west of Sitka Bay.
B–B′ Koppervik to Sitka Bay.
C–C′ Peak 2039 to Luck Point.

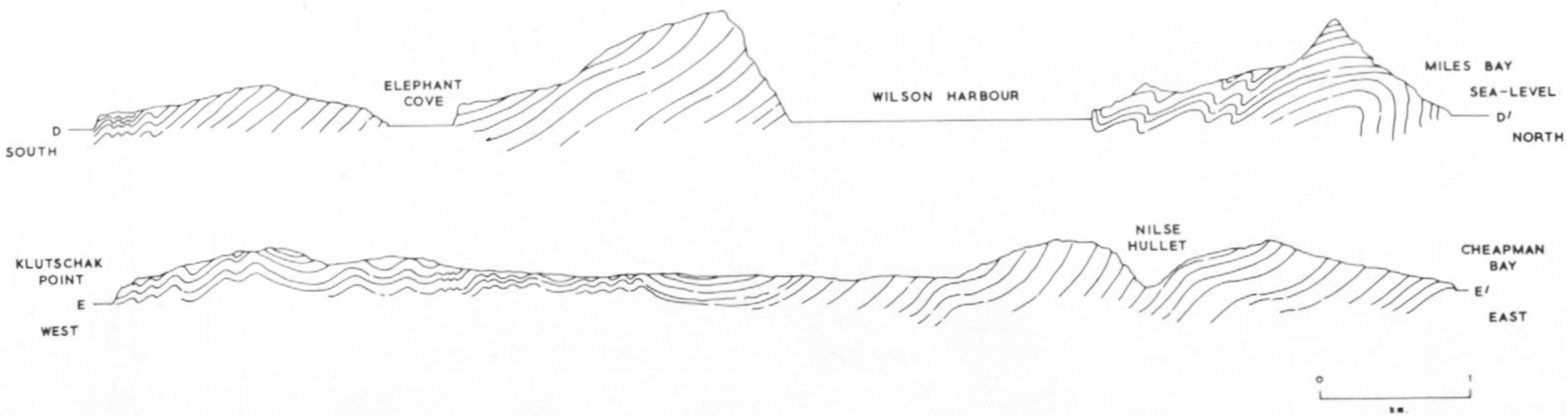

Fig. 4. Geological sketch sections.
D–D′ Anvil Stacks to Miles Bay.
E–E′ Klutschak Point to the south side of Cheapman Bay.

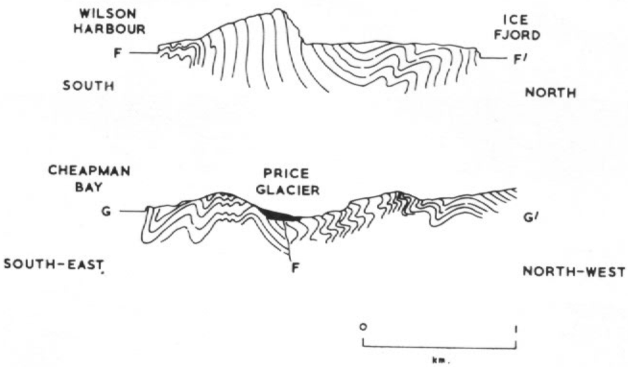

Fig. 5. Geological sketch sections.
F–F′ Wilson Harbour to Ice Fjord.
G–G′ Cheapman Bay to the south-west face of peak 2034.

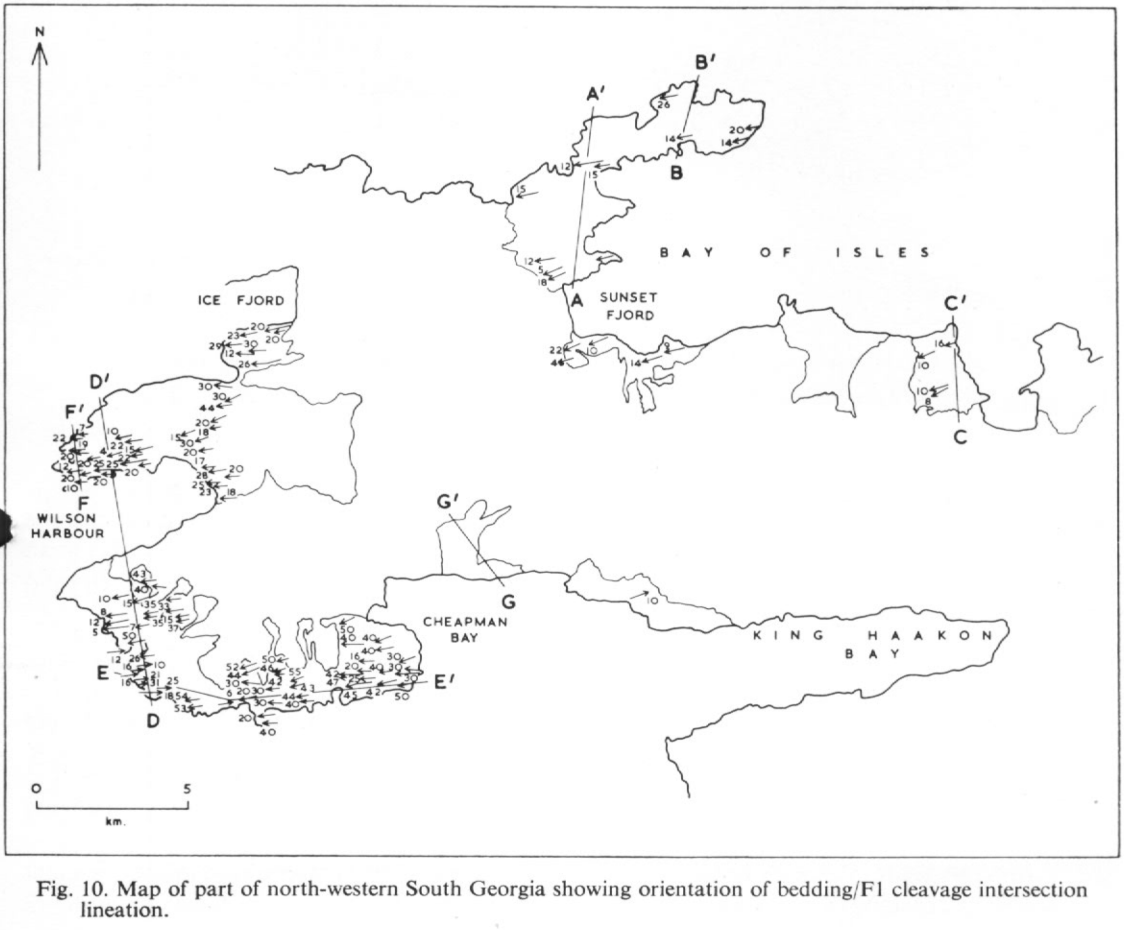

Fig. 10. Map of part of north-western South Georgia showing orientation of bedding/F1 cleavage intersection lineation.

