STRUCTURAL GEOLOGY OF PART OF SOUTH-EASTERN ALEXANDER ISLAND

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ABSTRACT. The tectonic structures imprinted on a thick sequence of Cretaceous clastic sediments exposed in south-eastern Alexander Island by a post-Aptian phase of deformation are described. The reaction of the sediments to tangential compressive stress is closely related to the observed facies zones in the trough of deposition. Active underthrusting of this trough in post-Aptian times by its eastern geanticline resulted in the *décollement* of the littoral- and shelf-facies sediments which were situated above the main axis of compression. In the littoral and sub-littoral rocks of the eastern part of the nappe so formed, discrete thrusts and complex "lubrication zones" of imbricate thrusts developed. These thrusts, which are broadly conformable with the bedding of the sediments, have been simultaneously gently folded together with the strata. The shelf sediments forming the western part of this thrust sheet were nearer to the stress axis where compression was entirely accommodated by folding. The folds are normal upright anticlines and synclines, but the intensity of folding is locally and regionally variable. The deep-water axial-facies arkoses, resting on or below the stress axis, have been isoclinally folded and intensely sheared. On this interpretation, George VI Sound is thought to have resulted essentially from the formation of a high, north–south, linear mountain escarpment in eastern Alexander Island by overthrusting. The distribution of joints and other small-scale structures in each zone is described and analysed, and is shown to be genetically related to the large-scale structures in the sediments in which they have developed.

ALEXANDER ISLAND is the largest of the islands lying off the west coast of the Antarctic Peninsula from which it is separated by George VI Sound, a narrow marine channel permanently occupied by an ice shelf. The eastern part of the island is formed by a complex range of parallel mountain chains which decrease regularly in height from north to south. This range extends westwards for about 20 miles (32 km.). To the west of these mountains there is an extensive, low-level ice piedmont pierced by groups of nunataks. Geological investigations to date have been restricted to the extreme eastern part of the island. In 1948–49 and 1949–50 V. E. Fuchs and R. J. Adie undertook reconnaissance topographic and geological surveys of the entire east coast of Alexander Island. Their observations were mainly on the stratigraphy and structure of the Mesozoic sedimentary rocks exposed between Block Mountain and Stephenson Nunatak. Between 1961 and 1963 B. J. Taylor surveyed a small area of these sediments in the vicinity of the British Antarctic Survey advance field station at Fossil Bluff. His study was concerned essentially with the detailed stratigraphy and palaeontology of these Aptian sediments. This paper describes the structural geology of part of the same sedimentary sequence to the south and west of Fossil Bluff. These areas, together with the features and geological stations referred to, are shown in Fig. 1.

Clastic sediments and pyroclastic rocks, the greater part of which are definitely Mesozoic in age, have been proved to occupy an area of approximately 3,000 sq. miles (7,750 km.^{2}) in Alexander Island. Since a general stratigraphical analysis is far from complete, an accurate figure for the thickness of the sediments cannot be given but a minimum thickness of 24,800 ft. (7,660 m.) appears to be present in the coastal exposures. These sediments, whose structures are described in this paper, are believed to represent a single cycle of epieugeosynclinal sedimentation in a narrow linear trough bounded on the east by a geanticlinal area of basement rocks and on the west by an intermittently active chain of volcanic islands. No stratigraphic breaks, unconformities or significant tectonic discontinuities have so far been detected in the field.

Since both the sub-horizontal sediments of the east coastal area of Alexander Island dip and the folds in the sediments farther west pitch at varying angles (about 5–30°) to the south-south-west, stratigraphically the younger horizons are encountered southwards across this area, if the absence of strike faults with significant dip-slip displacements is assumed. Evidence is presented elsewhere to support the contention that such faults are not present in this area (p. 18).

Due to the paucity or absence of fossils in the sediments of the western part of this area, which are of deep-water shelf and axial facies, and to the lack of continuity of outcrops, no

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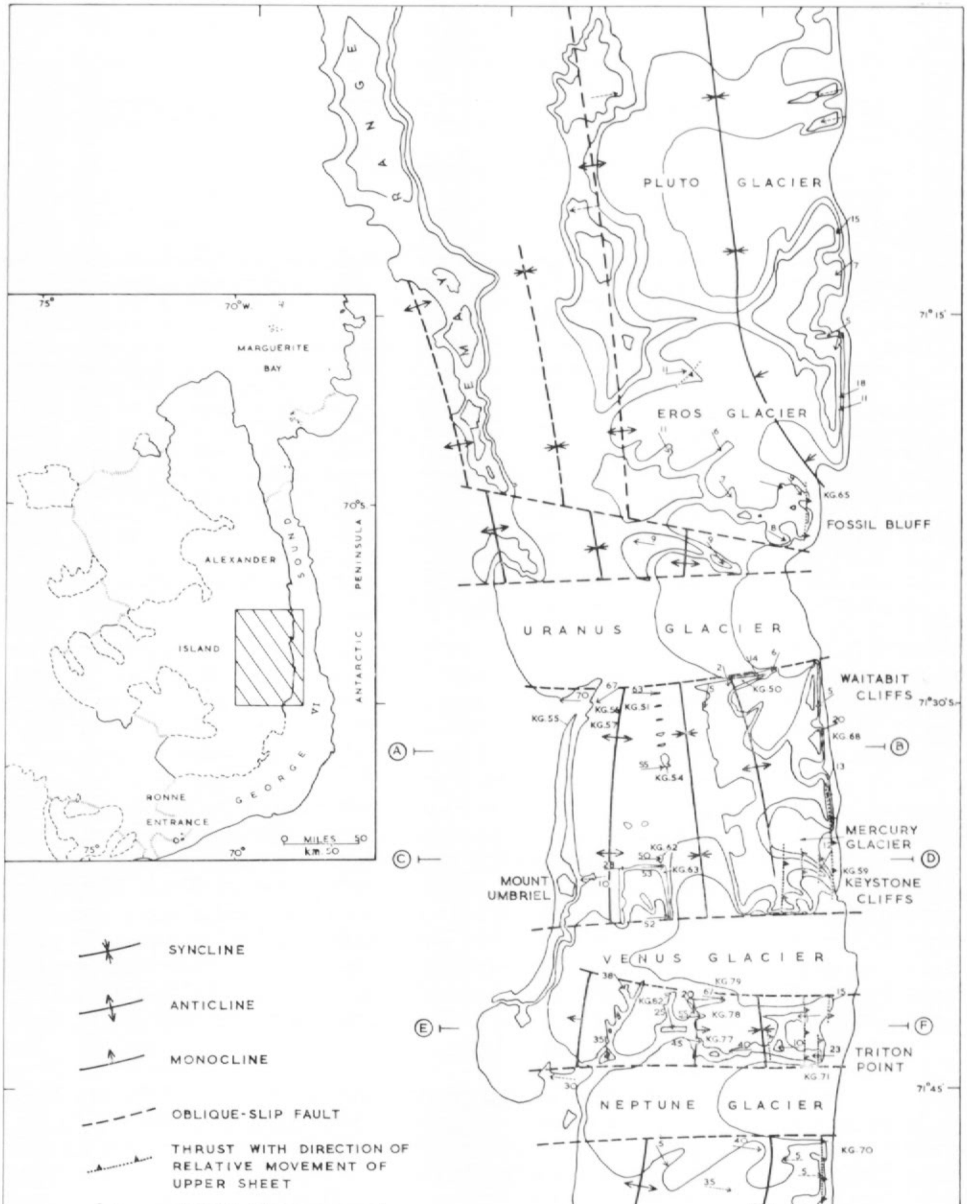

Fig. 1. A general structural map of the Cretaceous sediments of south-eastern Alexander Island, showing the disposition of the major features. Geological stations, localities where joints have been measured, and lines of section (Fig. 8) are also shown.

direct stratigraphical evidence for the relative age of the sediments exposed from east to west across this area is available. The sections given in Fig. 8 have been constructed on the assumption (which is supported by considerable direct evidence) that there are no major tectonic or stratigraphic time breaks and that the lithological changes are synchronous facies variations. The facies zone indicators are well defined and, although continuous outcrops are generally not available, localities where features of one zone are transitional into the succeeding one are frequent. The structures in the different zones are completely concordant and the structural reactions to stress correlate well with the deduced tectonic environment of each facies zone. The variation of such petrological indices as the quartz/feldspar ratio and ratio of stable to unstable constituents is smooth across the facies zones. The provenance of the detrital constituents as defined by their mineralogy is consistent in all zones.

At some time subsequent to the final infilling of the trough with coarse clastic material with associated coals, the entire trough was subjected to tangential compressive stress of east–west orientation, i.e. at right-angles to the axial trend of the trough.

The intensity of the compressive stress experienced by the sediments varied regularly parallel to the axis of the trough. Within the area discussed here, and probably throughout the island as a whole, the structures indicate that compression was greatest in the north and decreased in intensity southwards. The east to west variation in the pattern and intensity of the reaction of the sediments to the imposed stress is directly related to the tectonic environment of the sediments, and hence it correlates zonally with the facies disposition of the sediments which is also a function of their tectonic environment.

