GEOLOGICAL OBSERVATIONS IN THE COOPER BAY–WIRIK BAY AREA, SOUTH GEORGIA

By P. STONE

ABSTRACT. A sequence of cataclastites, schists, phyllites and slates crops out in part of south-eastern South Georgia. They have been produced by low-grade regional metamorphism to the biotite zone of the greenschist facies with local development of mylonites and myloblastites. The rocks are probably the metamorphosed equivalents of a facies variant of the Mesozoic Sandebugten-type greywackes which are exposed elsewhere on the north-east coast of the island. Epidiorite sheets, originally intruded at an early stage in the structural history of the area, show an increase in metamorphic grade towards the south-west. Four separate fold episodes have been recognized; possibly the earliest, andprobably the second and third, were co-axial and trend north-west. F1 structures can only be positively identified by the interference patterns produced by the superposition of minor F2 folds. The F3 structures are probably all congruous minor folds in one limb of a major antiform.

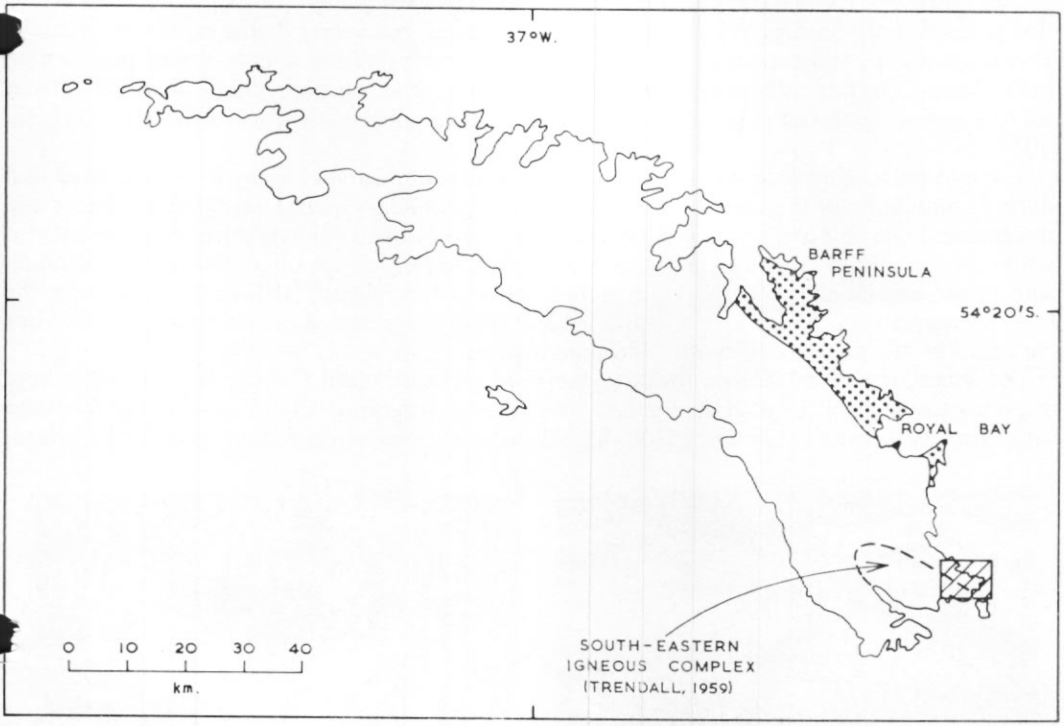


Fig. 1. Map of South Georgia showing the location of the area discussed (hatched), the approximate area of outcrop of the Sandebugten-type rocks (stippled) and the south-eastern igneous complex.

AN area in the south-east of South Georgia (Fig. 1) around Cooper Bay (lat. 54°47′S.; long. 35°48′W.) and Wirik Bay (lat. 54°45′S.; long. 35°51′W.) was geologically mapped during the 1973–74 summer field season as part of a continuing British Antarctic Survey programme. The geology of this area is summarized in Figs. 2–4.

From previous work (Trendall, 1959) it was known that a large intrusive body crops out to the west of Cooper Bay (the south-eastern igneous complex; Fig. 1), whereas tightly folded metasediments with a north-westerly hinge trend were intruded by pre-tectonic dolerite sills

Br. Antarct. Surv. Bull., No. 51, 1982, p. 43–53.

at Wirik Bay. Field work in 1974 showed that polyphase deformation of the sandstones, shales and interlayered dolerite sheets was accompanied by low-grade regional metamorphism to the biotite zone of the greenschist facies and resulted in a succession of schists, phyllites, slates and epidiorites. Locally, intense deformation has produced a well-developed cataclastic fabric. All of the folding in the Cooper Bay area is very intense and the accompanying penetrative fabrics have destroyed most of the original sedimentary characteristics of the rocks. Nevertheless, it is tentatively considered that the sediments of the Cooper Bay–Wirik Bay area were originally akin to Sandebugten-type greywackes (Trendall, 1959; Stone, 1980).