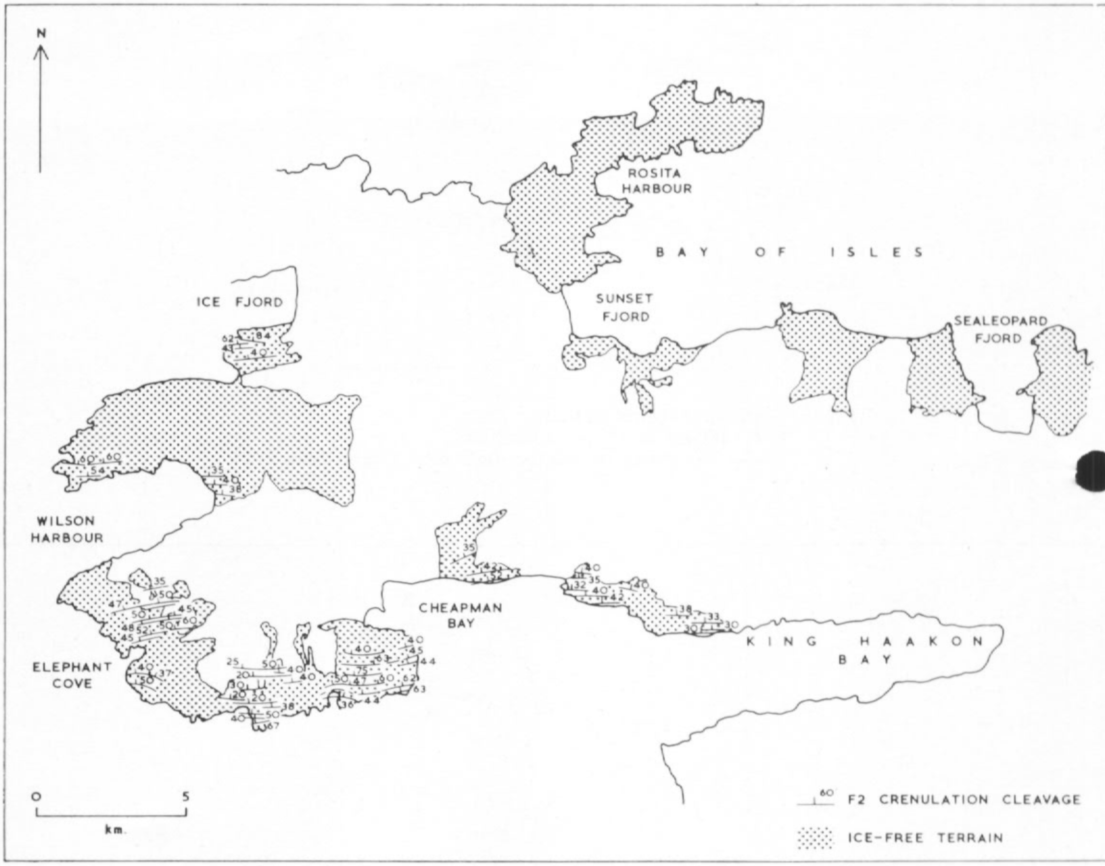

Fig. 11. Trend map of F2 crenulation cleavage for north-western South Georgia.

re-folding predominates. Changes in F1 fold style across the island can be recognized on two scales:

i. A gradual increase in wave-length of the major folds from an average of 400 m. on the Rosita Harbour peninsula to several kilometres in the Elephant Cove area. This is coupled with a decrease in over-folding towards the south. The over-folds to the north of Koppervik, with an inverted limb dip of about 70° (Fig. 3), give way to almost upright folds in the Elephant Cove and Cheapman Bay areas (Fig. 4).

ii. On the limbs of these large-scale folds, zones of intense deformation up to 1 km. in width have been observed. Fold style within these zones tends to remain fairly constant with a wave-length ranging from 50 to 100 m., but it changes from one zone to another in keeping with changes in the major fold style (Figs. 4 and 5). In the Paul Beach and Sealeopard Fjord areas, for example, hinge surfaces dip at about 40° to the south (Fig. 3). In Wilson Harbour, the hinge-surface dip increases to approximately 70° (Fig. 5) and on the south coast of the island, in the Elephant Cove area, these small-scale folds are upright (Fig. 4).

Minor F1 folds, although widespread throughout the Bay of Isles, are rare in the Elephant Cove (Fig. 2h) and Nilse Hullet (Fig. 2g) areas, presumably reflecting the decreasing intensity