STRUCTURAL ZONES

Coastal zone

Sediments of littoral and neritic facies occupy a narrow zone trending the length of the island and extending inland from the east coast for distances from 0·6 to 3·2 miles (1 to 5 km.). Initially their outcrop was shortened by repeated imbricate thrusting from west to east along planes dipping at low angles to the west to compensate for the compression. These thrust-planes are either concordant with the bedding or dip more steeply than it, giving a gentle cross-cutting relationship. Both the sediments and the included thrust-planes were then gently folded about axes trending north–south. This is clear, since the thrust surfaces can be observed in the field to be parallel to the bedding round the fold axes. They cannot, however, be followed into the zone of major folding because here the lateral shortening has been taken up by folding rather than by thrusting. No single thrust or thrust zone can be followed for more than 0·6 miles (1 km.) along the coastal cliffs, since the strike of these thrusts is only weakly discordant with that of the coastal strata, which have a moderate dip to the south-west in this area. However, such thrusts can be seen to have a considerable lateral extent and to be developed at many levels in the succession.

Such repeated folded thrusts are typical of the eastern margin of the circum-Pacific cordilleran mountain zone adjacent to the continental craton. Structures of a remarkably similar form have been described by Scott (1954) from the eastern Rocky Mountain foothills in Alberta, Canada, in sediments in a very similar state of dynamic metamorphism.

The thrust-planes are extremely variable and their form seemingly reflects the degree of induration of the rocks involved during the application of the stress. At certain stratigraphic levels in the succession, notably at Ablation Point, Fossil Bluff and Keystone Cliffs, a group of beds about 300 ft. (91·4 m.) thick appears to have acted as "lubrication zones" for the thrusting. The occurrence of such "lubricating horizons" has been described from most of the younger orogenic belts, possibly the best example being the *argille scagliose* of the northern Apennines (Page, 1963). The beds above and below this group are undisturbed structurally, whereas those involved in the shear movement have been extensively deformed, sheared and broken with the formation of overfolds and disconnected blocks of more cohesive material. These zones appear in places to be quite concordant with the sediments above and below them but elsewhere they are distinctly discordant. Fig. 2 illustrates a thrust zone of this type exposed at Fossil Bluff. This zone is about 260 ft. (80 m.) thick and it crops out just above the upper limit of the scree sheet. Its weak discordance with the bedding of the undisturbed rocks above and below it can be clearly seen. The rocks involved here are mudstones and siltstones that

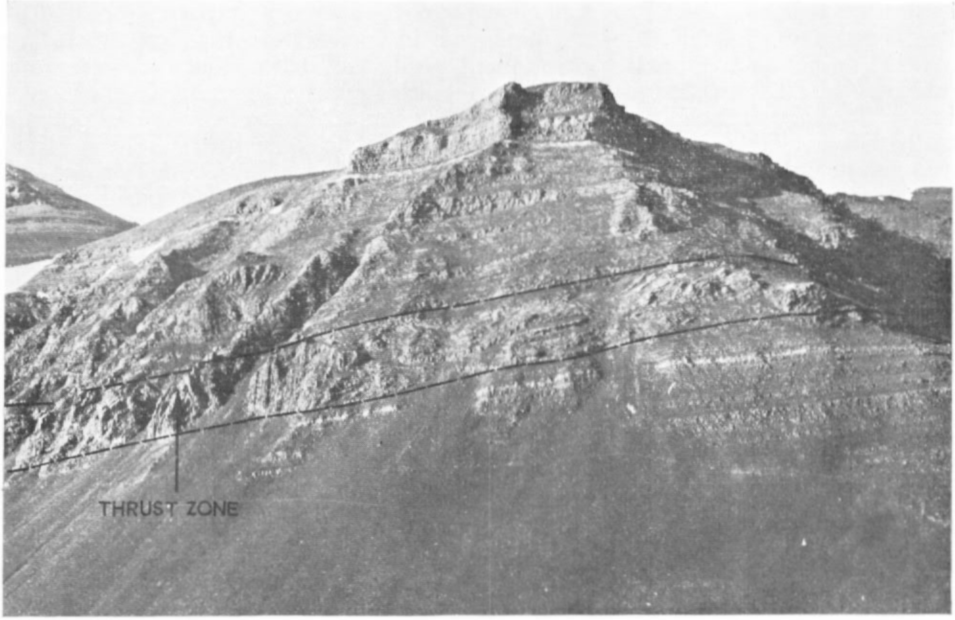

Fig. 2. A complex zone of thrusting about 260 ft. (79 m.) thick exposed on the east face of Fossil Bluff overlooking George VI Sound. The overall thrust displacement here is towards the east.

appear to have been well lithified before deformation. The mobile state of these sandstone beds during and after thrusting is shown by the fact that they have been injected in the form of dykes into the overlying undisturbed strata. Large blocks have been caught up in the shearing movements and their bedding can be seen to be randomly orientated with respect to that above and below the zone.

A striking development of imbricate thrust-planes confined to a certain group of beds is well exposed on the side of Keystone Cliffs facing north over Mercury Glacier. In addition to the repeated thrusting, the more cohesive sandstone units in the sequence involved have been contorted into rolled-up overfolds (Fig. 3a), which also demonstrate the following interesting feature. When viewed from the north, these folds appear to strike normally into the cliff behind them but on closer examination the sandstone beds can be seen to swing round the noses of the folds and become parallel to the trend of the cliff face, suggesting the influence of lateral shear along a plane parallel to the cliff. In later discussion of this feature (p. 18), the possible influence of an oblique-slip fault on this structure is postulated. Some impression of the re-folding of the structure and of the shearing of the enclosing mudstones can be obtained from Fig. 3a. A thrust zone of similar type on the eastern face of station KG.70 is illustrated in Fig. 3b. Here the rocks involved are sandstones and sandy mudstones, which appear to

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Fig. 3. a. A complex fold generated in cohesive arkoses embedded in plastic mudstones in the "lubrication" zone of thrusting at Keystone Cliffs. This has resulted from multiple shear stresses due to combined thrust and tear faulting. The scale is indicated by the figures on the scree.

b. An overturned fold in a complex zone of thrusting at station KG.70. The rocks forming the lower limb of the fold are concordant with those underlying the zone. The fold axis strikes north–south, normal to the direction of relative displacement of the upper beds to the east.

c. Two sub-parallel thrust-planes (tp) cutting massive mottled arkose and thin argillaceous interbeds at station KG.71, Triton Point. The upper thrust-plane, above the snow patch, is occupied by mylonitic material whose light colour is due to the presence of introduced quartz and prehnite.

d. A narrow thrust-plane cutting a cross-bedded mottled arkose at station KG.71, Triton Point. The thrust-plane is occupied by a layer of mylonite 10 in. (25 cm.) thick veined by secondary quartz and prehnite. The thrust-plane is cut by a late intrusive camptonite dyke.

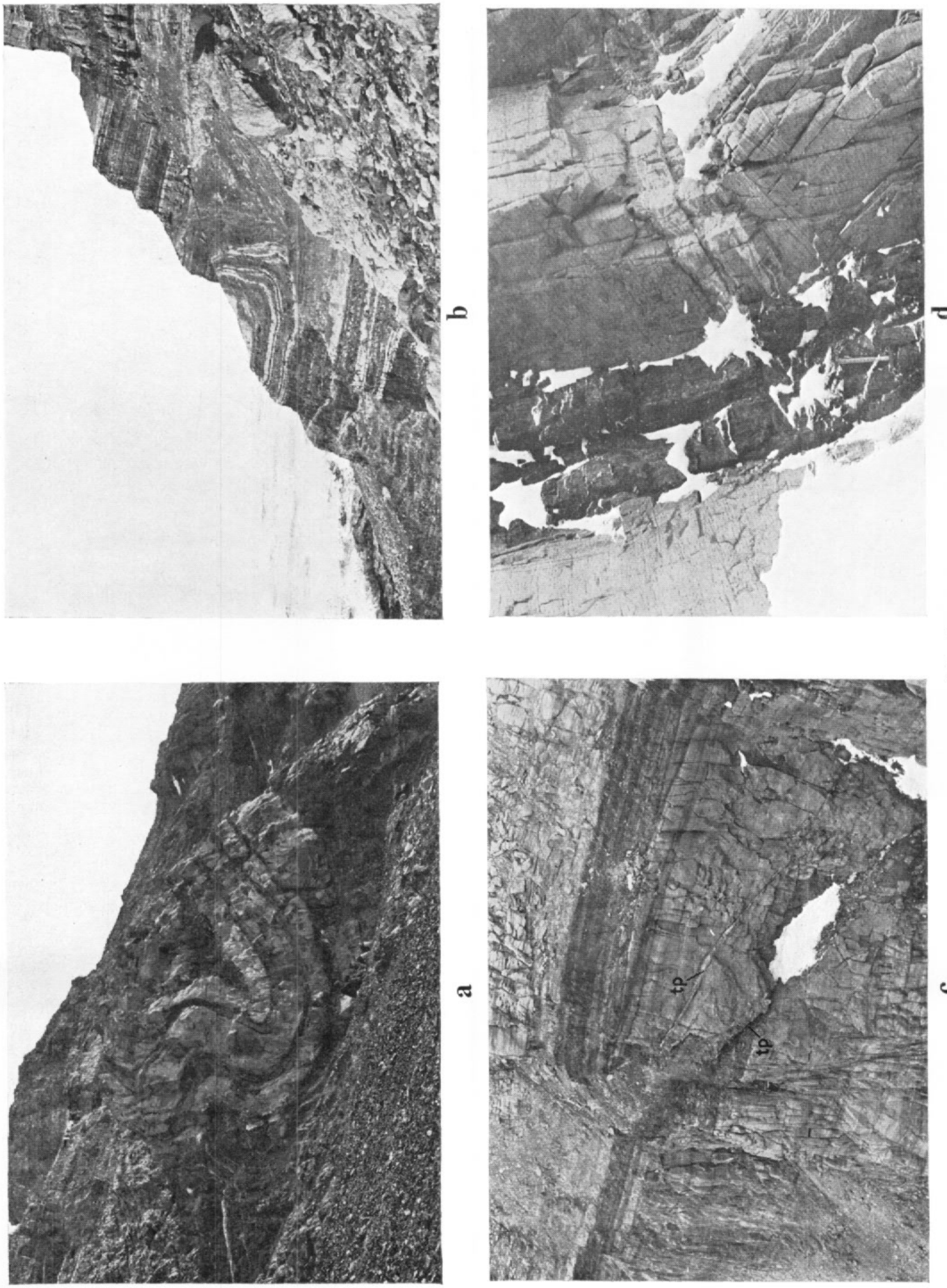

Fig. 3.

have been only weakly indurated during the deformation and have yielded to give folds overturned to the east. This fold can be followed for a considerable distance along the cliff face. Several minor thrusts of more limited extent lie below and sub-parallel to the main thrust zone.