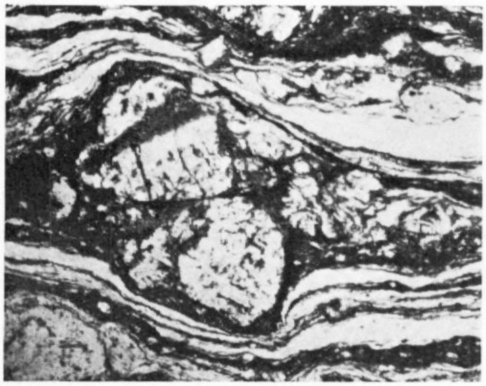
Petrology

Cataclastites

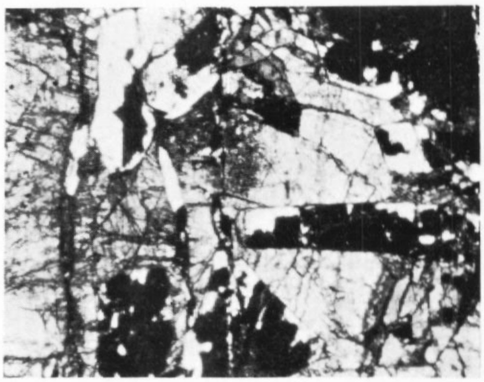
To the west of Cooper Bay a narrow belt of cataclastic rocks less than 1 km. wide trends north-west inland from the coast (Fig. 3). The cataclasis appears to have affected both the metasedimentary country rock and the margins of the adjacent south-eastern igneous complex (Trendall, 1959). In the southern part of Cooper Bay and on the south-west side of the small glacier flowing towards the bay the cataclastites are well exposed as pale grey or green to brown fine-grained flinty looking rocks. They are well banded but many of the bands are actually elongated streaks; some bands, composed entirely of recrystallized quartz, range up to 3 mm. in thickness. The fine cataclastic banding flows around relict porphyroclasts of white feldspar up to 4 mm. in diameter (Fig. 5a) and the overall appearance of the rock is that of a classical mylonite.

The feldspar porphyroclasts have been mechanically rounded and many have been fractured during granulation of the parent rock. In most cases, secondary quartz has filled the cracks and re-cemented the feldspars. Microcline and some orthoclase porphyroclasts are present but about 75 per cent of the relict feldspars are of plagioclase. Albite, oligoclase and some andesine occur commonly with the extinction lamellae often slightly deformed. Enclosing the feldspar porphyroclasts are very fine-grained lenticles and streaks of quartz, many of which are darkened by the presence of biotite and ore minerals.

The succession of cataclastic rocks to the north-west of south Cooper Bay probably corresponds to the "well foliated acid gneiss" described petrographically in some detail from the same area by Trendall (1959, p. 29–30, fig. 20), who also recognized their cataclastic nature.



a



b

Fig. 5. a. The fabric of a typical mylonite, suggesting anti-clockwise rotation of the porphyroclasts (M.671.2; ordinary light; ×100).
b. Augite in an ophitic relationship with cloudy plagioclase from the unsheared core of an epidiorite boudin (M.670.6; X-nicols; ×65).

