BRITISH ANTARCTIC SURVEY
SCIENTIFIC REPORTS
No. 109

THE GEOLOGY OF THE LEMAY GROUP, ALEXANDER ISLAND

By
R. W. BURN, M.Sc.
Earth Sciences Division, British Antarctic Survey

CAMBRIDGE: PUBLISHED BY THE BRITISH ANTARCTIC SURVEY: 1984
NATURAL ENVIRONMENT RESEARCH COUNCIL

BRITISH ANTARCTIC SURVEY SCIENTIFIC REPORTS: No. 109

THE GEOLOGY OF THE LEMAY GROUP, ALEXANDER ISLAND

By
R. W. BURN, M.Sc.
Earth Sciences Division, British Antarctic Survey

(Manuscript received July 1982; accepted January 1983)

ABSTRACT

The *LeMay Group* of Alexander Island consists of a thick sequence of predominantly unfossiliferous feldspathic sandstones, siltstones and mudstones, with subordinate conglomerates, basic lavas, tuffaceous sediments and cherts. The sandstones are mainly poorly sorted arkosic arenites and minor volcanic arenites, derived from an acid–intermediate plutonic and volcanic terrain with a subsidiary supply of metamorphic and sedimentary detritus. Sedimentary structures, together with the lack of fossils indicate that the bulk of the sediments were redeposited by turbidity currents or similar mechanisms, possibly in a deep-sea fan or trench environment. However, the presence of a Triassic neritic fauna, and abundant pyroclastic material in a volcanogenic sequence in the Lully Foothills of central Alexander Island suggest a different setting for the rocks in that area, for which the formal name *Lully Foothills Formation* is proposed.

Basic lavas, some of which show pillow structure, and basaltic/doleritic greenstones of uncertain origin are commonly associated with bedded chert-argillite, and appear to lie mostly in a north–south belt through the interior of the island. Although lavas in the Lully Foothills have depositional contacts with adjacent sediments, intense deformation marginal to lavas and greenstones in northern Alexander Island may have been caused by tectonic emplacement, and some of these rocks could be oceanic in origin. The cataclasis and chaotic disruption of bedding seen in association with the lavas and greenstones constitute a north–south trending zone of broken formation and (?) tectonic mélange in northern Alexander Island, which possibly extends also through the central and southern parts of the island.

The rocks have undergone polyphase folding and at least four episodes of deformation have been recognized in parts of the sequence. West-north-west–east-south-east to north-north-west–south-south-east strikes, and steep south-westerly dips predominate in northern Alexander Island. Locally, areas of downward-facing rocks indicate that inverted limbs or recumbent folds have been refolded. North–south strikes appear to be dominant in central Alexander Island, but the situation in the south of the island is not well understood.

The metamorphic grade of the rocks in northern Alexander Island increases north-eastward from zeolite and prehnite-pumpellyite facies sandstones, through pumpellyite-actinolite facies semischists to coarsely recrystallized muscovite-garnet schists of the greenschist facies. Local development of lawsonite and blue amphibole in metabasic lithologies in central Alexander Island indicates an intermediate to high-pressure facies series. This may represent part of a paired metamorphic belt, the amphibolite-facies gneisses of the Antarctic Peninsula constituting the corresponding zone of low pressure metamorphism.

Lithology, deformation and metamorphism suggest that at least parts of the LeMay Group accumulated in a subduction complex formed by the underthrusting of the sediment prism as Pacific Ocean crust was subducted at a trench along the western margin of the Antarctic Peninsula. The LeMay Group therefore constitutes an important part of the evidence for a (?) late Palaeozoic–early Mesozoic arc-trench system along the Pacific margin of Gondwana. However the presence of radiolarians of probable mid-Cretaceous age in northern Alexander Island indicates that part of the LeMay Group may have accumulated during subduction later in the Mesozoic.

CONTENTS

I. INTRODUCTION

Alexander Island is the largest of the chain of islands along the west coast of the Antarctic Peninsula (Fig. 1) measuring 400 km in length and 230 km at the widest point. Its northern limit (lat. 68° 46.5′ S) approximately coincides with a physiographic transition in the Antarctic Peninsula where the narrow, precipitous area of Graham Land broadens out into the more subdued topography of Palmer Land (Wyeth, 1977). The island extends southward to lat. 72° 40.5′ S, where Palmer Land swings westward. The eastern margin of the island is bounded by a gently recurved scarp, that is almost certainly fault-controlled and marks the western side of a graben in which the 25-km wide George VI Sound is situated. The topography of the island is dominated by steep-sided north–south trending mountain ranges composed of metasedimentary rocks of the LeMay Group (Figs. 2 and 3). In the northern Douglas Range these rise to nearly 3000 m. Early Tertiary volcanic rocks in the Elgar Uplands and Colbert Mountains form upland areas with a less severe topography, whereas the plutonic rocks of the Rouen Mountains form a high steep-sided massif. The low-lying western part of the island is formed by a gently sloping ice piedmont. Of the islands to the west, Latady Island is completely ice covered, Dorsey, Merger and Charcot islands have small areas of exposed rock, and Rothschild Island has well exposed mountain ranges.

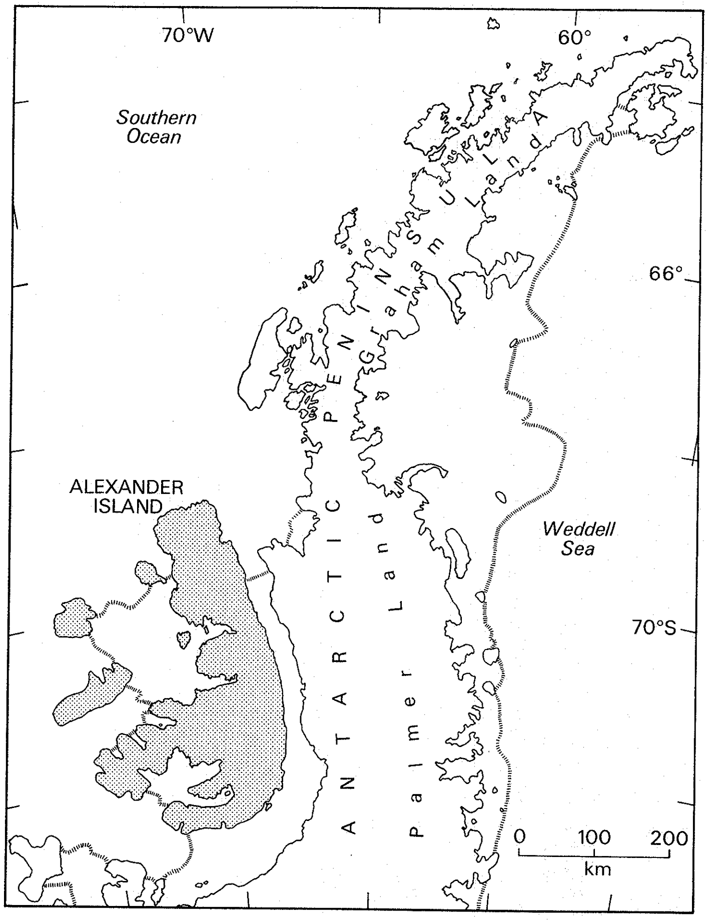
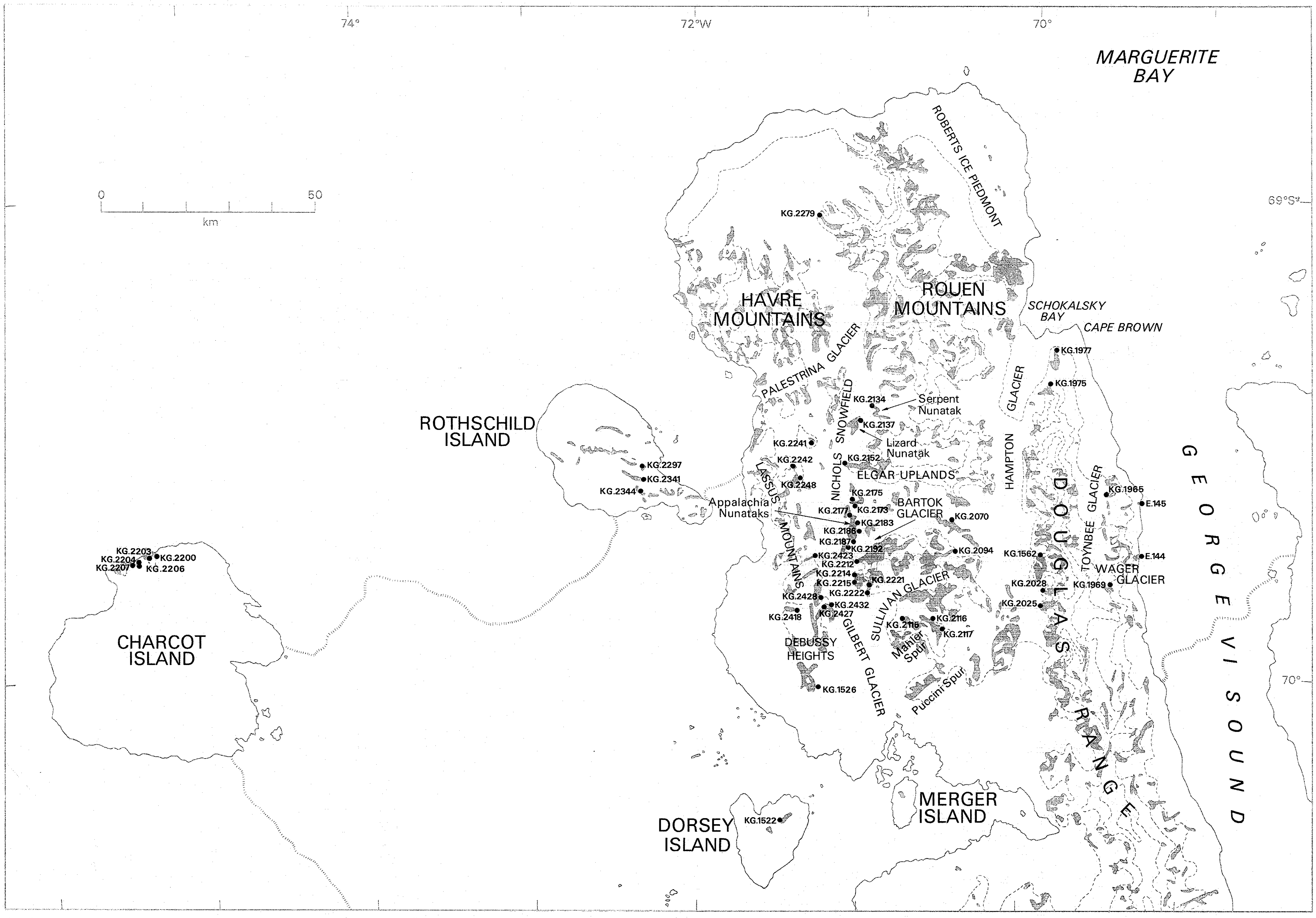