These complex thrust zones, or zones of failure, are superficially similar to the meta-depositional slump zones described and figured by Scott (1966) from the Upper Cretaceous sediments of Patagonian Chile. These sediments bear a striking lithological and structural resemblance to those of Alexander Island. In the Patagonian structures, however, the zones exhibit only local and gentle discordance with the underlying sediments. Regular isoclinal slump folds are common in places, showing erosional truncation at their upper contacts. Imbricate thrust structures have not been recorded from these zones.

In other parts of the succession, for example at Triton Point, the thrust-plane is a more restricted surface approximately 2 ft. (0·6 m.) thick and occupied by green-stained mylonitic material often cemented by secondary quartz, calcite and prehnite (Fig. 3c). A similar narrow thrust cutting cross-bedded mottled sandstone at the same locality is shown in Fig. 3d. Part of the actual thrust surface is shown in Fig. 4. The stepped and striated surface is defined in a 0·4 in. (1 cm.) thick layer of calcite. Here, as at several other localities, where both stepped and slickensided surfaces were examined, it was observed that the steep sides of the steps on one wall face the direction in which the other wall is known to have moved in the easterly directed thrusts. This observation is in accordance with the classical interpretation of stepped slickensides (Hills, 1963) rather than with the alternative hypothesis of Tjia (1964).

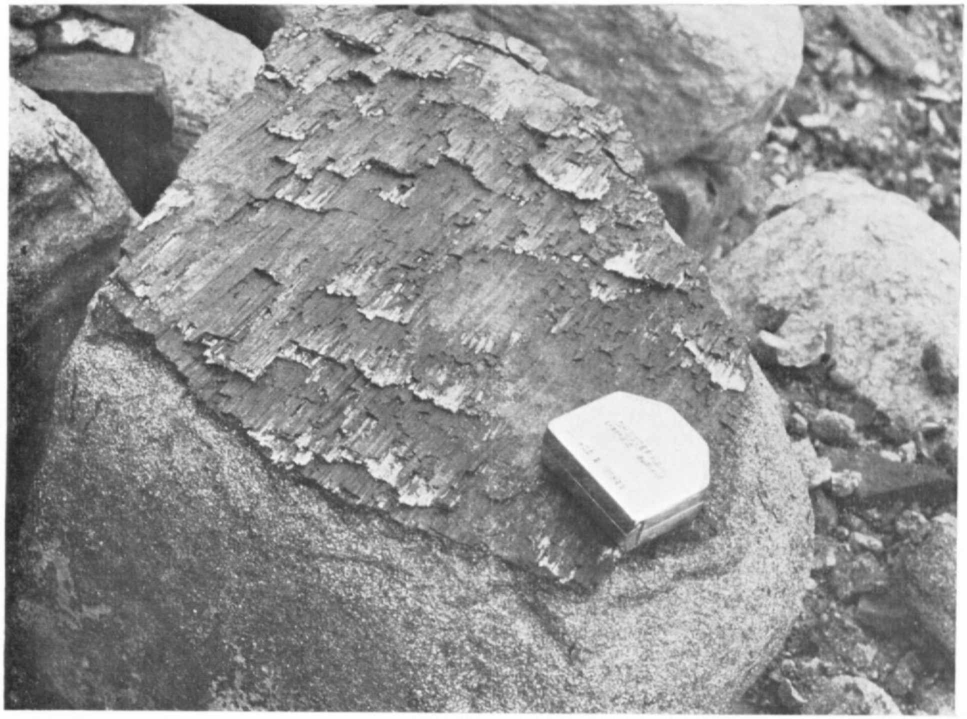

Fig. 4. Part of a slickensided thrust-plane on a loose block of mottled arkose. The stepped and striated surface is defined in a thin layer of secondary quartz, calcite, prehnite and chlorite.

Developed in association with these large-scale thrusts are many small-scale reverse faults of limited lateral and vertical extent, occurring predominantly in this coastal zone but also less frequently in the fold zone to the west. The majority of these smaller structures are of similar orientation to the larger ones, the thrusting being from west to east and the thrust-plane striking approximately north–south. However, the dip of the thrust-plane is generally steeper, ranging up to 70°, and the vertical displacement is about 3 ft. (0·9 m.). In these structures the thrust-plane is merely a closed, often slickensided surface, on which the shearing has been accommodated without associated brecciation of the wall rocks. Occasionally associated with these thrusts are fine, sub-parallel, open or quartz-filled shear cleavages developed in adjacent beds asymptotically to the thrust-plane. On a few of the minor reverse faults the slip of the upper block in the thrust is from east to west. These are thought to be conjugate planes of dislocation developed synchronously with the thrusts towards the east. These small thrusts can be most readily recognized when they cut laminations of varying colour or lithology. In the massive uninterrupted mudstone successions, shear movement on irregular planes, bedding or joint surfaces can only be recognized where slickensides are developed.

Central zone

In the area to the west of the coastal belt and extending for a distance of 10 miles (16 km.) inland from the coast, the sediments are the result of deposition in a neritic environment of intermediate water depth and on an intermittently unstable shelf. The outer or western edge of this shelf is marked by a narrow zone of rocks such as pebbly mudstones and slide breccias, the products of mass sliding on the relatively steep scarp face of the shelf. In the sediments of the central zone, normal synclines, anticlines and opposed monoclinal folds are developed. The disposition of these folds relative to the structural zones (Fig. 1) is illustrated in Fig. 5.

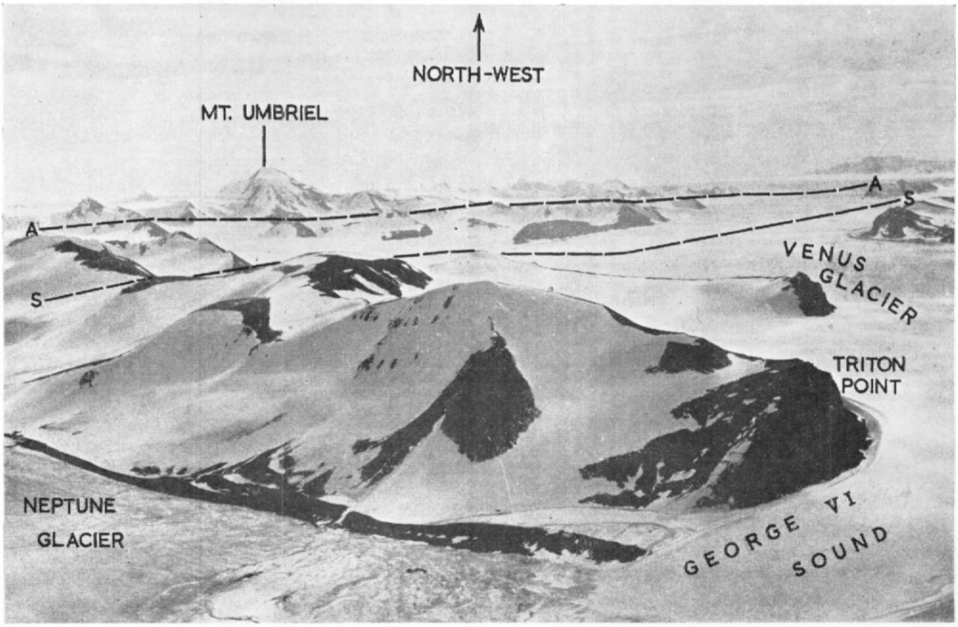

Fig. 5. A general view of the area in the vicinity of Venus Glacier, showing the disposition of the main fold axes. George VI Sound is barely visible in the extreme right foreground of the photograph. A—A. Anticlinal axis; S—S. Synclinal axis.

In general, the amplitude: wave-length ratio of these folds decreases rapidly southwards. In addition, the degree of folding of adjacent anticlines and synclines is mutually interdependent in that the compression at one place may be taken up by the tight folding of one of the folds, while some distance away and parallel to their axes the other fold has the smaller inter-limb angle. The resultant variation in the amplitude : wave-length ratio of the folds along their axes is distinct from the regional reduction in this ratio southwards. The first effect seems to be due either to differences in basement control or in related facies and diagenetic variation, whereas the second is a direct consequence of the north–south decrease in intensity of regional compression. The changes in fold type are described here from north to south and parallel to the regional trend.