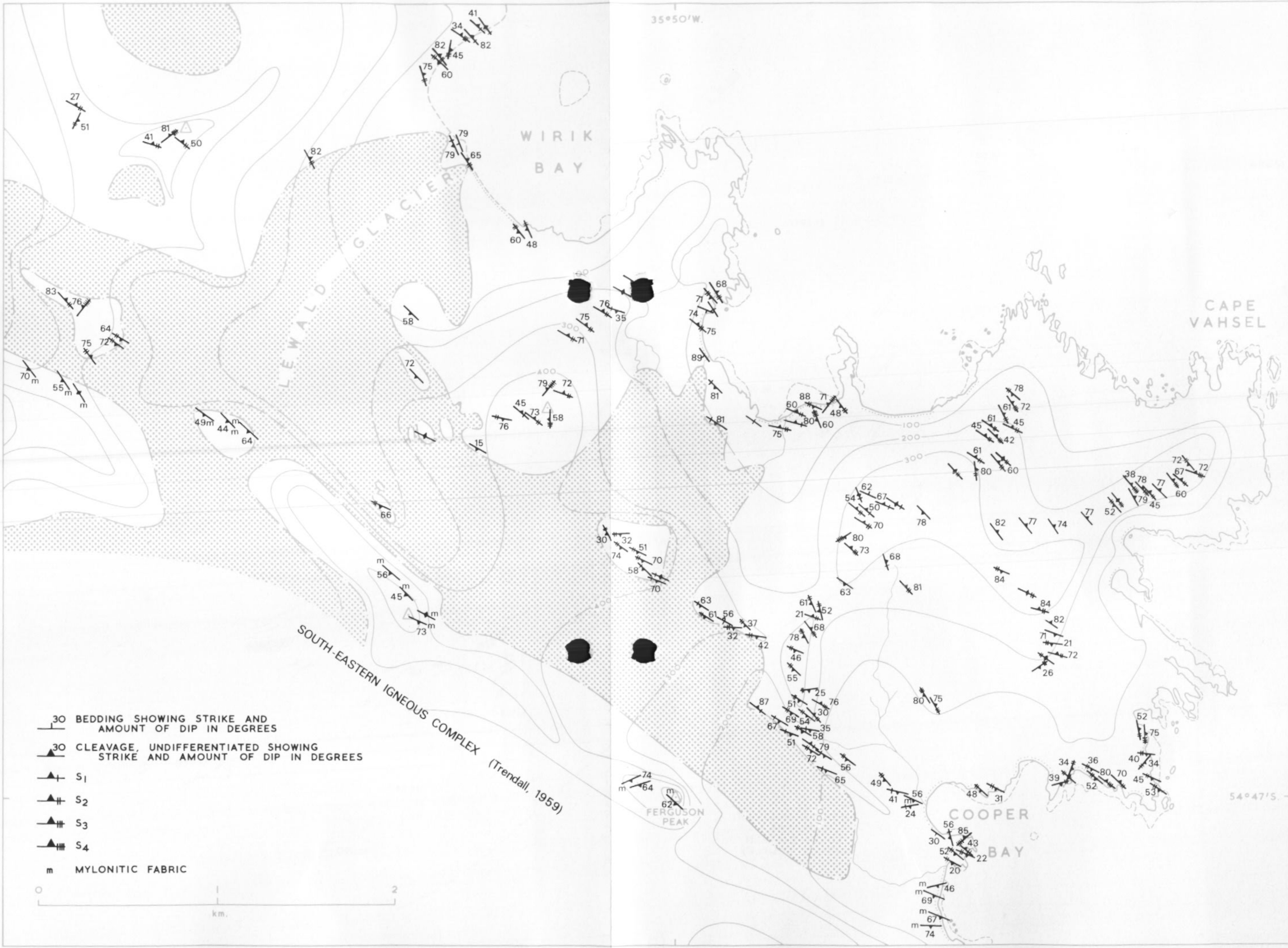


Fig. 3. Geological sketch map of the Cooper Bay–Wirik Bay area showing planar structures.

Fig. 2. Geological sketch map of the Cooper Bay–Wirik Bay area, showing the exposures of epidiorite and the inferred boundary of the south-eastern igneous complex.

[face page 44

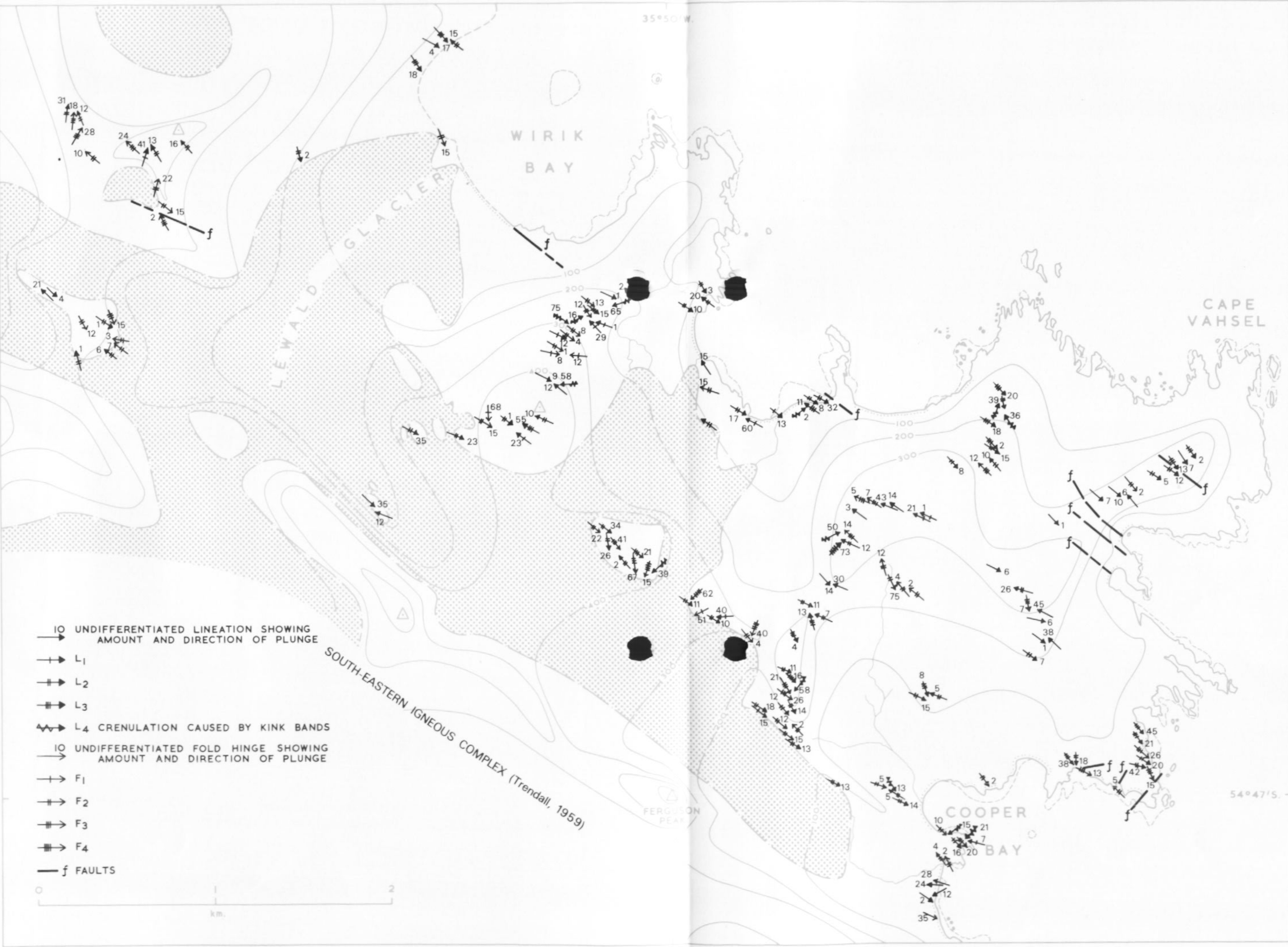


Fig. 4. Geological sketch map of the Cooper Bay–Wirik Bay area showing linear structures.

[face fig. 3

Whilst there has been considerable recrystallization of quartz, in some of the rocks the cataclastic fabric is still quite clear. This rock type can therefore be regarded as a true mylonite of the foliated holoclastic group as defined by Zeck (1974).