FIGURE 1
Sketch map of the Antarctic Peninsula showing the location of Alexander Island.

The stratigraphy of Alexander Island is summarized in Table I. Deformed metasediments and volcanic rocks of the LeMay Group, parts of which are Triassic in age, include the oldest known rocks on Alexander Island. In central eastern Alexander Island they are unconformably overlain by shallow marine and deltaic sedimentary rocks of the Fossil Bluff Formation, which range in age from late Jurassic to early Cretaceous, and are thought to represent a fore-arc basin deposited adjacent to a Mesozoic volcanic arc situated on Palmer Land (Suárez, 1976; Thomson, 1982). The present-day outcrop of the Fossil Bluff Formation is restricted to the east coast of Alexander Island, where it is juxtaposed against the LeMay Group along the LeMay Range Fault (Edwards, 1980*a*) (Fig. 3). Mesozoic rocks of this age are not known in the interior of Alexander Island, but the recent discovery of radiolarians of probable mid-Cretaceous age in south-western Elgar Uplands suggests that some rocks included in the LeMay Group as presently defined may be broadly coeval with parts of the Fossil Bluff Formation. Early Tertiary calc-alkaline volcanic rocks overlie the LeMay Group in the Elgar Uplands and Colbert Mountains (Grikurov and others, 1967; Bell, 1974). This volcanic activity was broadly coeval with the emplacement of intermediate to acidic plutonic rocks centred around the Rouen Mountains and Staccato Peaks related to an early Tertiary episode of subduction west of Alexander Island (Suárez, 1976; Care, in press; Burn, 1981). Intra-glacial eruption of olivine basalt lavas and hyalocastites in northern and western Alexander Island during the late Tertiary (Bell, 1973*a*; Burn and Thomson, 1981), intrusion of camptonite dykes into the rocks of the Fossil Bluff Formation, and the north–south block faulting responsible for the linear topography of the island, probably all occurred subsequent to the cessation of subduction beneath Alexander Island in the mid-Tertiary.

1. *Previous studies*

The presence of pre-Jurassic rocks on Alexander Island was first implied by Adie (1954) who collected sheared andesitic rocks at two localities on the eastern coast north of Wager Glacier (to which he tentatively assigned an early Palaeozoic age) and quartz-muscovite-schists from detritus in ice cliffs north of Schokalsky Bay, which he suggested might represent early Palaeozoic or Precambrian crystalline basement. Similar quartz-mica-schists in northern Douglas Range were thought by B. W. Care (*British Antarctic Survey Annual Report* 1975–76) to represent a metamorphic complex distinct from nearby low-grade metasedimentary rocks. However evidence is put forward in this report for including these occurrences with the LeMay Group. The interior of Alexander Island remained unknown until G. E. Grikurov made a short visit to central Alexander Island in 1964–65 (Grikurov and others, 1967) and recognized that the metasediments and metavolcanic rocks in this area were distinct from the Mesozoic rocks of the east coast of the island. The sequence was divided into 'lower horizons' of poorly sorted sandstone and siltstone and 'upper horizons' of


74°
72°W
70°
69°S
70°
0
50
km
MARGUERITE BAY
ROBERTS ICE PIEDMONT
HAVRE MOUNTAINS
ROUEN MOUNTAINS
SCHOKALSKY BAY
CAPE BROWN
PALESTRINA GLACIER
SNOWFIELD
GLACIER
Serpent Nunatak
Lizard Nunatak
ROTHSCHILD ISLAND
NICHOLS
ELGAR UPLANDS
HAMPTON
LASSUS MOUNTAINS
Appalachia Nunataks
BARTOK GLACIER
DOUGLAS RANGE
TOYNBEE GLACIER
WAGER GLACIER
GEORGE VI SOUND
SULLIVAN GLACIER
GILBERT GLACIER
DEBUSSY HEIGHTS
Mahler Spur
Puccini Spur
CHARCOT ISLAND
MERGER ISLAND
DORSEY ISLAND
KG.2279
KG.1977
KG.1975
KG.2134
KG.2137
KG.2241
KG.2242
KG.2248
KG.2152
KG.2297
KG.2341
KG.2344
KG.2175
KG.2177
KG.2173
KG.2183
KG.2186
KG.2187
KG.2192
KG.2070
KG.2094
KG.1965
E.145
E.144
KG.1562
KG.2028
KG.1969
KG.2025
KG.2423
KG.2212
KG.2214
KG.2215
KG.2221
KG.2222
KG.2428
KG.2432
KG.2427
KG.2418
KG.2115
KG.2116
KG.2117
KG.1526
KG.1522
KG.2203
KG.2204
KG.2207
KG.2200
KG.2206