King (1964) has described the sediments in the central Lemay Range as being "disposed in folds like corrugated iron". Just to the south of Uranus Glacier they are still of this type with wave-length approximately equal to amplitude, the main anticline having a closure of 2 miles (3·2 km.). The main syncline lying between this anticline and the coast changes its form very little as it is traced southwards. In the area surveyed it is distinctly asymmetrical and its axial plane dips at 85° to the west. In upper Venus Glacier, however, the folds are more gentle and of smaller amplitude with their axes plunging at angles up to 35° in places. Here the prominent anticline locally develops into opposed, tightly reflex monoclines, resulting in a box fold whose crestal beds plunge at 35° to the south. The eastern monocline (Fig. 6) is very well exposed at station KG.78. The steep eastern beds dip at 55° to 083° and the shallow western beds near the summit dip at 20° to 140°. The reasons for this change in fold type are discussed in the description of the associated joint patterns (p. 15). The more argillaceous beds in the core of this box fold are locally penetrated by intense quartz-veining which fills shear and tension gashes. Generally these surfaces are random and irregular, and they are the result of thickening and shearing in the core of the fold. At one locality, however, more regular sigmoidal tension gashes (Fig. 7) (Hills, 1963) were recorded.

Fig. 6. The eastern monocline (station KG.78) of the box fold shown in Fig. 8, viewed from the north (station KG.79) parallel to the fold axis. The mountain is on the south side of Venus Glacier 6 miles (9·6 km.) inland from the coast.

South of Neptune Glacier this box fold alters in form to a broad low-amplitude anticline and this fold continues to decrease in amplitude towards the south. The change in the form of the two main fold structures is outlined in Fig. 8. Due to the moderate southerly plunge of the folds, the variation in their structures (as shown here) is a result both of the vertical change in the fold profile due to the non-similar nature of the folding and of the regional north–south decrease in the intensity of compression. Other irregular controls, such as the influence of the basement and lithology on the folding process, further complicate the interpretation. Since these variables modify the accessible sections of the fold simultaneously, their individual effects cannot be distinguished.

Fig. 7. Well-developed sigmoidal tension gashes exposed at station KG.82 below the same monoclinal axis as in Fig. 6. Fine shear cleavage surfaces, infilled by secondary quartz and parallel to the axial zones of the gashes, can be seen in the lower right-hand corner of the photograph. The sigmoidal pattern is a result of drag shearing due to their position in the eastern limb of the box fold. The hammer shaft is 12 in. (30 cm.) long.

Western zone

West of the zone of slide deposits, which marks the outer edge of the marginal shelf, there is a broad zone (as yet of undetermined western extent) where the rocks are massive grey arkoses and subordinate shales of deep-water axial-turbidite facies. These sediments have been subjected to extreme compressive stress. In the northern extension of the Mount Umbriel massif these arkoses have an overall steep bedding dip to the west which is consistent with their position in the western limb of the main anticline. They are intensely cleaved and traversed by shear planes with the result that irregular autoclastic breccia lenses have developed and the stratification is virtually obliterated in places. Closely spaced, slickensided surfaces cut through the body of the rock. To the north-north-west of this area, in the western foothills of the Lemay Range, G. Grikurov (personal communication) recorded steeply dipping, isoclinally folded sediments locally overturned to the east. However, the age of the rocks involved there is in doubt and, although the structures are concordant and of similar style and intensity to those in this area, the sediments and volcanic rocks may belong to an entirely different, probably earlier, depositional cycle.

STRUCTURE IN ADJACENT AREAS

These structural features with a similar zonal distribution are thought to extend from the southern limit of outcrops near Stephenson Nunatak northward to the latitude of Transition Glacier, a distance of 110 miles (175 km.). At Transition Glacier, just north of Block Mountain, a distinct change in the structure of the coastal rocks can be observed from George VI Sound. The rocks that crop out on Block Mountain have the typical aspect of regularly bedded clastic sediments with a low dip similar to the coastal rocks farther south, whereas on the northern side of the glacier they have a dark, more massive appearance with only weakly

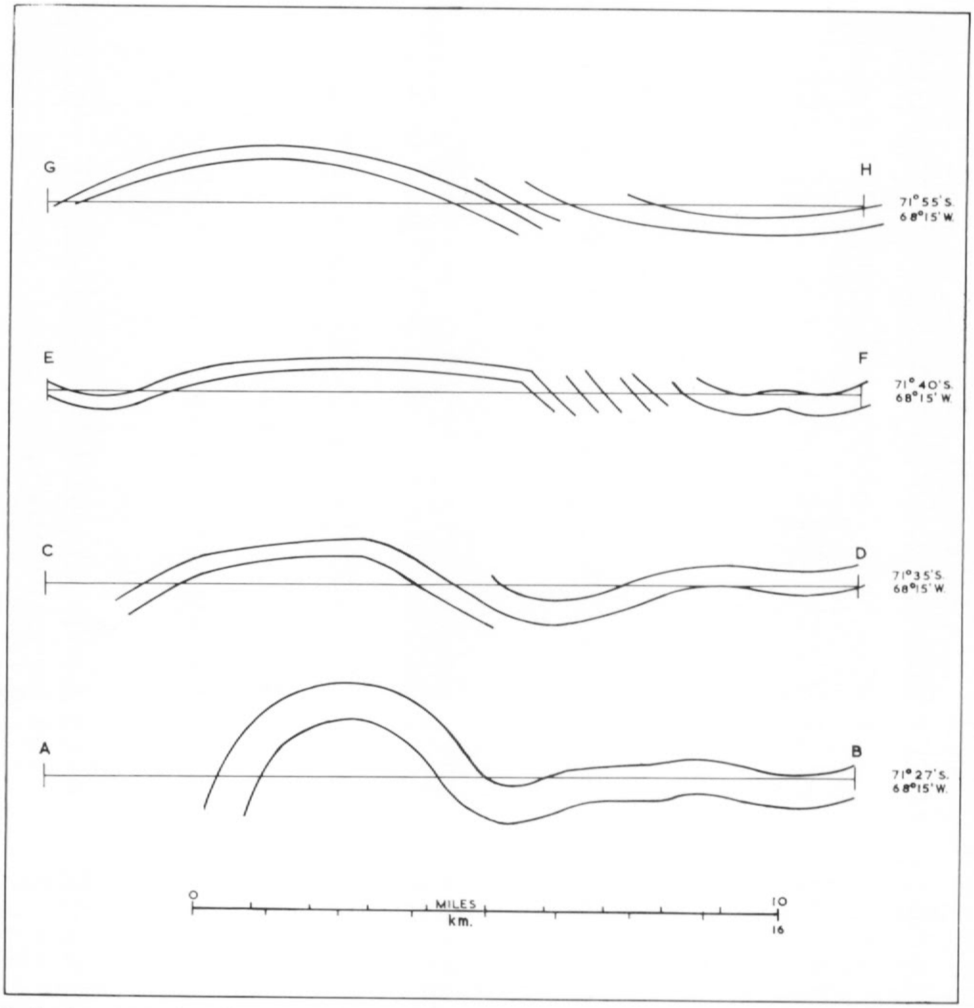

Fig. 8. Sections normal to the structural trend of this area, drawn along lines A—B, C—D, E—F and G—H (Fig. 1). These sections are in stratigraphical order in that the structures shown in section A—B are imprinted on the oldest rocks in the area, due to the southerly plunge of the fold axes. Since the degree of shortening apparently increases downwards, the change in the fold form results from variation in intensity of compression along the length of the basin, rather than from the probable concentric nature of the folding.

defined lamination on the outcrop. These relations could only be observed from a distance of about 0·3 miles (0·5 km.) because the area was inaccessible. The only direct evidence for the type of rocks cropping out on the eastern side of the Douglas Range north of Transition Glacier was collected at two localities on the east coast 1·9 and 9·3 miles (3 and 15 km.) north of Wager Glacier (approximately 56 miles (90 km.) north of Transition Glacier), where welded andesitic pyroclastic rocks that are severely sheared and injected by quartz veins crop out (Adie, 1954). In places they have been mylonitized by thrust shear. Adie has assigned these rocks to the Lower Palaeozoic on the basis of their considerably greater alteration than the Upper Jurassic lavas. The intense injection and shearing of these pyroclastic rocks is to be expected because of their position in the zone of coastal thrusting which has been described as increasing in intensity northwards, assuming that relative to the Mesozoic sediments farther south they are either part of the same depositional cycle or older deposits in the same trough.

JOINTS

Description of structures on joint planes

The Alexander Island sediments are everywhere cleaved by joints whose development shows the same zonal arrangement reflecting their close genetic relationship to the major structural features. These joints are best developed in the more indurated, fine-grained mudstones and massive arkoses, becoming less regular and less numerous in the coarser rocks. They are rare or absent in the conglomeratic horizons.

The joint surfaces are commonly quite smooth and planar, often with small rosettes of calcite crystals covering their faces, particularly in the mudstones. In the coastal zone, however, a large proportion of the shear-joint planes are distorted and several different types of structure result.