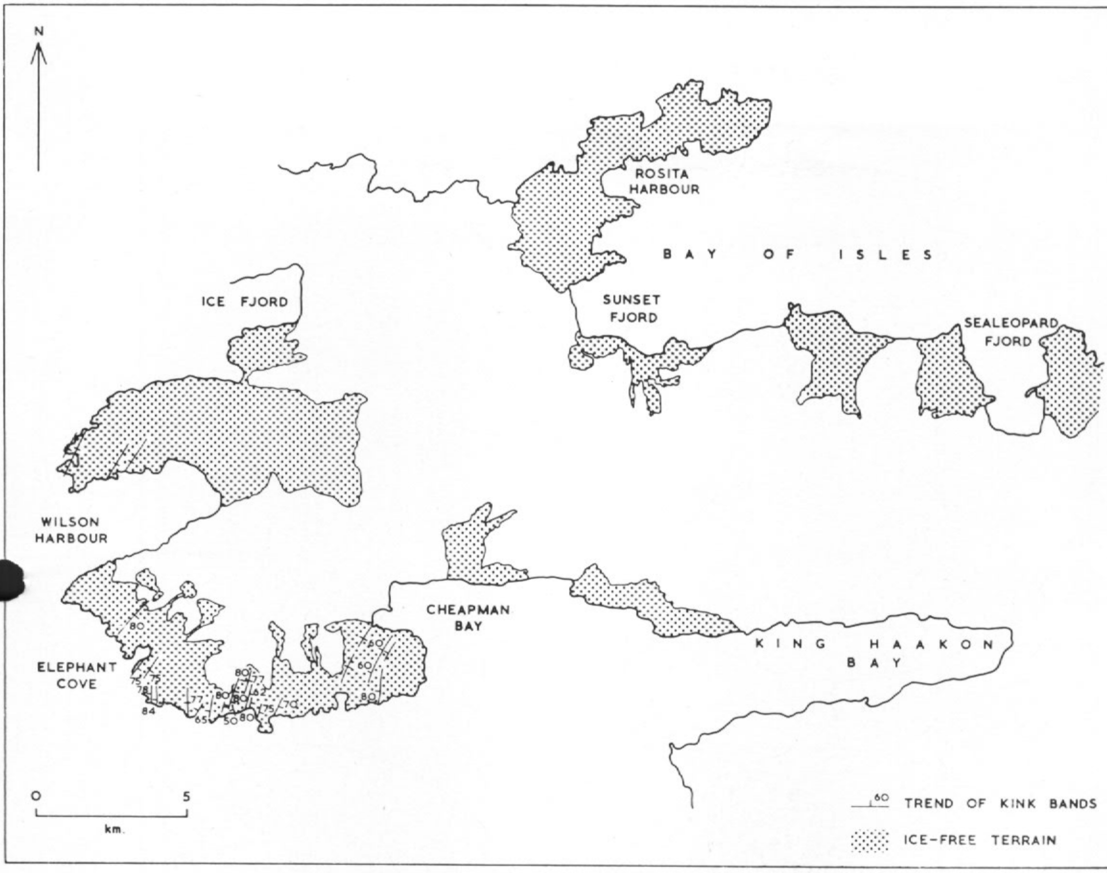

Fig.12. Trend map of F3 kink bands for north-western South Georgia.

Fig. 13. Re-folded F1 structure with a west-north-west hinge trend, 1 km. due north of Nilse Hullet.

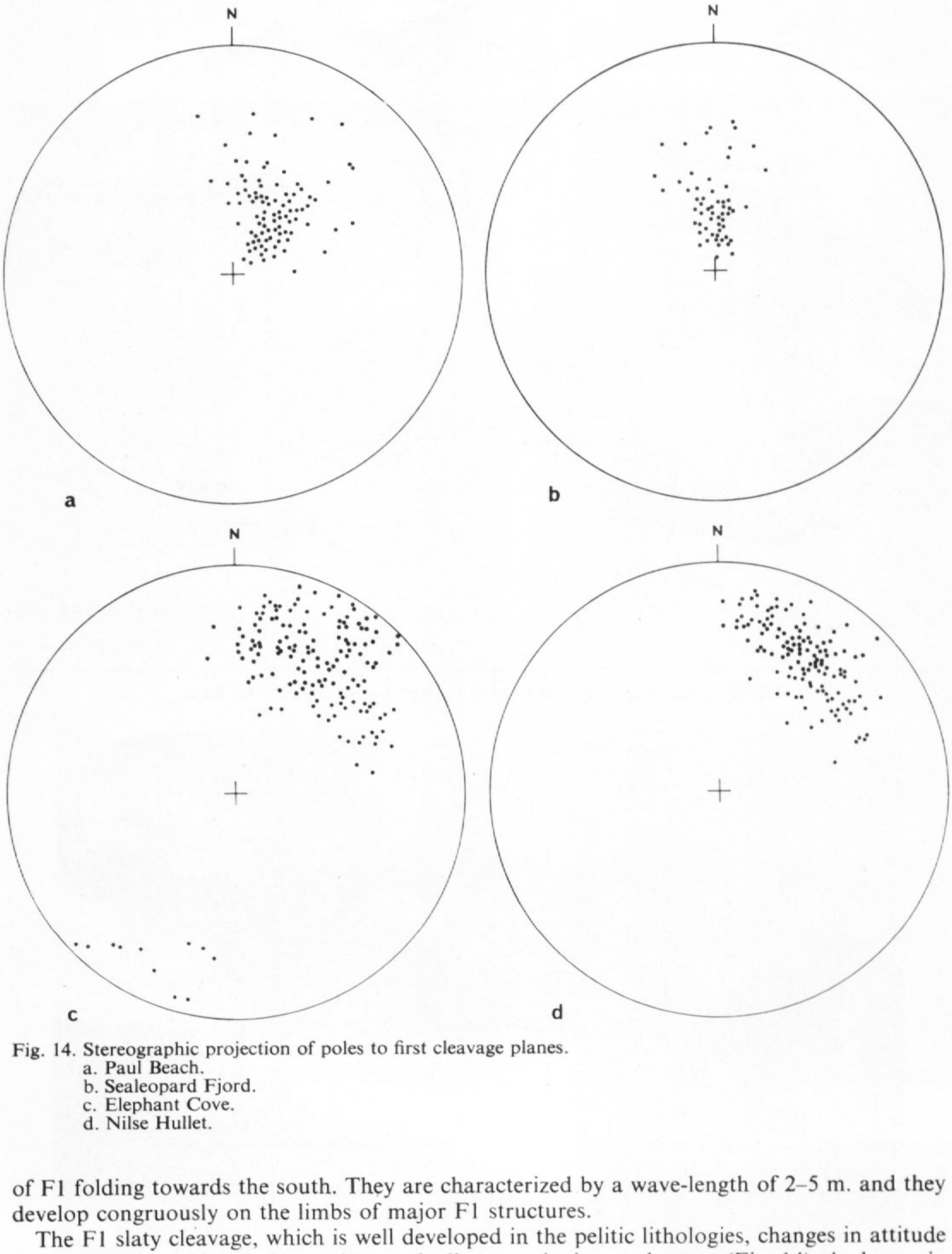

Fig. 14. Stereographic projection of poles to first cleavage planes.
a. Paul Beach.
b. Sealeopard Fjord.
c. Elephant Cove.
d. Nilse Hullet.

of F1 folding towards the south. They are characterized by a wave-length of 2–5 m. and they develop congruously on the limbs of major F1 structures.

The F1 slaty cleavage, which is well developed in the pelitic lithologies, changes in attitude across the island, the dip increasing markedly towards the south coast (Fig. 14). A change in strike of the first cleavage can also be seen on Figs. 8 and 9. In the Paul Beach area (Fig. 2b),