The pale grey, fine-grained banded psammitic rocks on the north-east side of the cataclastic belt also prove in thin section to have a cataclastic fabric. However, relict porphyroclasts are absent from these rocks and the fabric is formed by very fine-grained streaks and lenticles of recrystallized quartz. Some of the darker streaks contain a high proportion of biotite and ore minerals, and this concentration may have been caused by cataclastic differentiation. Despite the cataclastic influence, the fabric is almost entirely recrystallized, and using the classification of Zeck (1974) these rocks are myloblastites.

The relationship between the two successions of cataclastic rocks is far from clear. The planar fabrics of both have been re-folded and, in fact, the myloblastic fabric was probably formed during the earliest deformation episode recognized. The mylonites farther south-west cannot be associated so closely with any of the tectonic episodes but they were certainly folded during the third fold episode. The less advanced recrystallization of their fabric may mean that the mylonites are younger than the myloblastites and so the shear zone may have been activated more than once in the structural history of the area, once late in the F1 fold episode and again prior to F3. The presence of unusually large feldspar porphyroclasts in the mylonites close to the igneous intrusion may possibly be due to contact metamorphic effects prior to the pre-F3 shearing. Large feldspar phenocrysts are known to occur at some granite contacts, both in the granite and in the country rock (Turner and Verhoogen, 1960, p. 363), and a similar process may have occurred in the Cooper Bay area before later shearing produced the mylonites.

Low-grade metasediments (*greenschist facies*)

To the north-east of the cataclastic belt, between Cooper Bay and Cape Vahsel, a sequence of schists, phyllites and slates is exposed. The schists are widely distributed but they are best developed to the south and west of Wirik Bay. Typically, they are dark brown or dirty grey rocks with a penetrative cleavage accompanied by much recrystallization, especially of chlorite or mica. The relict grains enclosed by the schistosity only occasionally exceed 2 mm. in diameter, but where such relict grains are abundant the rocks are similar to the "foliated metagreywackes or *semischists*" described by Turner (1968, p. 31). However, fine-grained schists are more common and they grade, with decreasing grain-size, into black or dark brown phyllites and slates. The cleavage surfaces of the phyllites are fairly rough and irregular, and most of them contain fine quartzose laminae parallel to the cleavage. The phyllites and slates are widely exposed around Cape Vahsel in the north-east of this area.

The low-grade metamorphism accompanied intense polyphase deformation and the original bedding is now only represented by relict colour banding which forms green, blue-grey and brown psammitic layers ranging in thickness from 0·1 to 10 cm. This banding is generally parallel to the local planar tectonic fabric but it is thicker than the segregation laminae which are usually less than 0·1 cm. No surviving sedimentary structures or fossils were observed.

Although the relict sedimentary grains in the schists rarely exceed 2 mm. in diameter, the parent rock may have been much coarser since all of the grains have suffered recrystallization which merges the grain boundaries with the enveloping schistosity. Most of the surviving grains are of feldspar, either orthoclase (which may be patchily perthitic) or more commonly plagioclase (albite-oligoclase). Occasionally the orthoclase grains contain a graphic intergrowth of quartz. The plagioclase is invariably saussuritized so that epidote, sericite and rare calcite occur in association with the albite. Epidote is also present as small granular aggregates throughout the rock. Some of this shows anomalous blue interference colours and therefore it is probably clinozoisite. Relict detrital grains of quartz are also present but these are invariably partially recrystallized; in particular, polycrystalline quartz grains are difficult to distinguish from small streaks of segregated quartz and feldspar. Other quartzo-feldspathic streaks are much more extensive and some of them reach a thickness of 0·1 cm. Rarely relict grains can be distinguished; these are composed of a mass of microlitic feldspar laths, usually with a well-developed trachytic texture. These grains were undoubtedly derived from a lava and may indicate a compositional affinity between the original sandstone and the Cumberland Bay-type volcaniclastic greywackes which crop out over much of South Georgia (Trendall, 1959). However, the quartz content of the latter is very much lower than that of the Cooper Bay sediments.

The overall texture of the schists is therefore blastopsammitic with the relict sedimentary grains forming augen in the schistosity. The schistosity itself is primarily due to the growth of biotite and chlorite, and it is accentuated by the formation of quartzo-feldspathic segregation streaks. The biotite occurs as aggregates of tiny, orientated flakes which are pleochroic from a pale straw colour to pale brown. The chlorite has much the same form as the biotite but is pleochroic from very pale green to a yellowish green and rarely shows the anomalous blue interference colours indicative of penninite. Secondary quartz is very common as granular aggregates intergrown with biotite and chlorite, and the total quartz content, including a significant detrital fraction, frequently exceeds 50 per cent which is similar to that of the quartzose Sandebugten-type greywackes (Stone, 1980) that are exposed elsewhere on the north-east coast of South Georgia (Fig. 1).

In the phyllites, relict grains are much rarer and the fabric is dominated by a schistose arrangement of biotite, chlorite and quartz together with thin quartzo-feldspathic segregation lamellae. This phyllitic fabric merges with the slates which are composed almost entirely of a fine-grained secondary assemblage of biotite, chlorite and quartz.

Epidiorites

The boudinaged igneous sheets, first described by Trendall (1959) from Wirik Bay and ranging in thickness from a few centimetres to approximately 8 m., are interlayered with the metasediments (Fig. 2) and also show the effects of considerable metamorphism. The thinner sheets have been extensively sheared and are exposed as grey-green schists which are often difficult to distinguish from the country rocks. In the thicker sheets the coarse-grained cores are preserved as a pale grey-green crystalline rock in which a suggestion of an ophitic texture can occasionally be seen with a hand lens.