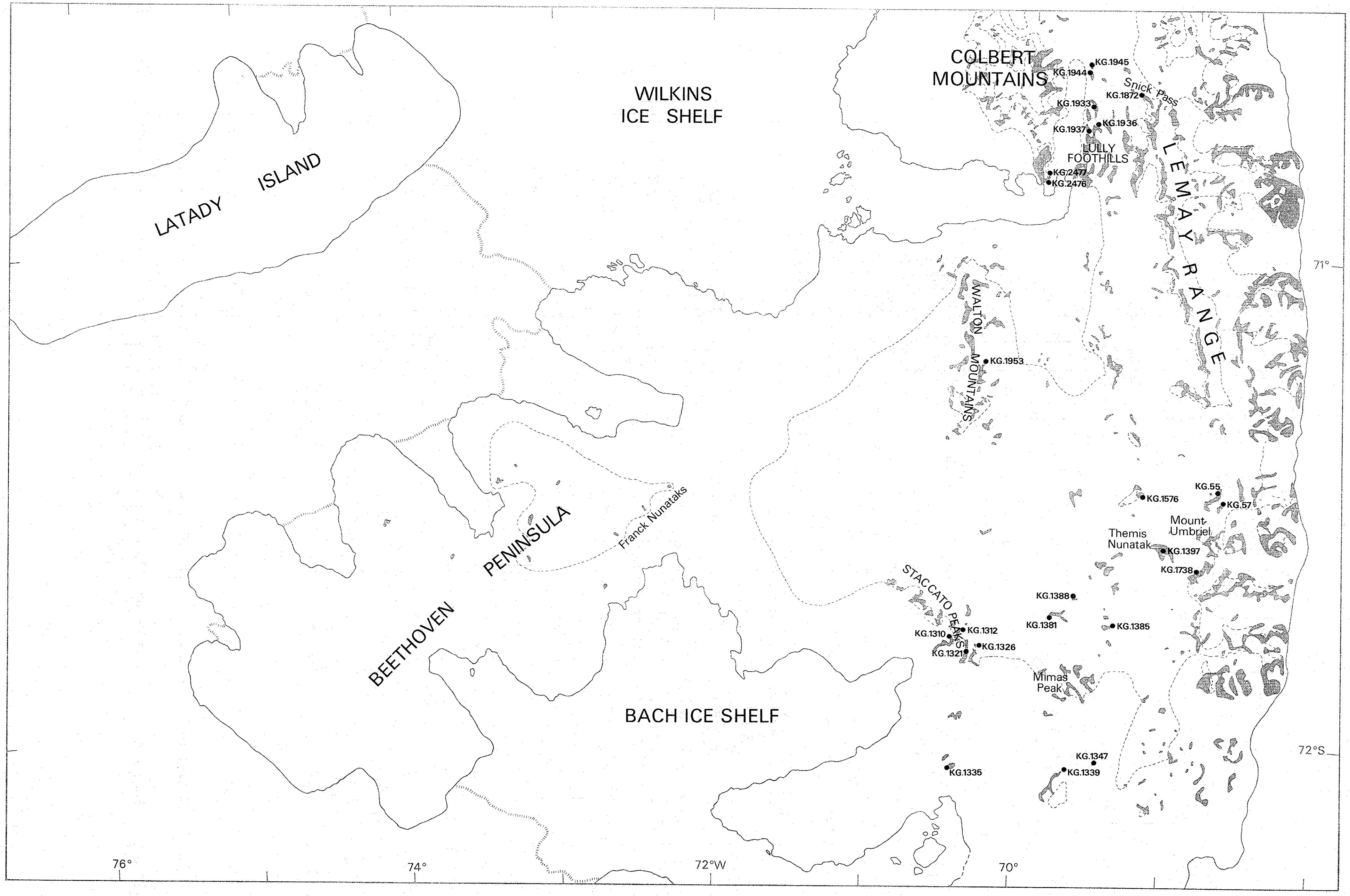


FIGURE 2a and b

Sketch maps of Alexander Island showing the place-names and station numbers mentioned in the text, outcrops and the main upland areas.

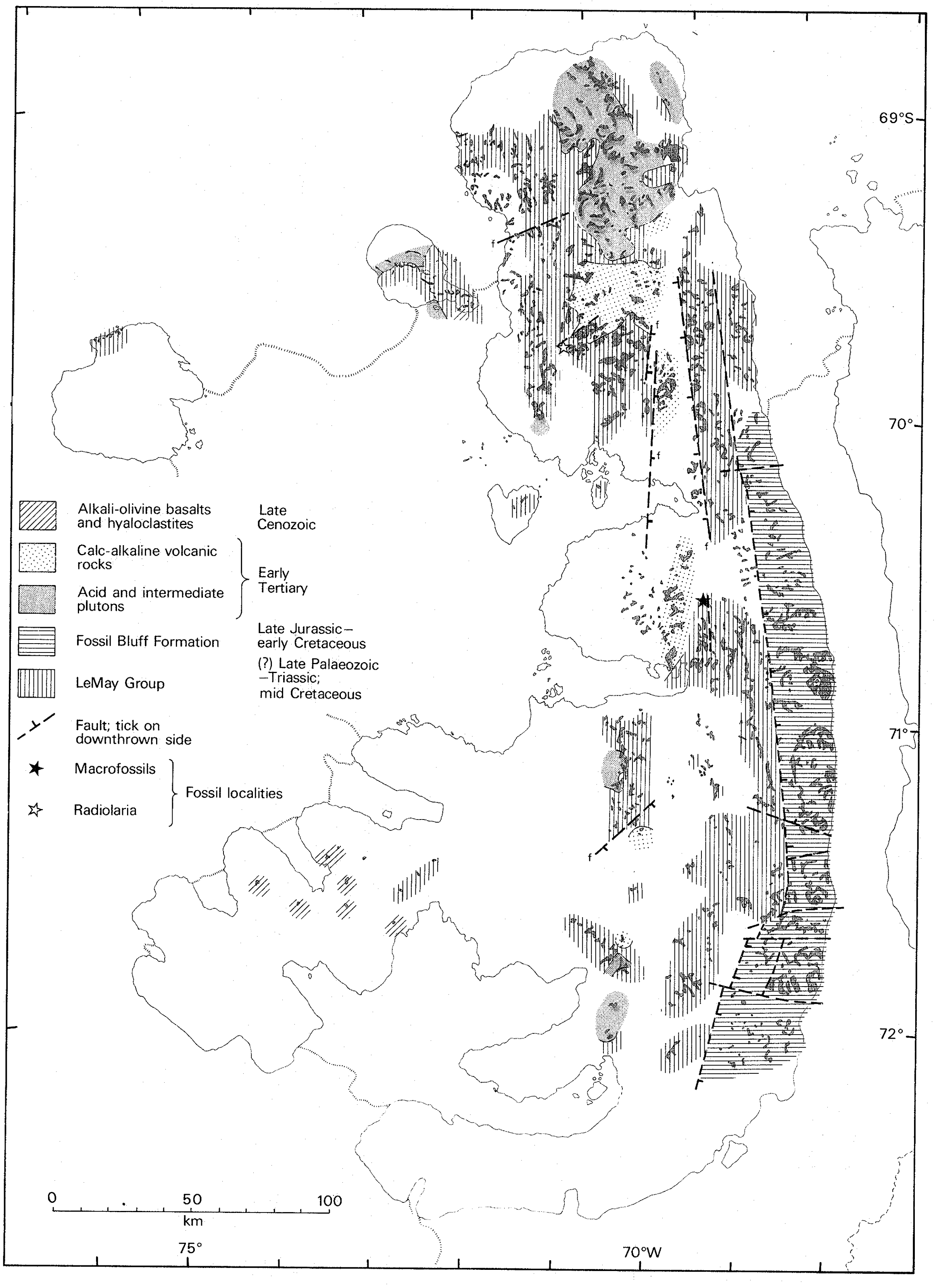


FIGURE 3
Geological sketch map of Alexander Island based on British Antarctic Territory 1/500 000 geological map: Alexander Island. British Antarctic Survey 1981 (BAS 500G series sheet 4, edition 1).

TABLE I
Summary of the stratigraphy of Alexander Island

Age	*Interior*	*East coast*
Late Tertiary	Olivine basalt lavas, dykes and hyaloclastites	Camptonite dykes
	Glaciated unconformity	
(?) Late Cretaceous to Early Tertiary	Intermediate to basic dykes Gabbro to granite plutons Basaltic andesitic to dacitic, and rhyolitic tuffs and lavas	
	Erosional unconformity	
Late Jurassic to Early Cretaceous	Western parts of LeMay Group possibly as young as mid-Cretaceous	Fossil Bluff Formation (gently folded shallow-water marine and deltaic volcaniclastic sediments)
	?	*Erosional unconformity*
(?) Late Palaeozoic to Triassic	LeMay Group (highly deformed feldspathic flysch-type sequence with minor cherts and pillow lavas)	LeMay Group

well sorted arkosic sandstone, and a late Palaeozoic age was suggested on the basis of lithological similarity with the 'Trinity Series' of north-eastern Graham Land. Subsequent palynological evidence (Grikurov and Dibner, 1968) suggested an early to Middle Carboniferous age. In a later paper, Grikurov (1971) introduced a fourfold division of these rocks into lower, middle and upper terrigenous 'series' and a fourth 'series' of mixed sedimentary and volcanic rocks. A possible lithological correlation of the 'upper terrigenous series' with the Jurassic 'Latady Series' of Southern Palmer Land suggested by Grikurov (1972) appears to be based on scant evidence. Bell (1973*b*) mapped southern Alexander Island and described poorly sorted dynamically metamorphosed subgreywackes and arkoses with few sedimentary structures, localized pillow lavas, and volcaniclastic sediments. A reconnaissance of northern Alexander Island (Bell, 1974) revealed the widespread extent of similar rocks in this area, and at least three phases of folding were recognized in both areas (Bell, 1975). Horne (1967 and 1969) suggested that rocks near Mount Umbriel, southern Alexander Island, similar to those in central Alexander Island described by Grikurov, represented a deep water facies variant of the Fossil Bluff Formation. Subsequently the discovery of the unconformity between the highly deformed rocks of the interior and the relatively flat-lying rocks of the Fossil Bluff Formation, and the major fault (LeMay Range Fault) which separates them along the eastern LeMay Range (Edwards, 1980*a*) confirmed the existence of a major discontinuity between the sedimentary rocks of the east coast and the interior of Alexander Island. A Triassic fauna of bivalves and gastropods from the Lully Foothills has been described by Edwards (1980*b* and 1982).