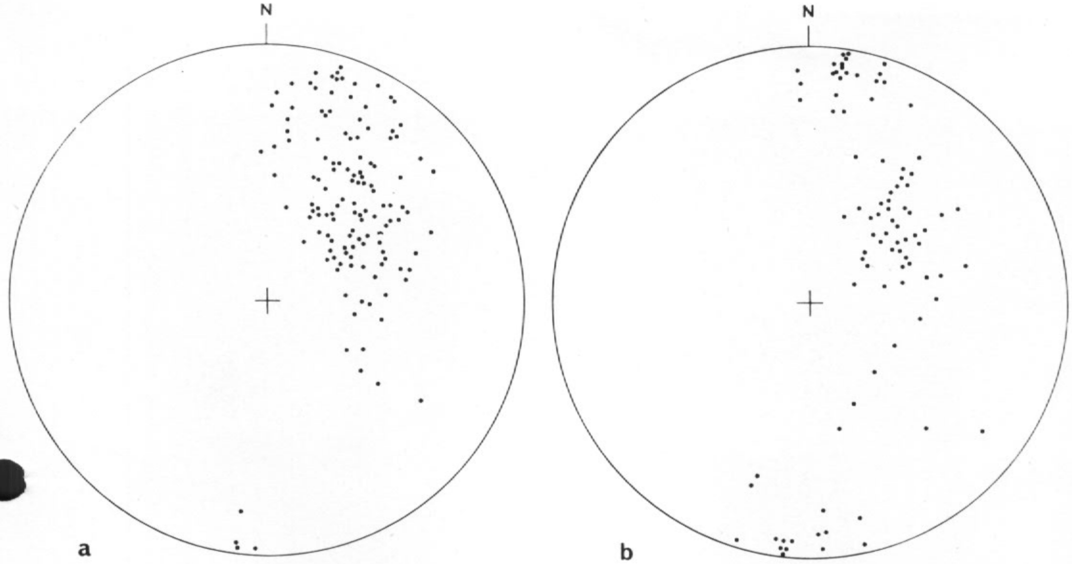

Fig. 15. Stereographic projection of poles to first cleavage planes.
a. Miles Bay.
b. Cheapman Bay.

the mean strike of the F1 cleavage is 295° (Fig. 14a) with a southerly dip of about 35°. This swings gradually to a strike of 260°, with the same dip, in Sealeopard Fjord (Fig. 2d) 8 km. to the east (Fig. 14b). On the south coast at Elephant Cove (Fig. 2h), a strike of 300° (Fig. 14c) swings to 295° (Fig. 14d), whilst the southerly dip increases from 65° to 70° in the Nilse Hullet area (Fig. 2g). Slaty cleavage planes from most areas plot stereographically as broad maxima (Fig. 14) with the exceptions of Miles Bay and Cheapman Bay, where poles to first cleavage planes define a girdle (Fig. 15a and b) about an east–west axis. These girdles are great circles indicating coincident F1 and F2 fold axes in the Miles Bay and Cheapman Bay areas. Girdle development in these areas is attributed to subsequent folding which cannot be discerned in the field but is reflected in the change in attitude of the early cleavage across the Cheapman Bay area (Fig. 9).

F1 linear structures, largely cleavage bedding intersections (Fig. 10), indicate a gentle westerly plunge of F1 fold axes. However, minor variations in the orientation of these axes do occur; a 20° plunge towards 270° (Fig. 16a) in Rosita Harbour (Fig. 2a) swings to 5° towards 260° in Sealeopard Fjord (Fig. 2d). Similar variation occurs to the south where a mean strike of 280° in Wilson Harbour (Fig. 2i) swings to 270° in the Nilse Hullet area (Fig. 2g). Stereographic analysis of bedding orientation reveals that F1 folds have been increasingly affected by a subsequent phase of deformation towards the south. In Rosita Harbour (Fig. 2a), a π-pole girdle is defined (Fig. 16a), its completeness indicating the rounded nature of the hinge zone. In Miles Bay (Fig. 2j), the girdle is incomplete and the F1 linear structures are slightly scattered (Fig. 16c). Fig. 16d shows a broad maximum for bedding data in the Elephant Cove area (Fig. 2h) with the F1 linear structures plotting as two clusters representing the limbs of a younger fold. Hinge traces and first cleavage trends (Figs. 6–9) also show the increasing effect of F3 re-folding on F1 structures towards the south coast of the island.

The first cleavage is intense in all lithologies but it is more regularly developed in the mudstones, the sandstones parting along more widely spaced clean-cut surfaces termed fracture

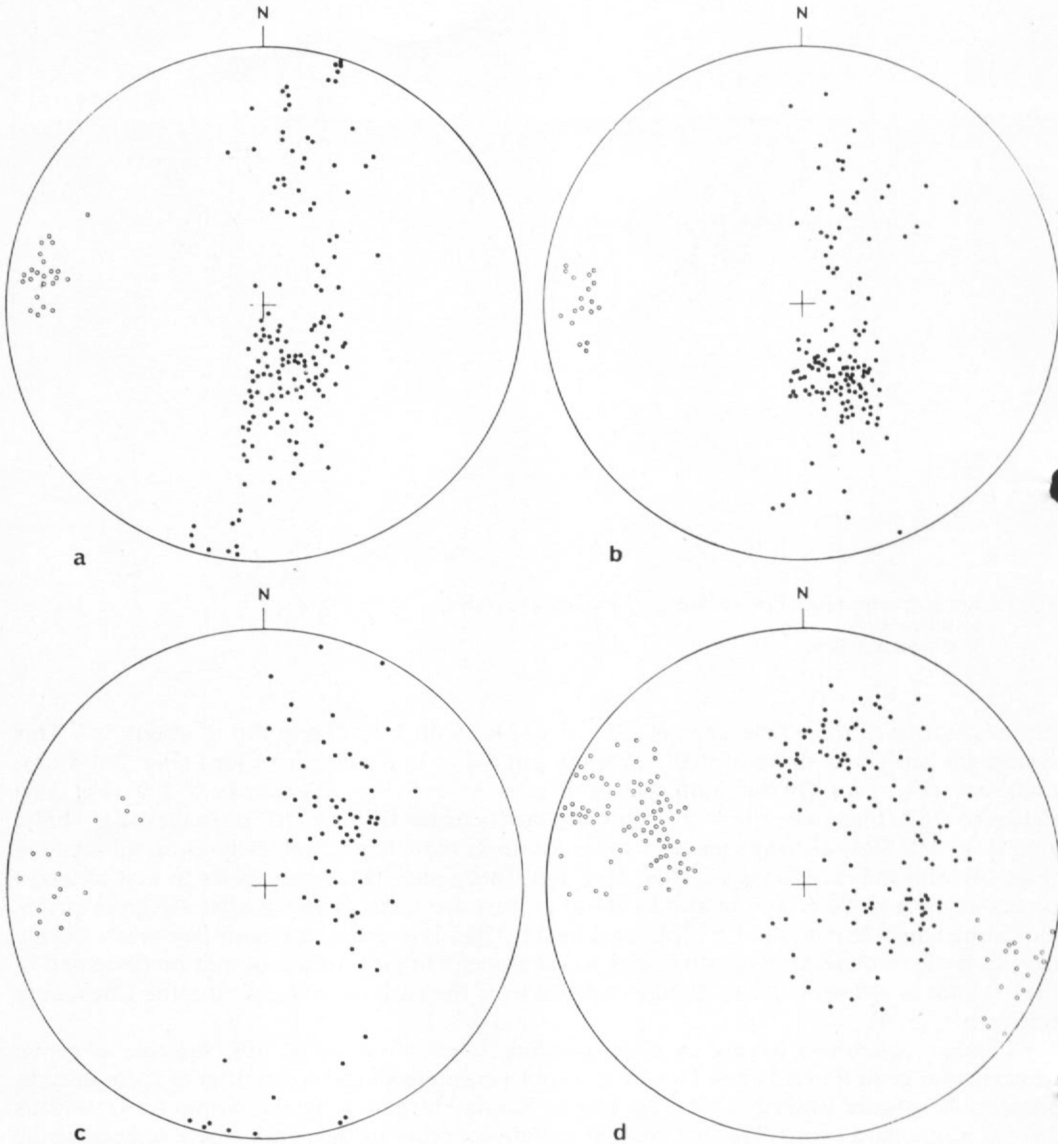

Fig. 16. Stereographic projection of poles to bedding and F1 linear structures.
a. Rosita Harbour.
b. Paul Beach.
c. Elephant Cove.
d. Nilse Hullet.