Thin sections of the coarse igneous material from the Cooper Bay area contain pale green hornblende and sodic plagioclase (albite-oligoclase) in an ophitic relationship. Rare phenocrysts of quartz are also present but most of the quartz occurs with chlorite in the interstitial groundmass. Leucoxene is abundant, in many cases moulded around the plagioclase laths and usually nucleated on relict ore, probably ilmenite. Some of the large hornblende plates are strongly pleochroic (α=pale brown, β=pale green, γ=dark green) and have acicular actinolitic fringes. Frequently, the plagioclase phenocrysts have been broken and re-cemented by quartz and chlorite filling the fracture planes; this effect increases in the thinner sheets and at the margins of the more massive intrusions. In extreme cases all of the feldspars are shattered and actinolite and fibrous uralite have completely replaced the original pyroxene. The surviving ophitic texture and quartz phenocrysts suggest that the original rock was an ophitic quartz-dolerite.

Farther north-east, towards Cape Vahsel, a change in mineralogy occurs. Progressively, the pyroxene is less altered to amphibole until in the Cape Vahsel area very little hornblende is present and a colourless non-pleochroic pyroxene, probably augite, is in an ophitic relationship with very cloudy plagioclase (Fig. 5b). The reason for this variation in metamorphic grade is not clear, especially as there is no sign of a similar variation in the metasediments. The sheets certainly pre-date at least some of the fold episodes and they possibly belong to the same suite as the early sills exposed elsewhere on the north-east coast of South Georgia (Trendall, 1959; Stone, 1980).

Structural Geology

In the low-grade greenschist-facies metasediments of the Cooper Bay–Wirik Bay area at least four distinct fold episodes have been recognized. The first three episodes were more or less co-axial, trending north-west, whereas the final episode has produced minor fold hinges and crenulation lineations perpendicular to the earlier trend. Trendall (1959, p. 27–28) described tight upright folds with north-westerly trending hinges in this area.

Fold episode 1 (F1)

The fold hinges recognized were only positively identified from the interference patterns produced by superposition of later F2 folds. A variety of interference patterns has developed (Fig. 6) and these approximate to the ideal types 2 and 3 of Ramsay (1962, 1967). As these

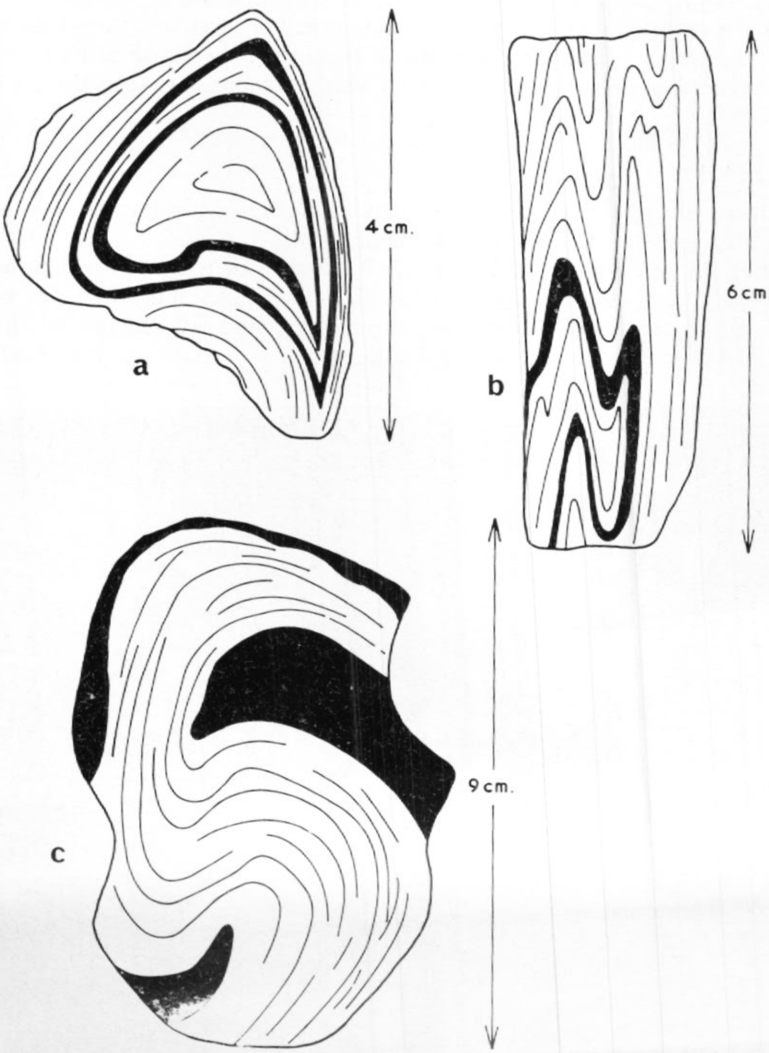


Fig. 6. Interference patterns produced by the superposition of F1 and F2 folds. a. M.665.11, type 2; b. M.667.3, type 3; c. M.665.10, type 3.

require that the attitude of the hinge surfaces of the original folds and the trend of their hinges are markedly dissimilar in each case, there must have been sufficient variation in the attitude and trend of the earlier folds to allow different styles of superposition to occur at different localities. Since type 3 patterns (Fig. 6) are by far the commonest style of interference structure, it seems likely that the overall trend of the F1 hinges was approximately parallel to the trend of the F2 hinges.

Throughout the area F1 lineations are folded around F2 fold hinges and some very small minor folds contained in the limbs of minor F2 folds have a hinge orientation markedly incongruous with the F2 hinge trend. These are also probably F1 structures and in most cases the S1 cleavage which is folded around the F2 hinges appears to be the hinge surface of the small incongruous folds.