Pressure trails. These are curved or sub-linear trails, averaging 2 in. (5 cm.) in width, of parallel step-like curved grooves, the length of the grooves being perpendicular to the length of the trails. They seem to represent bands where the joint faces were still in contact after the rest of the plane opened and therefore bore the shearing stress across the face.

Curved joint faces. Many of the coastal joints, particularly in the vicinity of Fossil Bluff, are undulatory in form. The regularity of the undulations on the joint faces varies. Occasionally they are corrugated, the corrugations having wave-lengths of 4 in. (10 cm.) and amplitudes of 1–2 in. (2·5–5·0 cm.); the axes of the corrugations are generally sub-horizontal. Other joint faces have a smoothly variable relief that is completely random. At the particular localities where this feature was observed, the rocks involved are banded siltstones of variable lithology and the nature of the jointing may be related to subtle variations in the hardness of the rocks.

Pseudo-ripple-mark. This structure was observed on a single joint face on Waitabit Cliffs (Fig. 9a). It is strikingly similar to depositional ripple-marking. This structure is believed to represent an extreme development of pressure trails and it originates in shear across the face. Small step-like indentations, similar to those forming pressure trails, intersect the "ripple" structures at a low angle (Fig. 9a).

Statistical analyses and interpretation

In the area surveyed 453 joint measurements were taken at 11 localities and statistical orientation analyses for these localities are based on the measurements. There are two clear limitations to this investigation: first, the small total number of joints measured increases the possibility of error than in a comprehensive survey, and secondly, this error may be affected by an observational bias towards the preferential measurement of the more obvious and accessible joint sets exposed by the fortuitous orientation of linear cliff faces and ridges.

Plots of joints at stations KG.50, 59, 65 and 68 are given in Fig. 10. These analyses for the coastal zone indicate that here there is a conjugate set of steeply dipping shear joints at approximately right-angles (Fig. 9b). According to theoretical results, the axis of maximum compressive stress is so orientated as to bisect the angle between conjugate sets of shear joints. This theoretical axis of compression (Fig. 10), derived from the joint analyses, agrees very well with the regional east-north-east to west-south-west axis of compression implied by the regional structures.

Plots of joints at stations KG.51, 54, 62 and 63, 82 and 78 are shown in Fig. 11. These joints, developed in the zone of open folding, are basically of a different type from those described above and they are closely related genetically to the folding of the rocks in which they are developed. At stations KG.51 and 54, a single set of joints with a moderate dip to the west has developed. As the rocks in the same position in the fold are followed southwards parallel to the fold axis, the strike of the joints swings from north–south to east–west and they alter to a conjugate set with orthorhombic symmetry as opposed to the distinct monoclinic pattern at stations KG.51 and 54. The reasons for this change in joint orientation can be related to the change in fold type. At stations KG.51 and 54 the rocks form the eastern limb of a normal upright concentric anticline (Figs. 1 and 8). Here they are interpreted as being a

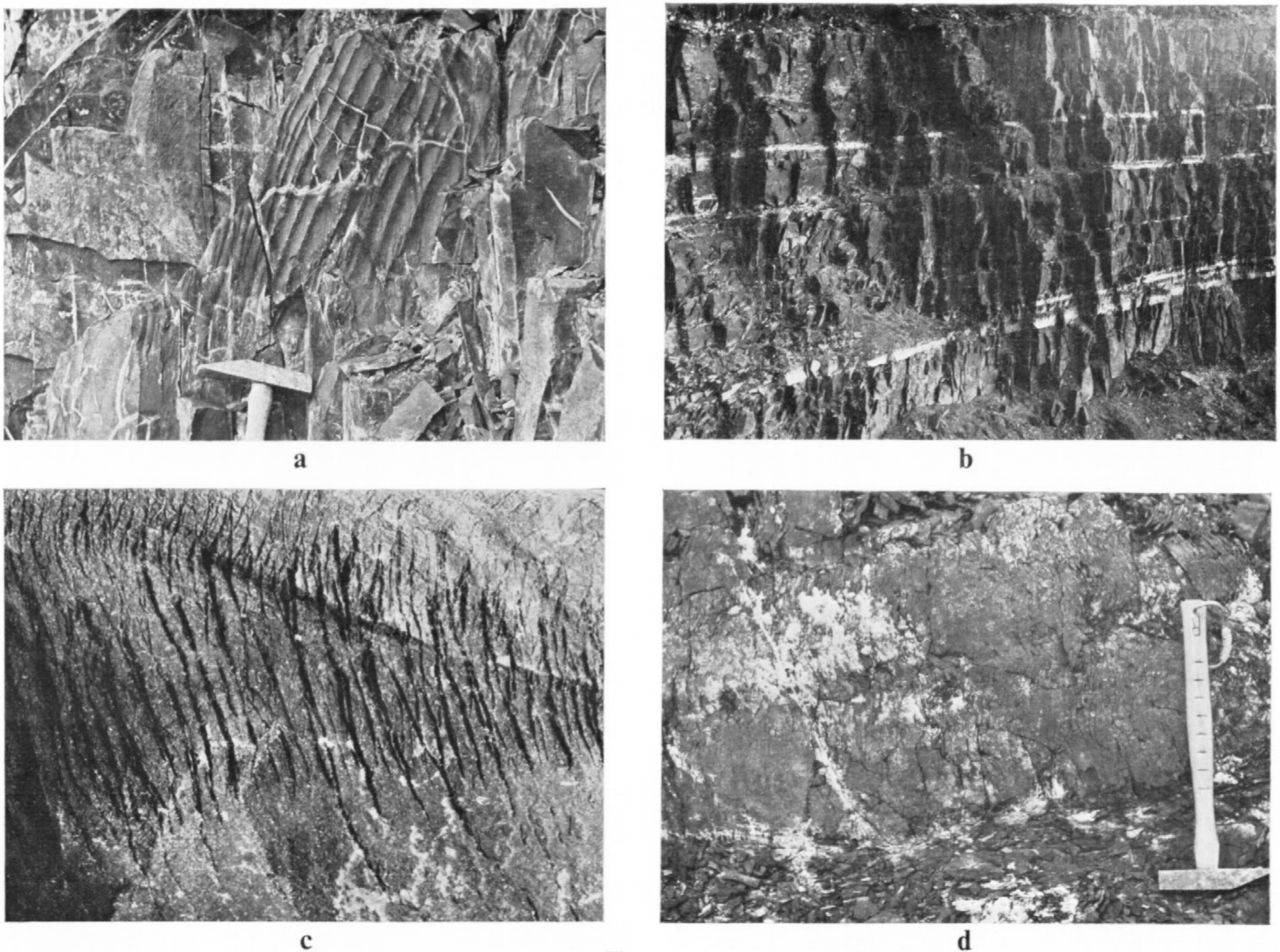

Fig. 9.

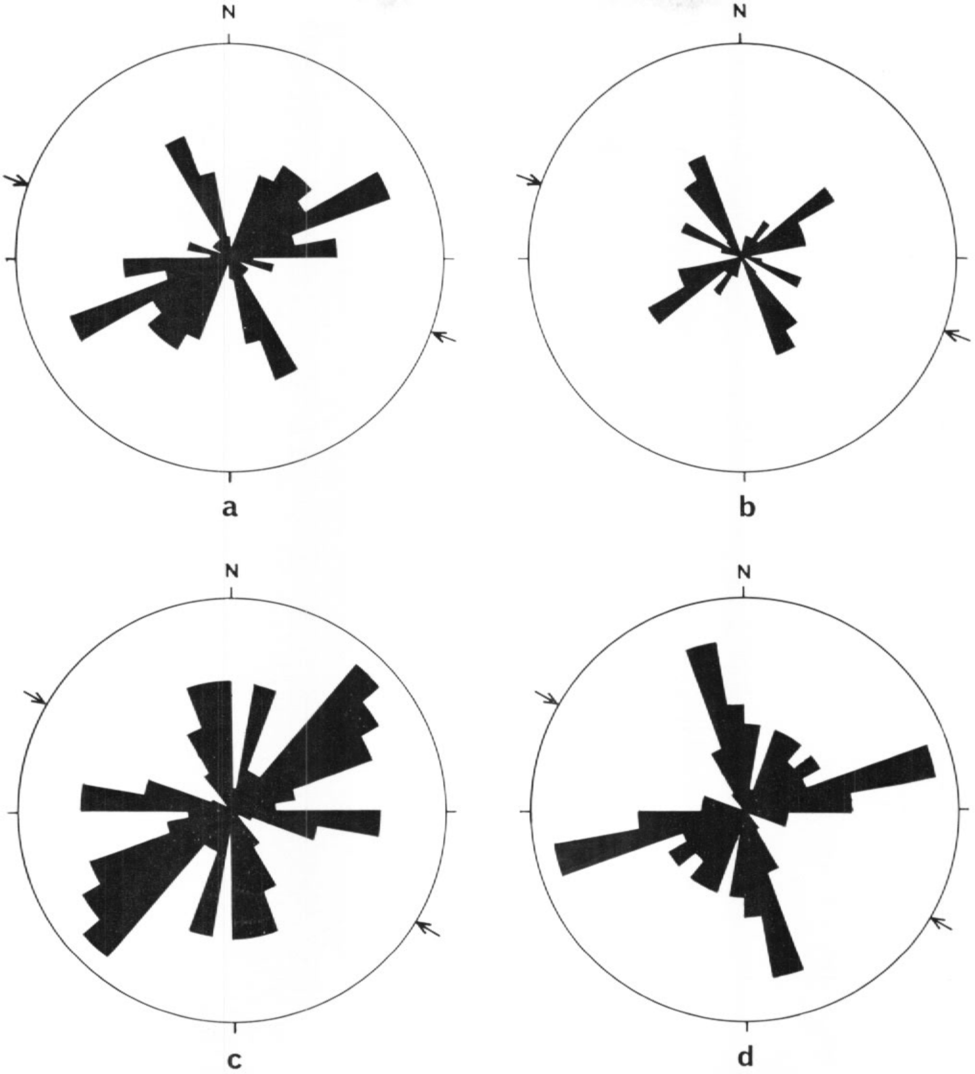

Fig. 10. Analyses of joints measured at stations KG.50, 59, 65 and 68. The inferred regional compression is shown by the arrows.
a. Station KG.65; b. Station KG.50; c. Station KG.68; d. Station KG.59.