cleavage (Fig. 17a). In thin section, the first cleavage in the pelitic units is seen as a flattening and elongation of the clasts due to recrystallization under tectonic control. Needle-like pyrite has grown parallel to the cleavage whilst, on a macroscopic scale, slate clasts and calcareous nodules up to 2 m. in length have been rotated parallel to the first cleavage (Fig. 18).

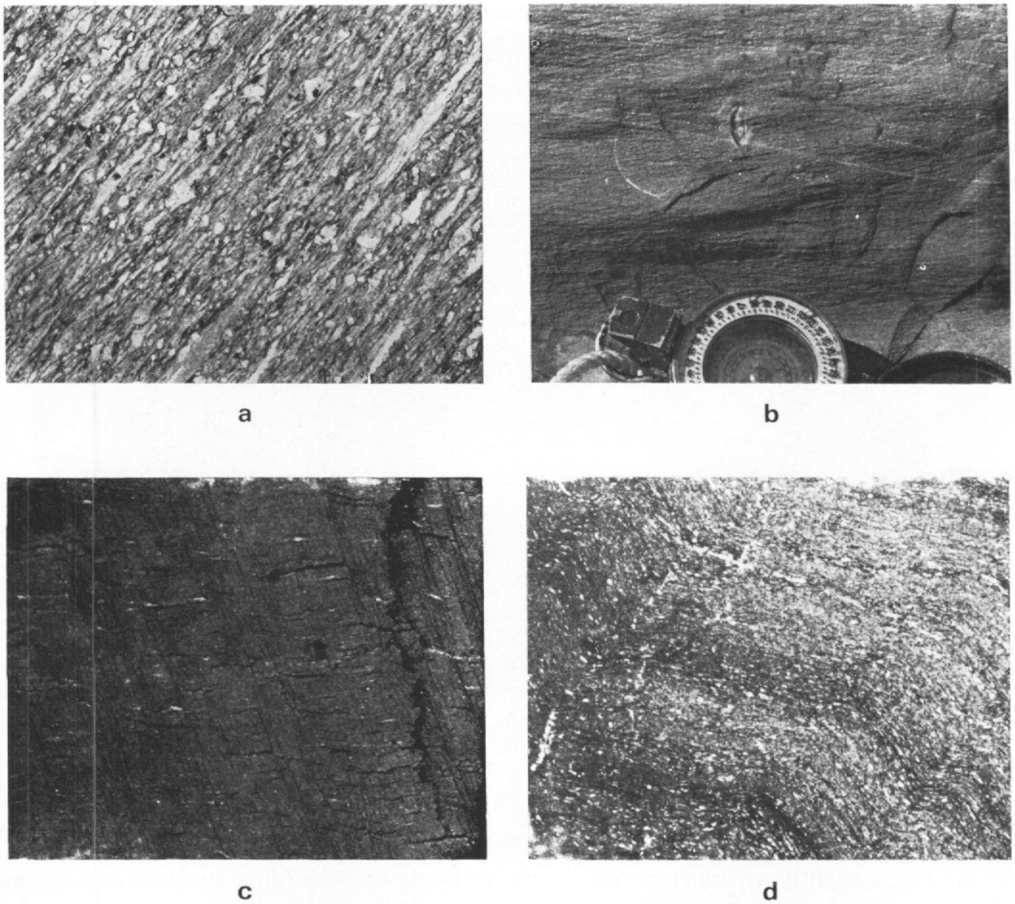

Fig. 17. Types of cleavage found in the greywackes of north-western South Georgia.
a. Photomicrograph of fracture cleavage in Cumberland Bay greywacke from Wilson Harbour (M.1688.1; ordinary light; ×25).
b. F2 crenulation cleavage producing a crinkle lineation in fine-grained sandstone on an F1 cleavage surface. The prismatic compass dial has a diameter of 5 cm.
c. Photomicrograph of F2 crenulation cleavage planes cutting pyrite which has grown in the plane of the first cleavage (M.1697.1; ordinary light; ×25).
d. Photomicrograph of kink band in Cumberland Bay greywacke from Elephant Cove (M.1226.7; ordinary light; ×25).

In contrast to the fine-grained rocks, which not only deform readily but also recrystallize more easily, the coarser sandstones and tuffs develop a fracture cleavage in the matrix between larger strained clastic grains. This shearing appears in thin section as a series of closely spaced dark lines of fine-grained material which wrap around the larger clastic grains of quartz, feldspar and lava fragments.

The pelitic units of the Cumberland Bay Formation are characterized by the development of a slaty cleavage, which is continuous with a fracture cleavage in the more competent sandstones. The gradual lithological change within each turbidite unit results in the cleavage developing a curved form through the bed, lying much closer to the bedding surface in the slates.

Fig. 18. Re-orientation of calcareous concretion into the plane of the F1 cleavage forming an asymmetric fold in the host greywacke. The pencil is 16 cm. long.

F2 Folding

F2 folds are slightly asymmetric with steep, northerly dipping hinge surfaces and an east-west hinge trend. Folding has developed on two scales: minor structures with a wave-length of less than 2 m. and large-scale folds with wave-lengths of several kilometres whose presence can only be inferred from stereographic analysis.

Minor F2 structures, typically developed in the Cheapman Bay area (Fig. 2f), are open folds with steeply inclined, northerly dipping hinge surfaces. Poles to S1 planes for Miles Bay (Fig. 2j) and Cheapman Bay (Fig. 2f) plot as girdles about east–west axes (Fig. 15). This systematic change in attitude of first cleavage planes indicates post-F1 deformation. The east–west trending girdle axes and a progressive northerly decrease in the dip of the first cleavage across the Cheapman Bay area (Fig. 9) is attributed to F2 re-folding. This change in attitude of the first cleavage planes takes place gradually over a distance of several kilometres, suggesting folds with a wave-length of the same magnitude. The intensity of F2 folding appears to decrease to the north and west of Cheapman Bay, so that in most areas this fold episode is represented only by a crenulation cleavage.