2. *Age of the LeMay Group*

Noting the similarities in lithology between rocks of the LeMay Group and the Trinity Peninsula Group of north-east Graham Land, Grikurov and others (1967) suggested that the former were of late Palaeozoic age; this was later supported by palynological evidence (Grikurov and Dibner, 1968). Eighty miospores were extracted from rocks of the Trinity Peninsula Group at Hope Bay and the LeMay Group of central Alexander Island. It was concluded that the palynomorphs from the two areas were similar, and by comparison with Russian species, had early to middle Carboniferous affinities. This work was critically assessed by Schopf (1973) who regarded the number of specimens of each form (assigned to five species belonging to the three genera: *Leiotriletes, Trachytriletes* and *Lophotriletes*) as sparse, and suggested that the material could be derived. He also commented on the fact that there were no species in common with the early–middle Carboniferous of South America, and cast doubt on the identification of the genus *Leiotriletes*, pointing out that similar forms range in age from early Devonian to Holocene. Unidentified trilete miospores and a single bisaccate pollen grain were extracted from samples from the northern Walton Mountains by Edwards (1980*c*) but only detrital wood and sapropelic material was found in rocks from the Lully Foothills and LeMay Range.

Macropalaeontological evidence for the age of the LeMay Group is restricted to a vitric tuff from the northern Lully Foothills (Edwards, 1980*b* and 1982) which contains a middle–late Triassic fauna of gastropods and bivalves. The bivalves show similarities to counterparts in the middle Triassic (Ladinian) succession of New Zealand and the middle–late Triassic (Ladinian–Carnian) Mine Series of Japan. Most of the gastropods have related forms in the middle–late Triassic of Peru, Chile and northern Argentina. It should be emphasized that this Triassic age can only be applied with confidence to the volcanogenic rocks of the Lully Foothills. However, the meagre palaeontological information narrows the time interval, in which the rocks in central Alexander Island underwent polyphase deformation, to between post-middle Triassic and pre-late Jurassic. The oldest reliably dated rocks of the overlying Fossil Bluff Formation are late Jurassic.

Several cherts from northern Alexander Island contain radiolarian remains, and two samples have been processed with a view to extraction and identification of radiolarians.

Sample KG.2214.3 from the east side of the Gilbert Glacier yielded an assemblage of forms which are probably mid-Cretaceous, but sample KG.2206.1 from Marion Nunataks, Charcot Island, was barren (written communication from D. L. Jones and B. Murchey, U.S. Geological Survey). The radiolarian locality is approximately 100 km north-north-west of the Lully Foothills macrofossil locality (Fig. 3). The possibility that parts of the LeMay Group extend in age up to mid-Cretaceous illustrates the dangers inherent in making stratigraphical correlations in such structurally complex and lithological monotonous terrains.

The only radiometric data relating to the LeMay Group are K/Ar dates of 105 [102]* and 110 [107] Ma from Corelli Horn and 165 [161] Ma from the western LeMay Range, which Grikurov and others (1967) suggested might reflect emplacement of plutonic rocks. This seems unlikely in view of recent geochronological evidence which indicates that plutonic activity in Alexander Island took place largely in the Tertiary (Burn, 1981). In addition, no large plutonic bodies or widespread hornfelsing has been reported in the areas from which the samples were taken. These dates are more likely to reflect diagenesis, deformation or uplift.

3. *Stratigraphical nomenclature*

The assemblage of rocks lying to the west of the LeMay Range fault was formally named LeMay Formation by Edwards (1982). The chosen type area included volcanogenic rocks in western Lully Foothills and primarily meta-sedimentary rocks in eastern Lully Foothills and north-western LeMay Range. In addition, Edwards included all other lithologically and structurally similar rocks in the interior of Alexander Island within the LeMay Formation. This formal name is unsatisfactory on two counts. Firstly, it includes rocks of the western Lully Foothills volcanogenic sequence (the only reliably dated pre-Jurassic rocks on the island) which is itself a distinct mappable unit that probably deserves formation status. This sequence contains pyroclastic material and unequivocal evidence of shallow-water deposition (p. 15) whereas the rest of the metasediments appear to contain epiclastic volcanic material and are believed to be of deep-water turbidite facies (p. 12), although Edwards (1980*b*) stressed that there are some sedimentary lithologies common to both. Secondly, the author believes that formation status is inappropriate to this vast assemblage of highly deformed, largely monotonous lithologies, which possibly range in age from late Palaeozoic to Cretaceous. It is proposed here that the LeMay Formation be upgraded to the *LeMay Group* and that the volcanogenic sequence of western Lully Foothills be named the *Lully Foothills Formation*. It is possible that future detailed work will allow other component formations of the LeMay Group to be mapped. The type area for the Lully Foothills Formation is the north-western and western Lully Foothills (cf. Edwards, 1980*b*).

4. *Stratigraphic implications of plate tectonic theory*

The succession within the LeMay Group is still poorly understood since only two pieces of palaeontological age information have been found so far from this large and structurally complex body of rock. The thickness of the succession cannot be reliably estimated owing to the complexity of folding (which involves refolding of inverted limbs of recumbent folds) and the difficulty in identifying faults and assessing displacements along them.

Evidence is presented in this report for regarding the bulk of the rocks in the LeMay Group as a subduction complex formed by accretion of sediments at the inner trench wall of a convergent plate boundary situated along the present-day position of the Antarctic Peninsula (p. 57). Such an interpretation may be the key to understanding the geology of Alexander Island, and would help to explain the complex structure and stratigraphy in the LeMay Group.

---

*Figures in square brackets denote ages recalculated using the physical constants recommended by the I.U.G.S. subcommission on geochronology (Steiger and Jäger, 1977).

II. SEDIMENTOLOGY

A. LITHOLOGY AND SEDIMENTARY STRUCTURES

The sedimentary rocks of the LeMay Group are dominated by sandstones, siltstones and mudstones, with local occurrences of conglomerates, pebbly mudstones and mud-flake breccias. Previous sedimentary observations were of a reconnaissance nature, and were hindered by the poor preservation of sedimentary features in many areas. Massive graded sandstones interbedded with black argillites near Mount Umbriel were described by Horne (1969). Thin persistently-bedded immature sandstones with subsidiary conglomerates and mudstones in southern Alexander Island show few sedimentary structures except for flute casts (Bell, 1973*b*). In northern Alexander Island, Bell (1974) noted similar rocks, sedimentary structures largely restricted to cross laminations, and ripple marks in some fine sandstones. Edwards (1980*c*) described graded bedding, cross laminations, parallel laminations, dune bedding, dish structure, mudstone rip-up clasts, load structures, scour marks and flute marks, from central Alexander Island. He interpreted the rocks of the LeMay Group in central Alexander Island in terms of a submarine turbidite fan model (p. 12).

At most localities in northern Alexander Island the sedimentary sequence is characterized by alternations of massive, medium to very coarse-grained sandstones in units up to 50 m thick, interbedded with mixed units of sandstone, siltstone and mudstone in varying proportions and thickness (Fig. 4). The sandstones and siltstones are highly indurated; they are grey-green, sometimes purple on fresh surfaces, and they usually weather grey or rusty brown. In hand specimens grains of white feldspar and dark vitreous quartz, and detrital flakes of muscovite and/or biotite are normally visible. Dark grey penecontemporaneous mudstone clasts are common in the coarser sandstones. Four lithofacies types were recognized in northern Alexander Island: conglomeratic rocks, massive ungraded sandstones, a medium to thinly bedded lithofacies and pelagic sediments. These are described in sections 1–4 and their main features summarized in Table II.

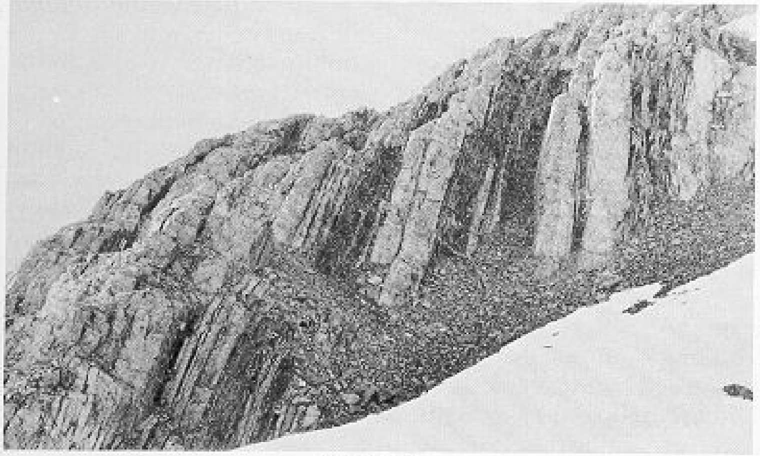


FIGURE 4
Massive sandstone beds (some showing multiple grading) alternating with packets of thinly bedded mudstones, siltstone and sandstone (some graded) at Mahler Spur (station KG.2117). The approximate thickness of the total succession in the photograph is 20 m.

1. *Conglomeratic rocks*

a. *Pebbly sandstones*. Rounded, subrounded and occasionally subangular to angular clasts of plutonic, volcanic, metamorphic and sedimentary rocks constitute up to 30% by volume of these rocks. Pebble sized clasts are the most common (0.5–1 cm), although cobbles up to 30 cm occasionally occur. Penecontemporaneous mudstone clasts are frequently present and vary in size from a few millimetres up to slabs 1.5 m by 0.25 m. In contrast to the hard-rock pebbles, these pelitic fragments are angular and often moulded around the former. The matrix consists of poorly to very poorly sorted medium to very coarse-grained sandstone containing little or no detrital mud.