Fig. 9. a. Pseudo-ripple-mark structure exposed on a joint face at Waitabit Cliffs. On the face illustrated the crests are sharp and the troughs are rounded. The wave-length of the structure is 1·2 in. (3 cm.), the amplitude is 0·4 in. (1 cm.) and the axes of the grooves dip at 66° to 065°.
b. A conjugate set of vertical shear joints developed in massive argillite at Waitabit Cliffs.
c. Two distinct trails of tension gashes of different sizes can be distinguished in a massive siltstone from station KG.77 (×1·3).
d. Crude axial-plane cleavage resulting from compression in the core of the main anticline particularly where it takes the form of a box fold in upper Venus Glacier. This photograph was taken just below the summit knoll of the mountain illustrated in Fig. 6.

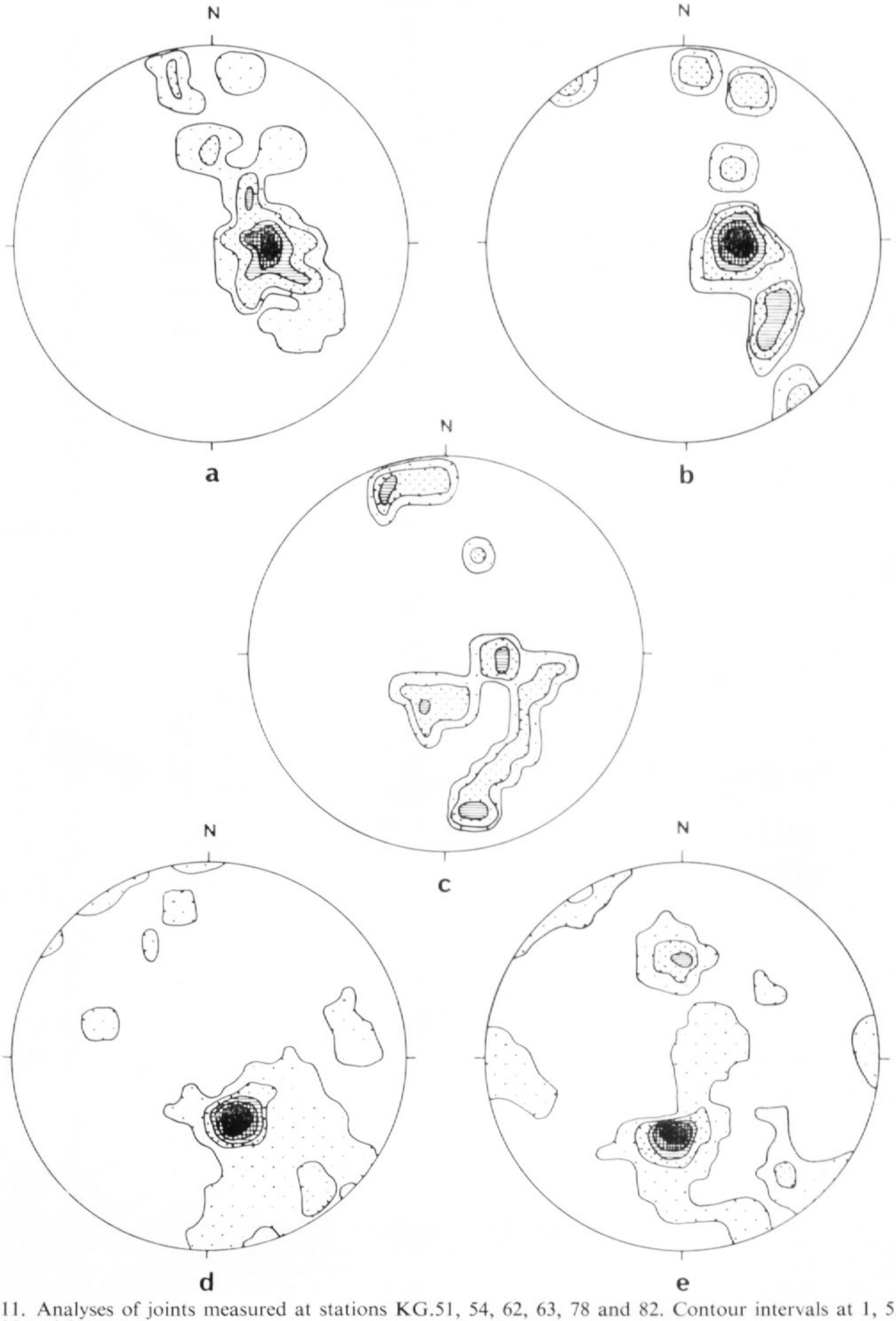

Fig. 11. Analyses of joints measured at stations KG.51, 54, 62, 63, 78 and 82. Contour intervals at 1, 5, 10, 15 and 20 per cent.
a. Station KG.51 (30 observations); b. Station KG.54 (20 observations); c. Stations KG.62 and 63 (15 observations); d. Station KG.82 (70 observations); e. Station KG.78 (70 observations).

single set of shear joints with normal orientation with respect to the fold structure. At station KG.78 the joints were measured on the steeply dipping rocks below the tight monoclinal fold shown in Fig. 6. Here the orientation analysis indicates a conjugate set of joints with opposed dip and identical strike. The orientation of the strike of these gently dipping joints parallel to the regional axis of maximum compressive stress is most unusual, and it seems to indicate that the abnormality both of the fold form and of the joint pattern are the consequence of an anomalous local stress pattern. The development of the low-amplitude box fold, whose eastern monocline is an incipient, easterly directed, low-angled overthrust, means that the minimum stress axis (the direction of easiest relief) was not vertical but east–west in a horizontal plane. The reason for the development of the abnormal stress pattern in this limited area is not clear. The relatively high vertical confining stress could be most easily explained as resulting from gravitational overloading of either depositional or structural type. The development of the box-fold form to which this jointing is apparently related is discussed further in connection with the regional tectonics (p. 18).

The total number of joints measured in the zone of more intense deformation (stations KG.55, 56 and 57) is too small to give anything but a general outline of the joint pattern (Fig. 12). The beds at stations KG.56 and 57 are less deformed than those at station KG.55, and they are the symmetrical equivalents of the joints at stations KG.51 and 54 across the anticlinal axis. Here there is one distinct set of shear joints dipping steeply at angles greater than 80° to the east. In addition there is a single subsidiary set striking west-north-west to east-south-east.

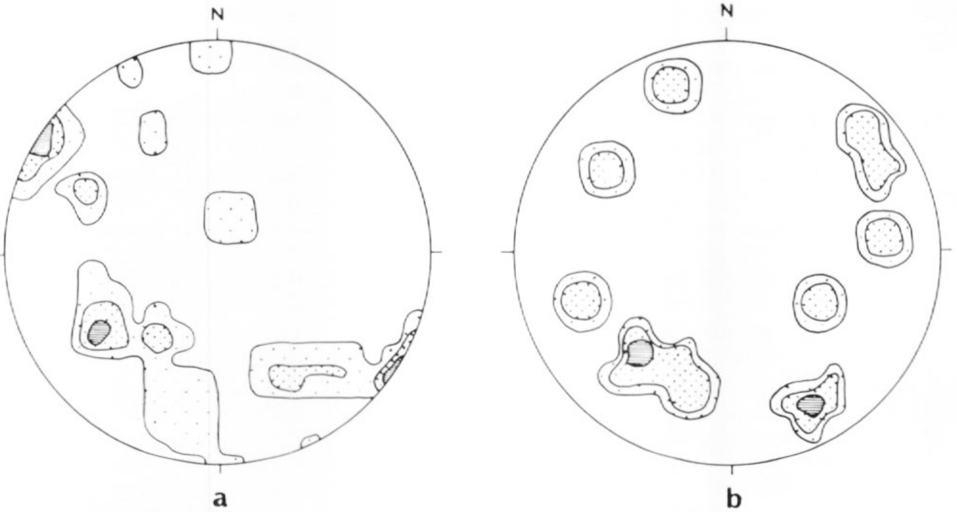

Fig. 12. Analyses of joints measured at stations KG.55, 56 and 57. Contour intervals at 1, 5 and 10 per cent. a. Stations KG.56 and 57 (25 observations); b. Station KG.55 (13 observations).

At station KG.55 only a few joint planes of adequate regularity could be found for measurement, the others being deformed by shear. The intensity of this deformation is reflected in the triclinic symmetry of the resulting diagram (Fig. 12b).