The F2 crenulation cleavage is strongly developed in the fine lithologies on the south coast of north-western South Georgia, producing a crinkle lineation on first cleavage surfaces (Fig. 17b). The crenulations tightly fold F1-orientated pyrite along the edges of the microlithons (Fig. 17c) and are themselves crossed by F3 kink bands. Stereographic projection of poles to F2 crenulation cleavage planes (Fig. 19) reveals a slight swing of F2 axial surfaces from east-north-east in the Elephant Cove area (Fig. 2h) to east–west in the area to the east of Nilse Hullet (Fig. 2g).

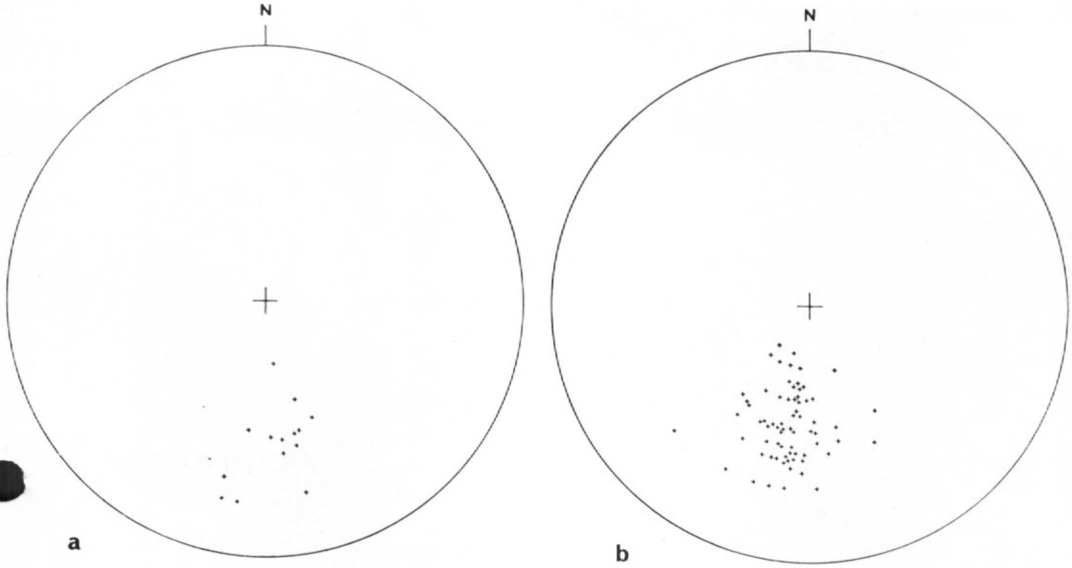

Fig. 19. Stereographic projection of poles to F2 crenulation cleavage.
a. Elephant Cove.
b. Nilse Hullet.

Marked variation in the trend of S1/S2 intersection lineations is attributed to F3 re-folding. On crossing an F3 monoclinal axis to the north-east of Nilse Hullet (Fig. 2g), the plunge of the S1/S2 intersection lineation increases from 8° to 28° and the direction swings from west to west-north-west (Fig. 20a). Similar variation in the orientation of S2 linear structures occurs in the Elephant Cove area (Fig. 20b).

Microscopically, F2 crenulation cleavage appears as the folding of micaceous and other flaky minerals into alignment in zones, sub-parallel to the hinge surfaces of the F2 folds (Fig. 17c). The first cleavage has been puckered into a series of generally asymmetric micro-folds with zones of weakness formed by the attenuation and shearing of the steep limb of these folds (Wilson, 1961).

F3 Folding

F3 folds are characteristically monoclinal with north-north-easterly striking hinges. Two scales of folding have been recognized: major monoclines with wave-lengths in excess of 1 km and much smaller-scale folds with steeply inclined to upright hinge surfaces and a typical wave-length of 50–200 m. (Fig. 4). F3 folds are parallel with a moderate hinge plunge of about 40° to the south-south-west. Major structures, with an average wave-length of 2 km. (Fig. 21), are typically developed in the Nilse Hullet area (Fig. 2g) but they die out northward towards the Bay of Isles. The style of folding also changes towards Elephant Cove, major monoclines giving way to intermediate and small-scale structures (Fig. 4). These smaller-scale folds are generally asymmetrical with steeply inclined to upright hinge surfaces.

Hinge surfaces in the Elephant Cove area (Fig. 2h) indicate upright F3 folding but 5 km. to the east, at Nilse Hullet (Fig. 2g), hinge surfaces dip steeply to the south-south-east. The northerly decrease in intensity of F3 folding is revealed by stereographic analysis of bedding and F1 cleavage and lineation data (Figs. 14–16 and 22). On the north coast of the island, bedding data define a π-pole girdle about the axial trend of the F1 folds (Fig. 13a) and the

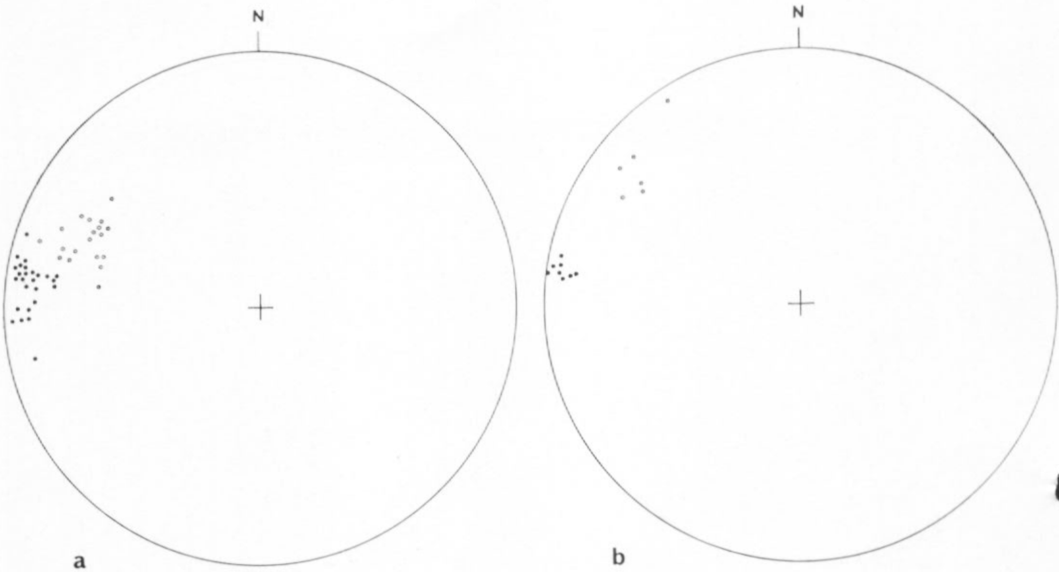

Fig. 20. Stereographic projection of F2 linear structures.
a. Nilse Hullet.
b. Elephant Cove.