To the north-west of Cooper Bay the myloblastites (as distinct from the mylonites) described previously are also folded about the F2 fold hinges. However, within the myloblastites the remains of earlier fold hinges can still be distinguished as relict structures sheared out along, and probably pre-dating, the cataclastic fabric. If these are the remains of F1 hinges, the myloblastites were probably formed in response to local cataclasis between the F1 and F2 fold episodes.

Fold episode 2 (*F2*)

Folds produced during this phase of deformation are well developed to the west and north of Cooper Bay as tight similar folds with limb lengths rarely in excess of 3 m. and usually much less (Fig. 7). Parallel to the hinge surfaces of the F2 folds a penetrative crenulation cleavage is developed (usually very finely spaced and less than 0·5 mm.) and along this the earlier S1 fabric shows varying degrees of transposition. Locally, and increasingly to the north-east, the transposition of the S1 surface becomes complete on a megascopic scale such that the S2

Fig. 7. Tight, similar F2 folds 0·5 km. west of Cooper Bay, station M.690. The hammer handle is 35 cm. long.

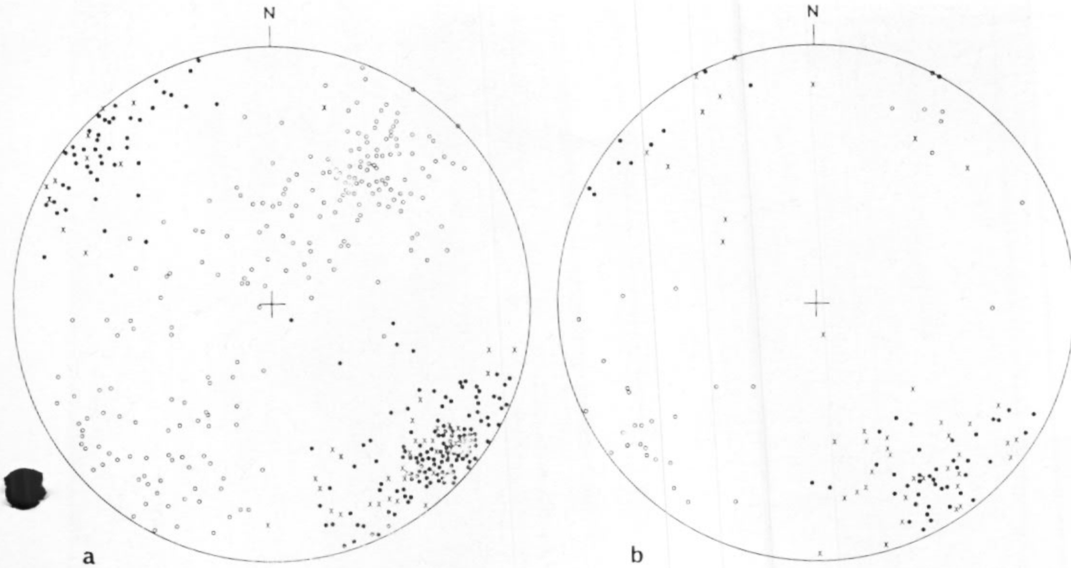


Fig. 8. Stereograms illustrating structural data from the Cooper Bay–Wirik Bay area.
a. F2 fabric data.
○ 214 poles to the S2 cleavage.
● 184 lineations.
× 45 minor fold hinges.
b. F3 fabric data.
○ 33 poles to the S3 cleavage.
● 50 lineations.
× 42 minor fold hinges and axes

micro-crenulation cleavage is virtually indistinguishable in the field from a slaty cleavage. Many of the epidiorite bodies are boudinaged within the S2 cleavage and, since they also preserve an internal planar fabric which, in some cases, seems to be continuous with this cleavage, they were probably intruded prior to the F2 fold episode.

The apparent intensification of the S2 fabric towards the north and east may reflect an intensification of the F2 fold episode but it may also be due to the finer grain-size of the slates and phyllites which crop out on the Cape Vahsel promontory. The dominant schistose fabric of many of the low-grade metasediments was probably formed during the F2 fold episode.

The F2 fold hinges and the lineations produced by the intersection of the S2 plane with earlier planar fabrics generally plunge a few degrees towards the south-east (Fig. 8a). The strike of the S2 crenulation cleavage planes is fairly constant, approximately 135°–315°, across this area but the dip shows considerable variation due to later folding. At sea-level in the Cooper Bay area, the S2 planes are generally gently or moderately inclined towards the south-west, but they show an overall increase to sub-vertical at higher altitudes and farther north-east (Fig. 3). When plotted on a stereogram the poles to S2 for the whole of the Cooper Bay–Cape Vahsel–Wirik Bay area are distributed about a great circle whose axis plunges 10° towards approximately 130° (Fig. 8a). This will reflect the axial trend of the last major phase of folding, F3.

Fold episode 3 (F3)

The third phase of folding which was responsible for the variation in attitude of the S2 cleavage (Fig. 8a) again has a south-east trend. The largest antiforms and synforms seen (Fig. 9) were similar, close and rounded, although considerable disharmony has usually developed between the more and less competent layers. The limbs of the larger folds contain congruous minor folds but in some cases small ripples which fold the S2 cleavage have gently curving axes.