MINOR STRUCTURES

Gash veins

Sinuous planes of sub-parallel tension gashes, generally near vertical and of random strike, commonly occur in the mudstones and siltstones of the coastal outcrops (Fig. 9c). The gashes average about 1 in. (2·5 cm.) long and 0·08 in. (2 mm.) wide, and they are usually wholly or partially filled with secondary iron oxides, quartz or calcite.

Sigmoidal tension gashes

Excellent examples of sigmoidal tension gashes, as defined by Hills (1963), are exposed at station KG.82. They are developed by shear tension in massive mudstones, their sigmoidal form being a result of drag shear due to their position in the eastern limb of the main anticline. The traces of fine, quartz-filled planar shear surfaces trend sub-parallel to the central shear zones of the tension gashes (Fig. 7).

Cleavage

In places shearing in the beds near the eastern monocline of the box fold has resulted in the development of a crude axial-plane cleavage in the mudstones (Fig. 9d).

INTERPRETATION OF THE TECTONICS

The exact mechanism of the tectonic processes, which have resulted in the structures described here, is difficult to define due primarily to the limited area studied so far, and in particular to the lack of data from the west side of the "Bellingshausen trough" which has not yet been found. Therefore, the deformation pattern must be interpreted initially on the evidence from part of the eastern side of the trough.

Only two possible interpretations of the structures described above seem to have ap[illegible] validity. Either the "Bellingshausen trough" was strongly compressed from the west, resulting in folding and overthrusting of the sediments on to a passive and resistant basement block east of the trough, or the sediments have been actively underthrust from the east by this same basement block with resultant eastwardly directed, low-angle thrusts and folding farther to the west. The main objection to the first hypothesis is that it seems unlikely that tangential compressive stress adequate to cause widespread thrusting could have been transmitted at a distance of at least 50 miles (80 km.) across the trough by apparently quite incompetent sediments which are in the process of folding (Aubouin, 1965, p. 209). However, an interpretation based on active underthrusting of the sediments from the east can be more easily reconciled both with the field evidence and with several theoretical and experimental observations.

A possible criterion for determining the absolute movement pattern in areas of widespread thrusting in arcuate mountain belts is that the direction of movement of the active basement block is radially outwards from the centre of the arc. In Alexander Island such an arcuate pattern is only weakly developed, the folds generally maintaining a remarkably persistent parallelism to the linear east coast of the island. In the south-east, and possibly in the extreme north-east of the island, the strike of the fold axes has a tendency to swing to the east, giving the structural lineament a slight concavity towards the east.

The thrust effects resulting from the compression of a thick clastic sequence by a resistant block have been studied experimentally by Link (1928*a*). His experiments indicated that the movement of an active but rigid basement block into a non-homogeneous sedimentary sequence results in various patterns of over- and underthrust structures, depending on the vertical distribution of applied stress across the face of the block relative to the depth of th[illegible] sediments. If the compression or shortening is greatest at depth and decreases towards th[illegible] surface, then a cone of shear develops giving rise to a high-angle overthrust at depth (below the axis of maximum stress) and a low-angle underthrust nearer the surface (above the axis of maximum stress) bounding a plateau uplift or wedge. There are close parallels between Link's experimental results and the present interpretation of the Alexander Island tectonics (Fig. 13). On this interpretation the zonal variation in structural response of the sediments can be seen to be a direct consequence of their tectonic environment of deposition. The sediments of the coastal zone are of shallow-water, littoral and neritic facies, and they accumulated on the marginal shelf adjoining the bounding geanticline near the eastern shoreline of the trough. These rocks escaped down-warping and folding on the initiation of compression from the east because of their position above the main stress axis. As shearing stress built up between the sediments and their basement, a fundamental zone of *décollement* developed initially at the base of the thrust sheet and later at various levels in the sedimentary sequence, the gliding planes tending to develop in the less-indurated horizons. The sediments on the outer part of the marginal shelf are deeper-water neritic deposits and they were situated

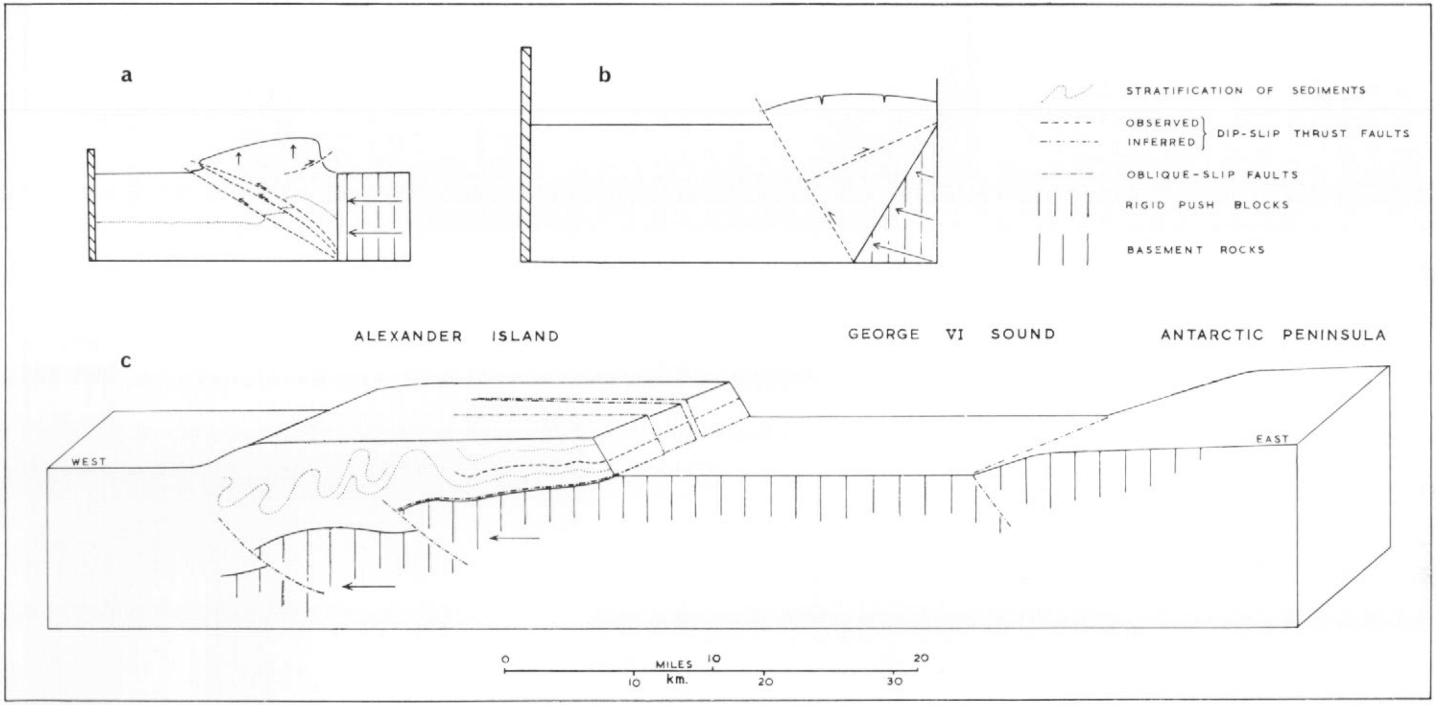

Fig. 13. A comparison between the experimental observations of Link (1928*b*, 1949) on the thrust effects resulting from the subjection of a sedimentary sequence to differential horizontal compressive stress (a and b) and the proposed tectonic model for the Alexander Island structures (c).

at a low enough level with respect to the surface of the eastern geanticlinal block to be subjected to lateral compressive stress in addition to the basal shearing stress that led to *décollement*. As a result, they folded to yield normal anticlines and synclines and local box folds (p. 15). To the west of this shelf there was a deep-water area forming the axial zone of the trough, in which grey arkoses with varying quantities of interbedded volcanic material (both lavas and pyroclastic rocks) accumulated. The bottom of the slope of the shelf edge is marked by the presence of typical submarine mass-slide deposits. Because they were either resting on or below the main axis of stress transmitted by the rigid shelf, these sediments were extensively sheared and tightly folded.

Complex zones of imbricate-folded thrusts such as those described here are typically developed in relatively shallow, unmetamorphosed sedimentary sequences overlying a resistant basement with strong unconformity. In such areas of so-called "thin-skinned tectonics" the thrusts are distinct planes of bedding *décollement* in contrast to the "vanished reversed limbs of overfolds" referred to by Bailey (1935). Two characteristics of such thrusts are their overall concordance but weak local discordance with the bedding of the intervening thrust slices, and the maintenance of this concordance as they grade into bedding shear surfaces in the folded zone of the parautochthonous nappe. A typical feature of the folds developed in sediments involved in thin-skinned tectonics is the development of box folds or flat-crested anticlines, in which one of the inclined axial planes of the opposed monoclines has a tendency to develop into a thrust or high-angle reverse fault. A box fold of this type with incipient thrusting on its eastern axial plane is well illustrated in Fig. 6. Such folds are typified by those in the Swiss Jura, which has come to be regarded as the type area of *décollement* nappe tectonics (de Sitter, 1956). In such areas the folding is generally observed to be of the concentric type, the fold profile flattening through older horizons down to the basal detachment plane. The pattern of the folding in Alexander Island cannot be determined at present, since the disposition of the structural elements in the sediments is such that nowhere is there a series of stratigraphic sections across the folds exposed at the same geographical point in the trough. The fold profiles shown in Fig. 8 are serial sections which, although exhibited in successive stratigraphic horizons, are also spaced geographically across the area. Hence the change in fold profiles is a function both of the probably concentric nature of the folding and of the varying stress pattern along the trough. From these sections it can be seen that the shallower folding is in fact exhibited in the youngest strata, indicating that the reduction in compressive stress southwards, where these youngest strata are preserved, is the controlling factor in the variation shown in the serial profiles.