Fig. 21. North-north-east trending F3 monocline, 3 km. north–east of Nilse Hullet.

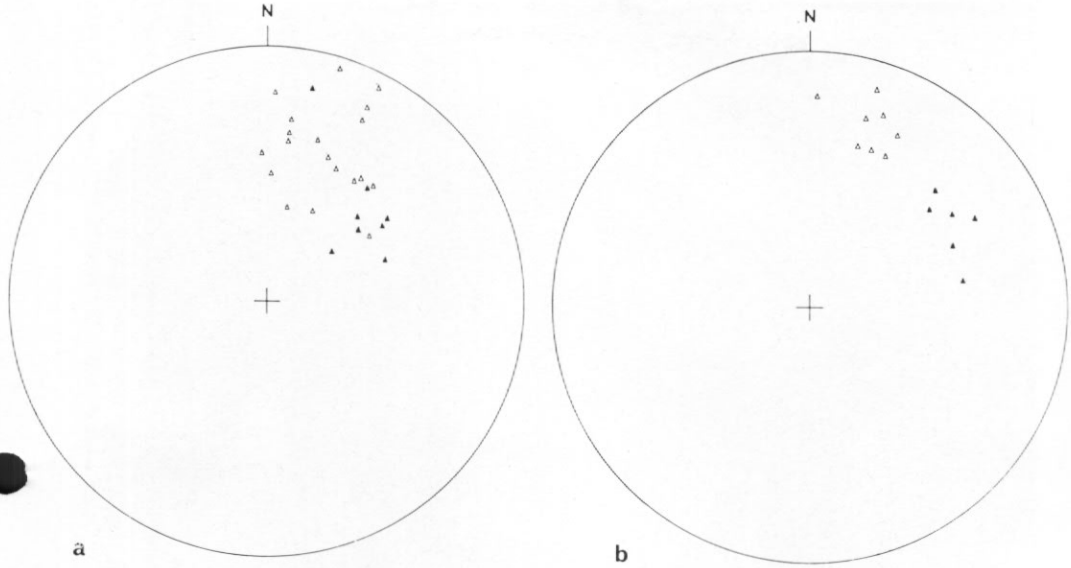

Fig. 22. Stereographic projection of poles to F1 cleavage planes.
a. Miles Bay.
b. Elephant Cove.

first cleavage planes plot as a cluster (Fig. 14a). Towards the south coast, the π-pole girdle is less complete and poles to first cleavage planes are scattered (Figs. 14–16 and 22). The early linear structures in Rosita Harbour are clustered around the east–west axes of the first folds but they are increasingly scattered towards the south where they are orientated parallel to bedding in the steep western limbs of the F3 monoclines (Figs. 16 and 23). The southerly increase in intensity of F3 folding towards the south coast is shown in Fig. 22 by the greater separation of the clusters of poles to first cleavage planes.

Kink Bands

Along the south coast of north-western South Georgia, first cleavage surfaces commonly show planes of kinking. The kink bands are either vertical or steeply dipping and trend north-north-east (Fig. 12). They show uplift of both eastern and western sides, and at one locality there are two distinct sets which intersect at a low angle. Thin-section examination of the kink bands shows a fairly constant fold shape (Fig. 17d). The width of the micro-lithons varies from 2 to 20 mm. in the more argillaceous rocks and from 5 to 30 mm. in the coarser lithologies. Lithological control of kink-zone width is much stronger, increasing with grain-size from 0·5 mm. in the pelitic units to 2 mm. in the greywackes.

In the Elephant Cove area, the kink bands appear to be parallel to the sub-vertical hinges of the north-north-east trending F3 folds (Fig. 24). The kink bands, developed in zones up to 200 m. wide, are generally associated with minor F3 folds. Both folds and kink bands decrease in intensity northward, dying out completely to the north of Ice Fjord (Fig. 12).

This spatial association suggests a direct tectonic relationship between the kink bands and the F3 folds but, according to Ramsay (1967), kink bands generally develop after orogenic deformation when the rocks are no longer in a ductile state. Kink-band development could therefore be attributed to a tightening up of the F3 folds during late-stage brittle deformation. However, Anderson (1964) has suggested that a complete transition exists from faulting

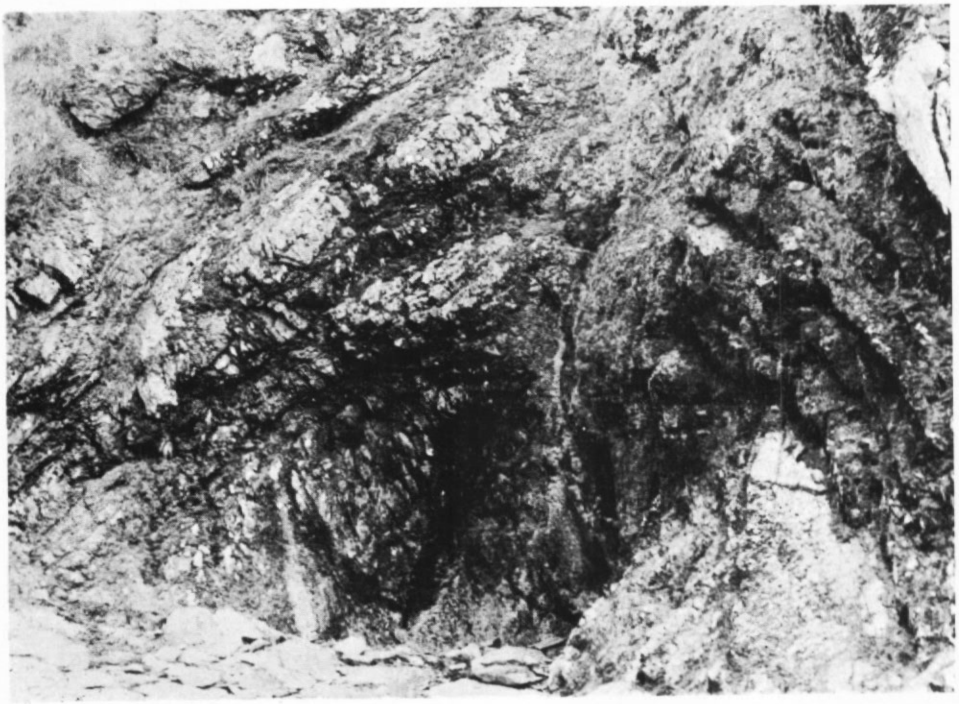

Fig. 23. Steeply plunging F1 fold in the western limb of an F3 monocline, Nilse Hullet. The cliff is 5 m. high.