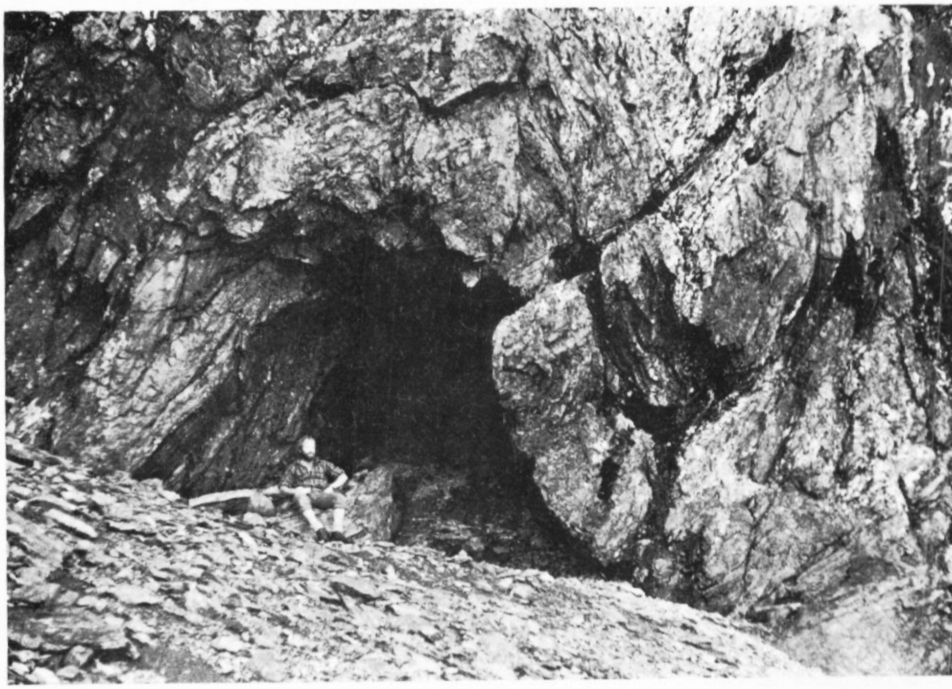


Fig. 9. An F3 antiform–synform system approximately 1 km. north-west of Cooper Bay, station M.679.

These folds typically occur as a localized group and die out along their axial traces (Fig. 10) and, although definitely post-F2, they are not entirely congruous with the major F3 folds. Possibly the hinges in these cases have been slightly re-orientated by the F4 fold episode.

To the west of Cooper Bay, minor F3 hinges re-fold the S2 crenulation cleavage, and minor hinges identical in size, style and trend also fold the mylonites (as distinct from the mylo-blastites) only a few tens of metres away. The mylonitic fabric was therefore probably formed prior to the F3 fold episode, possibly after the F2 fold episode, because the intense F2 structures seen in adjacent metasediments were not observed within the mylonite zone.

The F3 fold hinges, and the axes (Fleuty, 1964, p. 466) of the larger structures calculated from π and β diagrams, have a general plunge of up to 20° to the south-east (Fig. 8b). This trend is also shown by the intersection of the S3 crenulation cleavage with earlier planar fabrics (Fig. 8b). The crenulation cleavage, which is approximately parallel to the hinge surfaces of the F3 folds, is sub-vertical or steeply inclined and increases in intensity in the finer-grained lithologies to the north-east of this area. The spacing of the S3 cleavage planes ranges from 3 cm. to less than 1 mm. and sometimes gives rise to kink bands. When the poles to S3 are plotted on a stereogram (Fig. 8b), the north-west trend of the sub-vertical or steeply inclined cleavage is clearly defined.

The overall configuration of the F3 folds suggests that they are all congruous minor structures in the south-west limb of a major antiform whose hinge zone is situated farther north-east and trends towards the south-east. This is shown diagrammatically in Fig. 11 together with a composite cross-section illustrating the probable relationships between the first three phases of folding.

Fold episode 4 (F4)

Minor structures in the Cooper Bay–Wirik Bay area include small-scale open folds with a wave-length of less than 50 cm. in the more massive rock horizons with hinges plunging down-

Fig. 10. Minor F3 folds on the south coast of central Cooper Bay, station M.690. The hammer handle is 35 cm. long.

dip, and isolated kink or zig-zag folds with a short limb length never exceeding 2 cm. in the finely banded slates and phyllites. The kink folds may be continuous for a considerable distance along their hinge surfaces and form isolated sub-vertical kink bands trending north-east. These have caused a distinctive down-dip crenulation of earlier cleavage planes.

Summary of Geological Relations

The relict clastic grains in the metasediments of the Cooper Bay area range in composition from quartz, plagioclase, perthitic and graphic orthoclase to trachytic lava. The latter suggests compositional similarities with the Cumberland Bay-type greywackes described by Trendall (1959) but the plagioclase, perthite, graphic potash feldspar and possibly much of the quartz were probably derived from a granitic continental terrain. The high quartz content and probable provenance suggest a greater similarity with the Sandebugten-type greywackes (the type