The pebbly sandstones occur in beds 0.5–10 m thick, interbedded with massive sandstones. No obvious signs of channelling or lateral discontinuity were detected. The author did not observe normal or reverse grading, imbrication or stratification, but graded bedding and imbrication do occur in some rocks on Rothschild Island (Care, 1980).

Similar pebbly sandstones from western LeMay Range have been described (Edwards, 1980*c*; Grikurov, 1971). According to Grikurov some display inverted grading which is apparently the result of folding. Bell (1973*b*) reported some occurrences in southern Alexander Island.

b. *Mudflake breccias*. These are intraformational conglomeratic rocks containing dominantly mudstone, or occasionally siltstone clasts supported in a coarse to very coarse, poorly-sorted sandstone matrix. The mudstone fragments range in size from a few millimetres to 50 cm in size. They are normally angular with a cleanly broken appearance (Fig. 5), and are often tabular, although rounded to subrounded clasts sometimes occur. Some of these rocks contain large fragments of earlier-formed mudflake breccia, indicating that two episodes of erosion of partly lithified beds took place.

The breccias occur in beds 20 cm to 2 m thick and often have rather diffuse contacts against adjacent massive sandstones. No evidence of channelling or lateral discontinuity were seen although erosional bases truncating laminations in underlying sandstones are present at a number of localities. Internal structure in the form of stratification or grading was not seen by the author, although normal grading is present in some localities in western Douglas Range (personal communication from B. W. Care). No imbrication was observed, but a preferred orientation of tabular clasts parallel to bedding in many breccias appears to be a primary sedimentary feature (Fig. 6). At some localities strongly

TABLE II
Summary of characteristics of sedimentary lithofacies in the LeMay Group in northern Alexander Island
(Abbreviations: med = medium grained; cs = coarse grained; vcs = very coarse grained)

	Conglomeratic rocks			*Medium-thinly bedded lithofacies*		*Pelagic*	
	Pebbly sandstone	*Mudlake breccia*	*Massive ungraded sandstones*	*Sandstones*	*Siltstones*	*Mudstones*	*Cherts*
Bed thickness	0.5–10 m	0.2–2 m	1–10 m	20 mm–1 m	10–300 mm	< 8 m	20 mm–5 m
Packet thickness	–	–	1–50 m	1–2000 m		< 8 m	< 10 m
Grain size							
Typical	cs sand + pebble	cs sand + cobble	med–cs sand	med sand	–	mud	–
Range	silt–cobble	silt–cobble	med sand–granule	fine–vcs sand	–	mud	–
Scour marks	absent	absent	rare	present	absent	–	–
Pelitic clasts	common	common	common	common	absent	–	–
Turbidite							
Normal graded	very rare	very rare	absent	not common	not common	–	–
Bouma sequences	absent	absent	absent	not common	not common	–	–
Ungraded	present	present	present	common	common	–	–
Non-turbidite							
Cross-bedding	absent	absent	absent	very rare	absent	–	–
Lenticular bedding	absent	absent	absent	very rare	absent	–	–
Walker–Mutti facies	A	A	B	CD	DE	G	
Mode of deposition	(?) mass gravity flow		(?) mass gravity flow, possibly proximal turbidite	turbidite	turbidite and (?) bottom currents	pelagic	pelagic

FIGURE 5
Angular cobble-sized clasts of silty mudstone in mudflake breccia, Charcot Island (station KG.2204). The ice-axe head is 27 cm long.

FIGURE 6
Alignment of tabular pelite clasts in mudflake breccia. The underlying silty mudstones and sandstone beds show penecontemporaneous deformation, Charcot Island (station KG.2207). The ice-axe pick is 13 cm long.

flattened clasts parallel to a strong S_1 cleavage (p. 44) have clearly been tectonically deformed.

Intraformational breccias similar to those described above have also been reported from southern and central Alexander Island by Bell (1973*b*) and Edwards (1980*c*).

2. *Massive ungraded sandstones*

Much of the LeMay Group in northern Alexander Island consists of massive, thickly-bedded medium to very coarse-grained sandstones, in which little or no internal structure or lithological variation can be discerned. Rocks containing clasts predominantly of granule size are also present (gravelstones). It is not clear to what extent this is a primary sedimentary feature and to what extent sedimentary features have been obliterated by cataclasis, diagenesis or metamorphism. Beds are typically 1–10 m thick, ungraded and often have sharply defined planar tops and bases. Mudstone partings are generally thin and rather silty.

Sedimentary structures are scarce and there may be little trace of bedding over thicknesses up to 50 m through some massive sandstone successions. Faint diffuse *plane laminations*, consisting of light and dark bands 5–20 mm thick, are present at a few localities; the colour change is apparently due to variation in matrix content. *Load casts* and (rarely) *flute casts* are displayed on the bases of some beds.

Massive sandstone beds up to 3 m thick in Walton Mountains, central Alexander Island (Edwards, 1980*c*) are evidently comparable to the rocks described above. However, some are partly graded, having pebbly bases or grading within the top 15–20 cm. Sedimentary structures here include *scour marks, tool marks, diffuse plane laminations* and *dish structure*. The latter is a scaley pattern visible on steep or vertical sections through beds. Such structures have been described from thick ungraded sandstone units elsewhere and are believed to indicate deposition by fluidized sediment flow (e.g. Stauffer, 1967; Rupke, 1978).

3. *Medium and thinly bedded lithofacies*

Units consisting of frequent alternations of sandstone, siltstone and mudstone in variable proportions are interbedded with the massive sandstones (Figs. 4 and 7). Such units are typically 1–50 m thick with individual sandstone beds ranging from a few centimetres to about 1 m in thickness. The sandstones are poorly sorted with medium and fine-grained types predominating. A wide variety of sedimentary structures occur in sandstone beds in northern Alexander Island, including graded bedding, plane laminations, cross-laminations, cross-bedding, rare lenticular bedding, convolute laminations, flute and groove marks and load structures. *Graded bedding* is not common, and well-bedded sandstones are frequently ungraded, with equally sharp tops and bases. Graded sandstone beds with coarse-grained bases are usually 10–50 cm thick and generally have a few granule to pebble-sized clasts near the base; those with medium grained sandstone bases are generally thinner (between 10 and 30 cm). Graded bedding elsewhere on Alexander Island, has been described from the vicinity of Mount Umbriel (Horne, 1969), and western LeMay Range (Grikurov, 1971). It was not observed in southern Alexander Island by Bell (1973*b*),

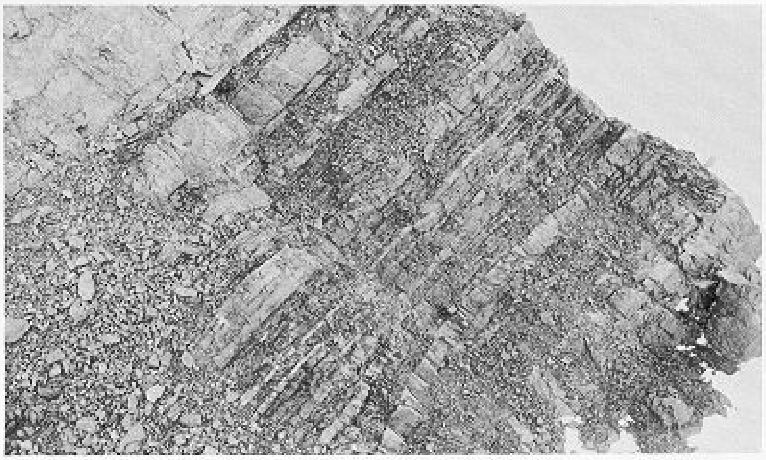


FIGURE 7
Thinly bedded flysch consisting of ungraded sandstone and siltstone beds with sharply defined tops and bases, interbedded with well cleaved mudstone, Lizard Nunatak (station KG.2137). Approximately 5 m of succession are shown in the photograph.