Transcurrent faults

In the 110 miles (180 km.) between Transition Glacier and Stephenson Nunatak, the northern and southern limits of outcrop of definite Mesozoic sedimentary rocks, the mountain ranges of the east coast of Alexander Island are transected at low levels by major transcurrent valleys now occupied by large glaciers flowing from west to east into George VI Sound. The most significant of these valleys are those occupied by Grotto, Jupiter, Uranus and Saturn Glaciers. The direct tectonic control of the morphology of these valleys, implied by their transcurrent relationship to the regional trend of the mountain chain and the marked linearity of their sides, has been recognized by Adie (1958) and King (1964). King regarded the coastal sedimentary blocks as being separated from each other by grabens representing subsidiary rifts genetically associated with the formation of the supposed rift of George VI Sound. However, no real mechanism was suggested for the development of a stress regime resulting in extensive rifting in two normally opposed directions.

In his experiments on the development of *en échelon* folds in arcuate mountain belts by the subjection of a sedimentary sequence to differential horizontal compressive stress, Link (1928*a*) noted the development of cross-cutting oblique-slip faults intersecting the folds at approximately right-angles. Evidence has already been given for the presence of a fault with a significant strike-slip component at Keystone Cliffs (p. 4). Linear geomorphological features, including the valley lineaments of Saturn, Uranus, Grotto and Hampton Glaciers are shown in Fig. 1. They strike normally to the fold axes and therefore have an overall convergence towards the east, which is consistent with Link's observation that the transverse faults converge on the centre of active compression. It is suggested, therefore, that these lineaments may be controlled by oblique-slip faults developed synchronously with the underthrusting and folding of the sediments. Closely similar transverse fracturing has been described by Katz (1962) from the sub-Andean fold belt of southernmost Chile east of the high cordillera. Although Katz did not attempt to relate these structures to regional stress dispositions, he stated that "some of this fracturing with an orientation perpendicular to the strike of the fold axes is interpreted as tension fracturing contemporaneous with the folding", indicating that the author most probably had in mind a tectonic model similar to that suggested here for the Alexander Island structures.

Orogenesis in Alexander Island

The preceding discussion of the tectonics of Alexander Island leads to the suggestion that the main episode of post-Aptian deformation of the "Bellingshausen trough" resulted in the elevation of a mountain block 200 miles (320 km.) long from north to south but of limited east–west extent in eastern Alexander Island. The present configuration of the mountain zone agrees very well with the theoretical scheme given in Fig. 13. On this interpretation the height of the mountains at the end of the main orogenic period and after any isostatic re-adjustment should be directly proportional to the degree of compression by thrusting and folding. It was observed by King (1964) that in the Douglas Range, which is the largest and most continuous of the Alexander Island ranges, a summit level which is locally a plateau remnant and elsewhere an expression of the average summit elevation is present. Its height gradually diminishes from the north where it is present at about 9,850 ft. (3,000 m.) towards the south to about 985 ft. (300 m.). There is, therefore, a close correlation between the degree of compression of the sediments and their present elevation in the mountain ranges. This increase in the degree of compression, and therefore of uplift towards the north of the range, results in the overall southerly pitch of the rocks involved. Progressively older groups of rocks are therefore exposed towards the north of the range.

The building of the mountain massif in Alexander Island has apparently not been followed by the intrusion of post-orogenic plutonic rocks. Despite an extensive reconnaisance field study and an examination of the comprehensive air-photograph cover of Alexander Island, no plutonic intrusions of any kind have been observed cutting the sediments. This seems anomalous in view of the proximity of these sediments to the Antarctic Peninsula, where there are extensive plutonic intrusions, the bulk of which were dated initially by Adie (1955) on stratigraphic evidence and later radiogenically (Halpern, 1962) as being late Cretaceous to early Tertiary in age. The apparent absence of such intrusions from this area may be the result of their genuine absence at any level due to some as yet undetermined tectonic control. Alternatively, it may be due to the fortuitous absence of outcrops in the exposures studied or it may be the result of a fundamental difference in the regional level of exposure between Graham Land and its off-lying islands and Palmer Land and its adjacent islands, particularly Alexander Island. A certain amount of general geological and topographical evidence appears to point to the existence of such a distinction but it is too meagre to justify discussion at this stage.

GEORGE VI SOUND

In any discussion of the tectonics of Alexander Island the structure and origin of George VI Sound must be considered. The Sound is an intermontane trough, the base of which lies below sea-level possibly due to the general isostatic depression of the continent beneath its ice load. Between lat. 69° and 72°S. it trends north–south, is 220 miles (350 km.) long and averages 15 miles (24 km.) wide. South of lat. 72°S. it swings westwards becoming wider as it opens out into the Bellingshausen Sea at Ronne Entrance.

The structure and origin of such intermontane troughs is still in dispute in spite of extensive study, particularly by petroleum geologists in the American cordilleras, and the accumulation of vast amounts of surface and sub-surface data. Despite the relative paucity of field evidence from this area, considerable speculation has centred on the structural origin of the Sound since it was mapped by the British Graham Land Expedition in 1936–37 (Stephenson and Fleming, 1940). The main hypothesis envisaged to date is that George VI Sound is a rift valley bounded by "faults" (King, 1964). This terminology is vague, since the unqualified term "fault" is open to several interpretations each characterizing a totally different tectonic environment. King (1964) has proposed that the Sound is a rift valley bounded by "normal" faults generated by the uplift of a cymatogenic arch. He did not, however, use the term "normal" in his paper. In order to avoid confusion, the terminology used in this paper follows the definitions given in *Glossary of geology*. The east coast of Alexander Island has the form of a steep escarpment with a weak but regular convexity towards the east, implying an origin controlled by tectonics rather than by fortuitous erosion. The elevated mountains of eastern Alexander Island and the adjacent sub-sea-level Sound trough have been interpreted as being separated by a zone of normal faults with downthrows to the east. In order to fulfil the requirements of a "classical" rift valley, a conjugate normal fault of opposite throw has been assumed along the eastern margin of the Sound. The west coast of the Antarctic Peninsula in these latitudes is less elevated and more deeply dissected than might be expected for a fault scarp of supposed Tertiary age formed of more resistant rocks than the opposing sedimentary scarp on Alexander Island. Small-scale graben structures, defined by normal faults, have been described by Knowles (1945) as controlling the topography in the vicinity of Cape Keeler on the east side of the Antarctic Peninsula in the same latitudes. King (1964) has cited this observation as satisfying the required symmetry of what he has considered the hemi-cymatogen of the Antarctic Peninsula.

These theories of normal rift faulting require a period of regional tension post-dating the regional compression of the area. Evidence of minor faulting parallel to George VI Sound which might have been expected to develop synchronously with the major normal faults is completely lacking in well exposed and favourably orientated sections. Several small faults (Fig. 14) with vertical throws of less than 60 ft. (18·3 m.) and striking either at right-angles or obliquely to the trend of the Sound have been observed both by B. J. Taylor (personal communication) and the author. On the present interpretation of the regional tectonics, these are thought to be small-scale representatives of the postulated major oblique-slip faults.

Fig. 14. A small fault with an apparent vertical displacement of 1 ft. (0·3 m.) cutting siltstones and yellow arkoses at Waitabit Cliffs. The hammer shaft is 12 in. (30 cm.) long.

During the preceding discussion of the regional orogenesis an alternative interpretation of the origin of the Sound was suggested (p. 19). The uplift of a thick sequence of superimposed thrust sheets due to over-riding their marginal geanticline would result in the development of an eastward-facing mountain front or escarpment, whose linearity would depend primarily on the original degree of linearity of the western margin of the geanticline. Palaeogeographic evidence indicates that this was quite marked, because the eastern coastline of the "Bellingshausen trough" and other palaeogeographic boundaries closely parallel the present linear east coast of the Alexander Island. This high escarpment would overlook the trough of George VI Sound, whose elevation would be reduced both by the underthrusting movement and by isostatic depression by loading of the superimposed thrust sheets. On this hypothesis the structure of the eastern margin of the Sound may have several interpretations but its role in the development of George VI Sound seems to have been a minor one.

Summary and Conclusions

The tectonic structures in the rocks of south-eastern Alexander Island are considered to be the genetically related results of a single phase of post-Aptian deformation of the sediments and volcanic rocks filling the "Bellingshausen trough". These compressive forces, although possibly prolonged and variable in intensity both in space and time, were consistent in orientation. The tectonic model proposed essentially involves the underthrusting of the sedimentary sequence by its rigid marginal geanticline, the strains produced in the sediments varying in relation to their disposition with respect to the main stress axis. Consequently, there is also a close correlation between the depositional facies zones and the zones of similar structural response. This is believed to be the simplest interpretation consistent with the recorded field observations and it is shown to be supported both by other theoretical and experimental conclusions. Comparable interpretations have been proposed for structural patterns developed in sedimentary provinces situated in similar regional tectonic environments.

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