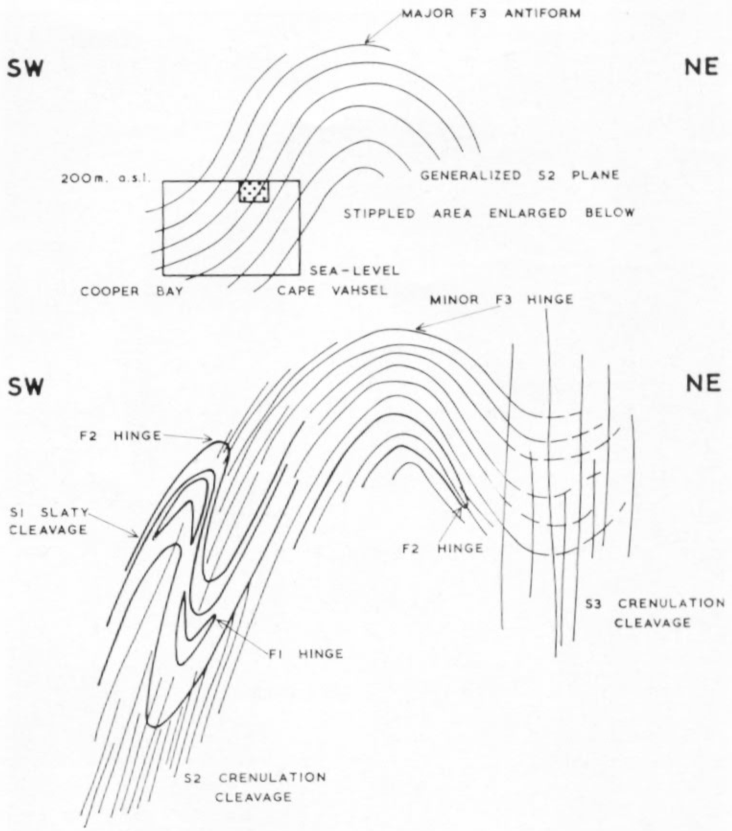


Fig. 11. The relationship between the fabrics produced by the first three fold episodes shown diagrammatically.

area described by Stone (1980)), although perthite has not been described as a detrital component of these quartzose greywackes. Conversely, felsite, which is an important detrital component of the Sandebugten-type rocks, was not seen in the metasediments from Cooper Bay.

TABLE I. A SUMMARY OF THE STRUCTURAL HISTORY OF THE COOPER BAY AREA

Fold episode	
F4	Local minor folding and kink-band formation
F3	Folding of the earlier fabrics into a large-scale, upright antiform–synform system. Formation of the S3 crenulation cleavage. Fold hinges trend south-east
	Formation of mylonites by intense cataclasis at the north-eastern margin of the igneous complex
F2	Folding and low-grade regional metamorphism to the biotite zone of the greenschist facies. Formation of the S2 crenulation cleavage. Fold hinges trend south-east
	Local compression and shearing to produce the Cooper Bay myloblastites
F1	Folding and formation of the S1 slaty cleavage

Therefore, there are important compositional differences between the rocks in the Cooper Bay–Wirik Bay area and both of the major greywacke types exposed elsewhere in South Georgia, but purely on the quartz content the closest similarity is with the Sandebugten-type rocks.

The structural history of the Cooper Bay area is summarized in Table I. The intrusion of the quartz-dolerite sheets, now metamorphosed to epidiorites, pre-dates the F2 fold episode.

The grade of metamorphism and the intensity of the folding in the Cooper Bay area are both higher than at any other point on the north-east coast of South Georgia. However, at least three fold episodes have been recognized in the Sandebugten-type rocks between Barff Peninsula and Royal Bay, whilst two or three phases of deformation have affected the Cumberland Bay-type rocks immediately south of Royal Bay (Stone, 1980). The structural complexity of the Cooper Bay area is therefore comparable with that of the rest of the north-east coast of South Georgia and the higher metamorphic grade may be a continuation of the trend in the Sandebugten-type rocks in the Barff Peninsula and Royal Bay areas, where the metamorphic grade and intensity of folding increases towards the south (Stone, 1980). If this is the case, the major upright F3 antiform with a north-westerly trending hinge suggested in Fig. 11 may correlate with the large-scale upright synform with a north-north-easterly trending hinge thought to be the main F3 (Cape Charlotte phase) structure affecting the Sandebugten-type rocks in the Royal Bay area (Stone, 1980). However, detailed structural correlations have not been possible and hence the use of F1, F2, etc. to describe structures in the Cooper Bay area does not imply correlation with the fold phases described from other parts of South Georgia (e.g. Stone, 1980).

Thus the major difference between the rocks of the Cooper Bay metamorphic zone and those elsewhere on South Georgia is compositional. The Cumberland Bay and Sandebugten-type rocks are now regarded as facies variants (Dalziel and others, 1975; Stone, 1980), so it is quite possible that the rocks in the Cooper Bay area represent a further lateral facies variation within the same Mesozoic turbidite sequence. Nevertheless, the available evidence does not completely eliminate the possibility that the original sediments of the Cooper Bay–Wirik Bay area were completely unrelated to the Sandebugten-type and Cumberland Bay-type greywacke successions.

Acknowledgements

The advice and criticism of Dr. P. W. G. Tanner was of considerable value during the preparation of the manuscript, and the editorial assistance of Dr. R. J. Adie is gratefully acknowledged. Sincere thanks are also due to G. A. Holden for companionship and support during the field work. Professor A. Williams provided facilities in the Department of Geological Sciences, University of Birmingham.

MS. received 13 October 1975

REFERENCES

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.

Fleuty, M. J. 1964. The description of folds. *Proc. Geol. Ass.*, **75**, Pt. 4, 461–92.

Ramsay, J. G. 1962. Interference patterns produced by the superposition of folds of similar type. *J. Geol.*, **70**, No. 4, 466–81.

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

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

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

Turner, F. J. 1968. *Metamorphic petrology, mineralogical and field aspects.* New York, San Francisco, St. Louis, London, Toronto, Sydney, McGraw-Hill Book Company.

——. *and* J. Verhoogen. 1960. *Igneous and metamorphic petrology.* 2nd edition. New York, Toronto and London, McGraw-Hill Book Company, Inc.

Zeck, H. P. 1974. Cataclastites, hemiclastites, holoclastites, blastoclastites, and myloblastites—cataclastic rocks. *Am. J. Sci.*, **274**, No. 9, 1064–73.