FIGURE 8
Cross-bedding in coarse sandstones, Lizard Nunatak (station KG.2137). The height of the photograph frame is approximately 1.5 m.

but extensive cataclasis hinders sedimentological observations there. Some sandstone beds contain *plane laminations*. These are sometimes associated with graded bedding, suggesting that they represent the lower interval of plane laminations in Bouma's (1962) turbidite model. *Small-scale cross-laminations* (set height less than 5 cm) are common in fine sandstones up to 10 cm thick, but laminations of the climbing ripple type, characteristic of turbidites, were rarely observed. *Cross-bedding* (set height more than 5 cm) was found at a few localities in northern Nichols Snowfield in medium to coarse sandstone beds (Fig. 8), and cross-bedded sandstones have also been reported from western LeMay Range (Edwards, 1980*c*). Occasionally, features resembling linguoid ripples occur on tops of ungraded sandstone beds. Examples of *lenticular bedding*, consisting of isolated lenses of sand 'floating' in mud, and *flaser bedding*, in which mud is preserved in ripple troughs, occur rarely in sandstones of the bedded lithofacies. In northern Nichols Snowfield some plane-laminated, medium-grained sandstone beds 10–20 cm thick pass upwards into discontinuous streaks and lenses of sandstone in black silty mudstone (Figs. 9 and 10). The vertical sequence is:

Pelitic interval	5–10 cm
Lenticular bedded division	10–20 cm
Plane laminated division (sometimes also graded at base)	10–20 cm

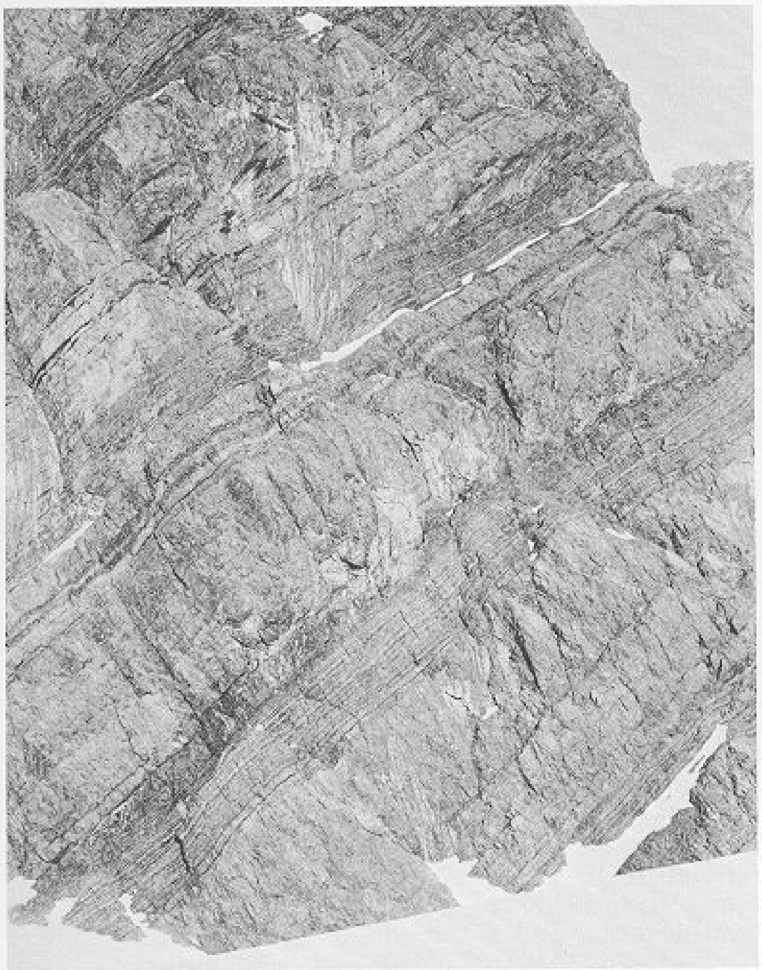


FIGURE 9
Massive ungraded sandstones alternating with packets of bedded sandstone, siltstone and mudstone, Lizard Nunatak (station KG.2137). Approximately 50 m of succession are shown in the photograph.

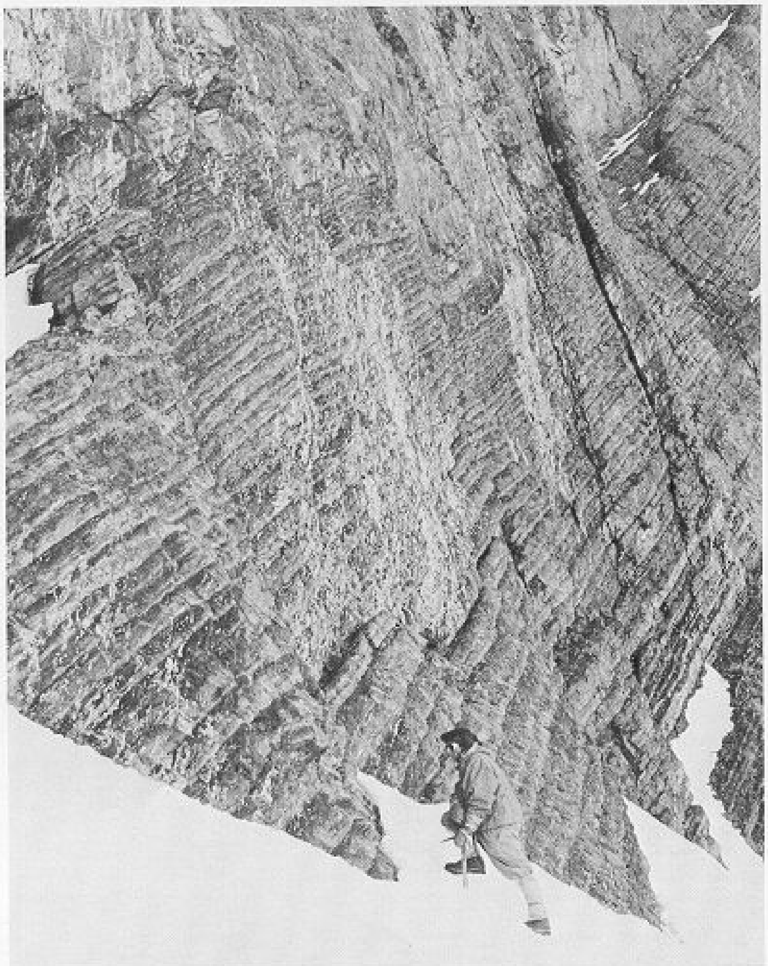


FIGURE 10
Close view of one of the bedded packets at station KG.2137. The sandstone beds appear to represent *ab* and *b* Bouma divisions and pass upwards into lenticular bedded sandstone/muddy siltstone.

The plane laminated and graded lower divisions appear to be *b* and *ab* turbidites (after Bouma, 1962). This sequence of divisions forms bedded units 5–10 m thick separated by up to 10 m of massive sandstone (Fig. 9). Flaser and lenticular bedding have also been reported from a locality in north-eastern Walton Mountains (personal communication from C. W. Edwards). *Convolute laminations* (i.e. crumpled laminae in a bed enclosed by undeformed strata) are sometimes present, usually overlying an interval of plane laminations in fine to medium grained sandstone. There appeared to be no consistent sense of overturning, and crests of convolutions were not seen to be eroded. *Load casts* are common at the bases of sandstone beds, and in some examples bodies of sand are partly or wholly detached from the overlying bed, producing 'ball and pillow' structures (Fig. 11). *Flute marks* (Fig. 12) are less abundant, and generally fall within the conical and elongate symmetrical classes of the fourfold classification erected by Dzulynski and Walton (1965). *Groove marks* were only observed at four localities in northern Alexander Island. Evidence of *slumping* (i.e. the widespread disruption of sedimentary layers under the influence of gravity) was seen only at two localities, in the western Elgar Uplands and on Charcot Island. In the western Elgar Uplands, numerous beds in a sandstone/mudstone sequence are sheared, disrupted and attenuated without development of slickensiding or cataclasis. 'Ball and pillow' structures are present at bases of sandstone beds (Fig. 11). Tight folding and disruption of several metres of thinly bedded sandstone and siltstone beds on Charcot Island is attributed to slumping on account of the limited thickness of strata affected, the broken and discontinuous nature of the beds, and lack of cataclasis. *Injection structures* resulting from the injection of liquefied sediment into lithified or semi-lithified rocks are encountered occasionally in northern Alexander Island. Sandstone injected into mudstone may be in the form of thin dykes, or irregular bodies.

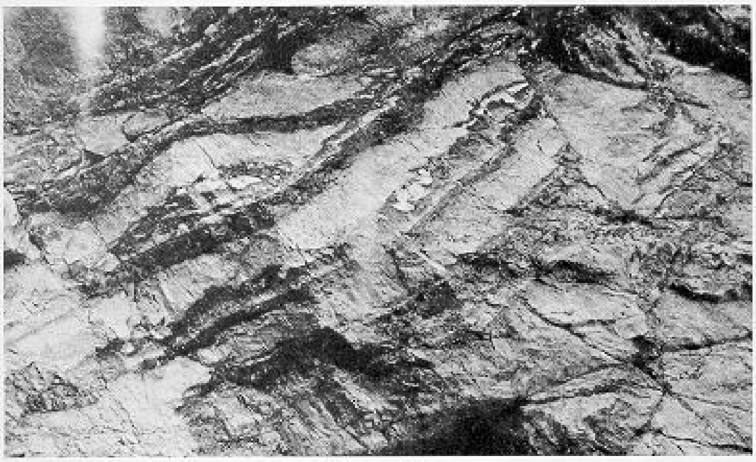


FIGURE 11

Load casts at the bases of graded sandstone beds, some of which have been disrupted, possibly during slumping, western Elgar Uplands (station KG.2152). The height of the photograph frame is approximately 1.3 m.