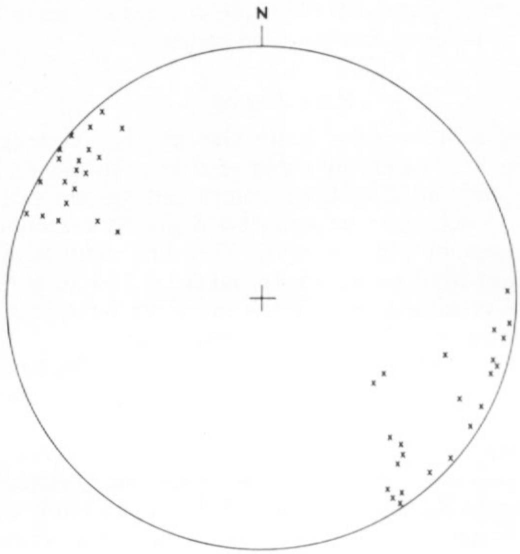

Fig. 24. Stereographic projection of poles to F3 kink bands for the Elephant Cove area.

through kink banding to crenulation cleavage. While not accepting the idea of a complete transition, Dewey (1965) has described several types of kink band, some of which, when narrow and closely spaced, produce a crenulation cleavage. More recent work by Williams (1972) has shown that in many large folds, crenulation cleavage in pelites grades laterally into a system of kinks. The transition is marked by increasingly angular micro-folds and the disappearance of faults between the micro-lithons. Similar transitions are occasionally seen in the kink bands which deform the Cumberland Bay rocks when the angular margins of the tabular fold zones give way to the rounded fold style associated with crenulation cleavage. The kink bands in north-western South Georgia are therefore considered to be a partially developed F3 crenulation cleavage which is roughly axial planar to the F3 folds.

Structural Correlations

F1 folding and associated slaty cleavage are well developed in the Cumberland Bay Formation along the north coast of South Georgia at both the north-western and south-eastern ends of the island. However, there is a marked decrease in the intensity of F1 deformation from the north-east to the south-west coast of the island. The F2 crenulation cleavage in north-western South Georgia strikes east–west and is axial planar to major upright folds. The orientation of this second cleavage is at variance with that in the Royal Bay area where the F2 planar fabric is moderately inclined towards the south-south-west and is axial planar to large-scale, slightly overturned folds (Stone, 1980).

The formation of both F1 folds and the superimposed F2 structure is attributed to a single pulse of compressive stress. The orientation of the first cleavage and the vergence of the first folds indicate that they were produced by a shearing movement directed towards the north. A northerly directed compressive force would be expected to generate more intense folds in the south, but in this area the F1 folds die out in a southerly direction. The northern vergence of the F1 folds together with an apparently anomalous southerly decrease in intensity of folding could be explained by gravity gliding.

Further stress resulted in the folding of the first folds into a series of open gentle anticlines and synclines and the development of minor F2 structures on the limbs of the first folds. These F2 structures in the north-western part of the island are characterized by sub-vertical hinge surfaces, and so might have arisen when northerly directed over-folding of the F1 type was prevented by collision of the deformed sediments with a resistant barrier.

F3 folds are particularly well developed in the Elephant Cove–Nilse Hullet area but they die out to the north and east. Large-scale north-north-east trending folds with axial planar kink bands have not been seen elsewhere in the Cumberland Bay-type rocks but Dalziel and others (1975) described an anastomosing and commonly conjugate crenulation cleavage in the Cumberland Bay Formation at Dartmouth Point. These crenulations strike west-north-west and may similarly be associated with the F3 folds.

Dalziel and others (1975) suggested that the Cumberland Bay and Sandebugten sediments were deposited in a marginal basin between a volcanic arc, built on a sliver of South American continental crust, and the main South American continent. They considered that the basin closed when the arc moved back towards the continent in Middle Cretaceous times. If this process involved subduction beneath the South American craton, the Sandebugten sediments could have been scraped off the basin floor. During the resulting polyphase deformation of the Sandebugten Formation, major over-folds were formed verging to the south, despite the northerly directed plate movement. On the volcanic arc side of the basin, the northerly directed compressive stress caused over-folding of the Cumberland Bay sediments which were subsequently thrust northward over the previously deformed Sandebugten Formation. Dalziel and others (1975) and Stone (1980) believed that this overthrusting occurred during the major phases of over-folding.

Unlike the northerly verging F1 structures, the F2 folds in north-western South Georgia are upright, and so they may have been generated by collision of the arc with the continent or by the thrusting of the Cumberland Bay Formation over the Sandebugten-type greywackes.

The origin of F3 folding is obscure but its sporadic distribution and axial planar kink banding indicate development in the final stage of orogenesis.

Acknowledgements

I wish to thank Professor A. Williams for use of facilities in the Department of Geological Sciences, University of Birmingham. The advice and criticism of Drs. P. W. G. Tanner, C. M. Bell and P. Stone is acknowledged with thanks. I am particularly grateful to my colleagues, J. Flick, T. Gannon, D. Habgood, R. N. Mortimore and D. Orchard, for their invaluable assistance in the field.

MS. received 5 November 1975

REFERENCES

Anderson, T. B. 1964. Kink bands and related geological structures. *Nature, Lond.*, **202,** No. 4929, 272–74.

Dalziel, I. W. D., Dott, R. H., Winn, R. D. *and* R. L. Bruhn. 1975. Tectonic relations of South Georgia island to the southernmost Andes. *Geol. Soc. Am. Bull.*, **86,** No. 7, 1034–40.

Dewey, J. F. 1965. Nature and origin of kink bands. *Tectonophysics*, **1,** No. 6, 459–94.

Ramberg, H. 1963. Evolution of drag folds. *Geol. Mag.*, **100,** No. 2, 97–106.

Ramsay, J. G. 1967. *Folding and fracturing of rocks*. New York, McGraw-Hill Book Co.

Skidmore, M. J. 1972. The geology of South Georgia: III. Prince Olav Harbour and Stromness Bay areas. *British Antarctic Survey Scientific Reports*, No. 73, 50 pp.

Stone, P. 1980. The geology of South Georgia: IV. Barff Peninsula and Royal Bay areas. *British Antarctic Survey Scientific Reports*, No. 96, 45 pp.

Trendall, A. F. 1953. The geology of South Georgia: I. *Falkland Islands Dependencies Survey Scientific Reports*, No. 7, 26 pp.

———. 1959. The geology of South Georgia: II. *Falkland Islands Dependencies Survey Scientific Reports*, No. 19, 48 pp.

Williams, P. F. 1972. Development of metamorphic layering and cleavage in low grade metamorphic rocks at Bermagui, Australia. *Am. J. Sci.*, **272,** No. 1, 1–47.

Wilson, G. 1961. The tectonic significance of small scale structures, and their importance to the geologist in the field. *Annls Soc. géol. Belg.*, **84,** 423–548.