FIGURE 12

Flute marks on the base of a sandstone bed, Appalachia Nunataks (station KG.2187). The ice-axe head is 27 cm long.

Siltstones mostly range from 1 to 30 cm in thickness and sedimentary structures are restricted to plane laminations, cross laminations (sometimes defined by heavy mineral grains) and rare graded bedding. Black and dark brown mudstone partings mostly range between 20 cm and 1 m in thickness and sometimes contain occasional silty laminae a few millimetres in thickness.

4. *Pelagic mudstones and chert*

In this lithofacies are included thick black mudstones, rare radiolarian mudstones and chert. Black mudstones up to 8 m thick are occasionally found in association with both massive sandstones and bedded sequences. Only one radiolarian mudstone was observed. It forms a 3-m bed with a purple centre and green margins, and crops out high on an inaccessible cliff face on Charcot Island. It is not known what the adjacent rocks are, but massive sandstones and mud-flake breccias are abundant in the vicinity. Red and green cherts are usually associated with pillow lavas, and such occurrences are described later (p. 24). In the rare instances where it occurs without lavas, chert is found as grey beds, 2–40 cm thick, interbedded with chlorite-rich argillite.

B. SEDIMENTARY ENVIRONMENT

Previous suggestions for the environment of deposition of the LeMay Group sediments have agreed with the 'eugeosynclinal' setting proposed by Grikurov and others (1967) and Bell (1973*b* and 1975). The only evidence for shallow-water deposition is the neritic fauna described by Edwards (1980*b*) from a tuffaceous sequence in the Lully Foothills. Since there is no sedimentological data for this area, the apparently anomalous features of these rocks are discussed elsewhere (p. 15). Horne (1969) interpreted massive graded sandstone beds near Mount Umbriel as proximal turbidites. Suárez (1976), drawing on the work of Bell (1973*b*, 1974, 1975) described the LeMay Group as consisting mainly of unfossiliferous distal turbidites deposited in a trench oceanward of an inferred volcanic arc. The rocks were referred to by Edwards (1982) as 'flysch-type deposits of sandstone turbidite greywacke and argillite'. Units displaying sequences of the ideal turbidite model (Bouma, 1962) were recognized by Edwards (1980*c*) who described the rocks of the Walton Mountains and part of the LeMay range in terms of a submarine turbidite fan facies classification scheme. A similar approach is adopted below in the interpretation of the sedimentological information available for the rocks of northern Alexander Island. First, the mode of deposition of the three main lithofacies recognized in northern Alexander Island will be discussed in more general terms.

The conglomeratic rocks and the massive ungraded sandstones show a number of features not typical of classical turbidites. Both are characterized by thick ungraded beds lacking internal structure, except for diffuse plane lamination in some sandstone beds. Flute and other scour marks appear to be absent from conglomerates and rare in massive sandstones. Sequences of the Bouma (1962) turbidite model were not recognized. In these respects the rocks resemble coarse, thickly bedded flysch deposits elsewhere in the world which have been termed 'fluxoturbidites' (e.g. Dzulynski and others, 1959). Stauffer (1967) described thick massive sandstones with sharp tops and bases and diffuse plane laminations from California, which are very similar to many beds in northern Alexander Island. The relative importance of the three gravity-flow mechanisms for sediment, turbidity flow, grain flow (maintained by grain-to-grain interactions) and fluidized sediment flow (maintained by escaping pore fluids) in the accumulation of such deposits is not well understood, but the recognition of the channellized nature of 'fluxoturbidites' has led to the currently accepted view that they represent the infillings of submarine channels incised into the lower continental slope or submarine fans (e.g. Stanley and Unrug, 1972; Walker, 1976). The moderate to high degree of rounding exhibited by some of the larger clasts in these sediments can be attributed to transport in fluvial and neritic environments prior to resedimentation in deep water (Stanley and Unrug, 1972).

Features of the medium to thinly bedded lithofacies are summarized in Table II. Recognizable Bouma sequences were seen at a number of localities, frequently associated with scour marks. The turbidites are mostly of the *ae* type, with 1–30-cm graded beds, although some *ace* sequences were found. Some thick sandstone units show multiple grading and it is probable that many of these thick, apparently massive sandstones represent amalgamated proximal turbidites. The observation that Bouma sequences were not recognized more widely and that *ae* types are most common among those which were found, may be due to obliteration of sedimentary structures by the effects of diagenesis/metamorphism and cataclasis. Many cross-laminated and plane-laminated beds may represent Bouma divisions *b* and *c* but cannot be confidently identified as such where they are not associated with recognizable Bouma sequences. Cross-bedding and lenticular bedding are not typical of the ideal turbidite model and the rare occurrence of these structures is not incompatible with the deposition by turbidity currents of the majority of the rocks of the medium to thinly bedded lithofacies. Cross-bedding has been reported from a number of sequences that also contain features typical of turbidites (e.g. Hubert, 1966; Thomson and Thomasson, 1969). From theoretical considerations Allen (1970) has shown that cross-bedding might be expected instead of plane laminations or ripples in coarse beds deposited by fast-moving turbidity current. Lenticular bedding has been described from silty mudstones among turbidites in New Zealand (Ballance, 1964) and has been interpreted as the result of reworking of turbidites by bottom currents. A similar explanation is favoured for the occurrence of lenticular bedding in rocks of the LeMay Group.

At present, a detailed sedimentological analysis of the rocks of the LeMay Group is not possible. However, it appears that the deposits in northern Alexander Island, like those in parts of central Alexander Island, can be reasonably described in terms of a submarine turbidite fan model. The main purpose of such models (e.g. Walker and Mutti, 1973; Mutti and Ricci-Lucchi, 1975) is to facilitate rapid description and comparison between flysch basins by using a facies classification based on bed thickness, grain size, sandstone to shale ratio, bedding regularity, sole marks, internal structures and textures and palaeoecological factors (Table III).

TABLE III
Facies scheme for the classification of flysch (after Walker and Mutti, 1973)

Bouma sequence not applicable	Facies A	Coarse-grained sandstones and conglomerates A1 Disorganized conglomerates A2 Organized conglomerates A3 Disorganized pebbly sandstones A4 Organized pebbly sandstones
Beds can reasonably be described using the Bouma sequence	Facies B	Medium-fine to coarse sandstones B1 Massive sandstones with 'dish' structure B2 Massive sandstones without 'dish' structure
	Facies C	Medium to fine sandstones – classical proximal turbidites beginning with Bouma's division A
	Facies D	Fine and very fine sandstones, siltstones – classical distal turbidites beginning with Bouma's division B or C
	Facies E	Similar to D, but higher sand/shale ratios and thinner more irregular beds
Bouma sequence not applicable	Facies F	Chaotic deposits formed by downslope mass movements, e.g. slumps
	Facies G	Pelagic and hemipelagic shales and marls – deposits of very dilute suspensions

By analogy with modern turbidite fans, facies associations have been recognized which are believed to be diagnostic of upper, middle and lower fan environments. The pebbly sandstones in northern Alexander Island fit the description of Walker and Mutti's subfacies A3 (disorganized pebbly sandstone) and the massive ungraded sandstones are similar to subfacies B2 (massive sandstones lacking dish structure). The medium to thinly bedded lithofacies probably contains components of facies C, D and E. Pelagic mudstone and chert corresponds to facies G. In northern Alexander Island, pebbly sandstones occur in association with massive ungraded sandstones and variable (usually subsidiary) amounts of rock belonging to the medium to thinly bedded lithofacies. This association has features in common with facies associations regarded by Walker and Mutti as characteristic of inner and middle fan channel deposits. No large-scale channels were recognized in the LeMay Group but since such features may be up to several hundred metres wide, their presence in highly folded strata may have been overlooked. There is some evidence for slumping in rocks of this association on Charcot Island, suggesting slope instability. The most widespread lithofacies association in northern Alexander Island is that of ungraded massive sandstones with rocks of the medium to thinly-bedded lithofacies. Beds are regular and continuous, and sandstone to shale ratios are usually greater than unity. This association resembles Walker and Mutti's middle fan depositional lobe facies association. At this stage it is not possible to discern much significant pattern in the areal distribution of these two facies associations in northern Alexander Island except that the proposed inner or middle fan channel association appears to be best developed on Charcot Island and in the western Elgar Uplands.

Edwards (1980*c*) tentatively recognized two facies associations in central Alexander Island occurring in LeMay Range and Walton Mountains. The LeMay Range facies consists of coarse thick sandstone beds with irregular discontinuous bodies of conglomerate (locally incised into a thick shale sequence) which it was suggested might correspond to channel-fill lag deposits of the inner fan. Occurrences of well-bedded shale and sandstone containing *cde* Bouma sequences were interpreted as inter-channel turbidites. The Walton Mountains facies consists of thick sandstones and pebbly sandstones with thin mudstone partings. Sedimentary structures in the sandstones are restricted to graded bedding, diffuse parallel laminations, dish structure, scour marks, tool marks and load structures. Edwards proposed that these rocks formed part of the non-channellized 'outer-fan association' of Mutti and Ricci-Lucchi (1975) which is broadly analogous to the mid-fan depositional lobe or suprafan of Walker and Mutti (1973).

To summarize, there is considerable evidence that the majority of sedimentary rocks of the LeMay Group of northern and central Alexander Island were deposited in a submarine turbidite fan environment, and facies associations characteristic of channellized inner or middle fan and non-channellized middle fan have been tentatively recognized. This assessment of the available sedimentological information clearly supports earlier workers' suggestions (based only on the flysch-type unfossiliferous nature of the rocks) of a deep water turbidite environment, and it is consistent with deposition in a trench as proposed by Suárez (1976). Although the main lithologies and assemblages can be described in terms of a submarine fan model, Walker (1976) has pointed out that these models are based on data from relatively small modern fans and may not be strictly applicable to large depositional basins in which longitudinal currents may be one of the factors affecting the dispersal of sediments. The huge area over which the LeMay Group crops out certainly indicates the existence of a basin of 'geosynclinal' proportions, probably a trench in which deposition and incorporation of deformed sediment into the inner slope took place over tens of millions of years. The lack of consistent changes in proximality normally detected in smaller basins may be due to the complex interaction of inputs from several fans, with subsequent destruction of parts of the sequence during subduction.

C. TRACE FOSSILS

A number of types of trace fossil have been described by Edwards (1980*c*) from bedded sandstone/mudstone sequences. Five types were recognized, all of which were interpreted as water/sediment interface or shallow burrowing forms:

i. *Helminthopsis* sp., meandering tracks up to 2.5 mm wide.
ii. *Planolites* sp., smooth, straight or broadly curving trails or near-surface burrows 3–4 mm wide.
iii. *Chondrites*-like system of radiating and diverging shallow burrows.
iv. *Kouphichnium*-type markings, delicate forked burrows less than 1 cm long.
v. Sequential track, a linear sequence of rounded depressions preserved on the base of a sandstone bed overlying mudstone at a locality in Walton Mountains.

The first three were all interpreted as tracks of more or less systematic deposit feeders, and are similar to forms ascribed to bathyal depths. The fourth, it was suggested, might have been formed by the fins of a small bottom-living fish-like creature. The sequential track is the most enigmatic, and although it resembles the track of a vertebrate, this possibility is incompatible with evidence for deep-water sedimentation in the area.

D. PALAEOGEOGRAPHY

Little can be deduced regarding the configuration of landmasses and sources of sediment while the rocks accumulated. Palaeocurrent indicators in northern Alexander Island are too few to be statistically valid and the complexities of structure (probably involving refolding of recumbent F_1 structures by at least two later fold phases) make even these few readings impossible to interpret with confidence. Bell (1973*b*) obtained a current direction from the north from flute marks in southern Alexander Island, and Edwards (1980*c*) found flute, scour and groove marks in central Alexander Island, that indicated east–west palaeocurrents. The palaeocurrent data were corrected for only the main north–south orientated folding episode (four significant phases of folding were recognized in the region) so that little reliability can be attached to the results. A predominance of east–west palaeocurrents is, however, compatible with sediment supply from an arc massif in the vicinity of Palmer Land.

Distribution of more proximal conglomeratic and massive ungraded sandstone lithofacies might be expected to give an indication of the location of the nearest land mass. These lithologies are best developed on Charcot Island, Rothschild Island, western Elgar Uplands, and west central LeMay Range. This distribution might be taken to suggest sediment supply largely from the north and west, but here again, complexities in structure and the possibilities of some rocks being allochthonous (p. 53) allow little confidence to be placed in such an interpretation.

The only reliable indication of the proximity to a shoreline is found in the Lully Foothills Formation of central Alexander Island where tuffaceous sandstones contain a shallow-water fauna of coelenterates, gastropods, bivalves and echinoderms (Edwards, 1980*b* and 1982) which have undergone little transportation. Delicate leaf impressions are further evidence of the lack of resedimentation. The Lully Foothills Formation differs from the rest of the LeMay Group not only in its undisputable shallow-water origin, but in the abundance of vitroclastic volcanic debris it contains (p. 29). Unfortunately, the relationship between these rocks and the rest of the LeMay Group, with which they are juxtaposed along a north–south fault (Edwards, 1980*b*), is not clear and the central position of this sequence within the known area of extent of the group is puzzling. The possibility that the Lully Foothills Formation accumulated in a fore-arc basin is discussed on p. 57.

In view of lack of evidence for a source of sediment to the west, the most likely setting for the deposition of the sediments of the LeMay Group is a basin along the margin of Gondwana, fed by an abundant supply of continental clastic material from the east, probably via submarine canyons.

III. SEDIMENTARY PETROLOGY

A. PETROGRAPHY

This section is concerned mainly with the least deformed and metamorphosed sedimentary rocks. The textural and mineralogical reconstitution of sandstones to semischists and schists, and the effects of cataclastic deformation are dealt with elsewhere (pp. 34, 36). Subgreywackes and arkoses from southern Alexander Island and arkosic and lithic arenites from the north of the island were described by Bell (1973*b* and 1974). The sandstones of both areas are characterized by angularity and poor sorting. Arkosic sandstones, subgreywackes, lithic greywackes and lithic arenites are among the sandstone types present in central Alexander Island (Edwards, 1980*c*). The chief variation in the sandstones is the content of volcanic material, which may constitute up to 70% of some rocks in southern Alexander Island (Bell, 1973*b*). Such variations in composition are discussed in more detail on p. 21.

Sandstones, which probably constitute 50–70% of the exposed rock at most localities, are mostly medium grained but range from very coarse to very fine. They show little textural variation and are usually poorly to moderately sorted (cf. Pettijohn and others, 1972). Some siltstones are well sorted. Undeterminable fine-grained material may be abundant in some sandstones, but this appears to have been derived largely from alteration of feldspar and unstable rock fragments, and wackes are not thought to have been common among the original sediments (p. 21). This is borne out by the fact that the amount of fine grained 'matrix' increases with progressive recrystallization through textural zones 1–3 (see p. 34). Pebbly sandstones and mudflake breccias are bimodal in terms of grain size, with pebble to cobble-sized clasts in a poorly or very poorly sorted medium to very coarse sandstone matrix.

The following account of the detrital and secondary mineralogy of the sedimentary rocks is based on the study of 136 thin sections from northern and southern Alexander Island.

1. *Detrital mineralogy*

Quartz usually occurs as angular to subangular or occasionally subrounded to rounded grains. Clear grains, with rounded embayments filled by devitrified glass, found in some sandstones from Nichols Snowfield and the vicinities of Themis Nunatak and Mimas Peak are clearly of volcanic origin. Double terminated volcanic quartz was recorded in one thin section (KG.1576.2). Monocrystalline quartz grains are usually slightly to moderately strained, but strain induced lamella twinning and heavily cracked grains occur in some cataclastically deformed rocks. The abundance of unstrained quartz in some less-deformed rocks implies that much of the strained extinction is the result of subsequent deformation rather than a quality inherited from the provenance area. Some grains contain minute bubble inclusions, suggestive of a hydrothermal vein origin, and rare grains with acicular rutile inclusions (e.g. specimen KG.1347.1) are probably derived from a plutonic terrain.

Polycrystalline quartz is a common constituent of most sandstones, but it is always subordinate to monocrystalline grains. Strongly orientated, strained aggregates with sutured grain margins are clearly of metamorphic origin and probably came from a gneissic terrain.

Plagioclase grains are typically angular to subangular, but they sometimes occur as squat subhedral laths suggestive of a volcanic origin. In zeolite and prehnite-pumpellyite facies rocks it is seldom albitized, although usually peppered with fine grained alteration products, chiefly sericite, pumpellyite, prehnite, calcite and epidote. Complete pseudomorphs consisting of a mass of sericite, sometimes accompanied by dusky high relief pumpellyite and (?) sphene, are not uncommon in some rocks. Most grains display albite twinning, or less commonly carlsbad-albite twinning, but some are untwinned. Extinction angles indicate compositions mainly between An_{33} and An_{38} (andesine), with a few determinations as calcic as An_{60} (labradorite) from volcanic arenites in the Debussy Heights area. Plagioclase of

FIGURE 13
Detrital grain consisting of chess-board albite intergrown with quartz; arkosic arenite (KG.2116.1; X-nicols; ×110).

oligoclase-andesine composition occurs in sandstones in central Alexander Island (Edwards, 1980*c*). Subhedral grains, sometimes with compositional zoning are probably volcanic in origin, but myrmekitic intergrowths of quartz and plagioclase indicate a plutonic and/or metamorphic contribution. Some clear plagioclase with 'chess-board' twinning (Fig. 13) is probably of plutonic origin. Positive optic sign and Becke line observations indicate some of these grains are at least as calcic as An_{14}. The origin of this type of twinning is discussed on p. 20.

Potash feldspar is present in rocks up to and including the prehnite-pumpellyite facies of metamorphism, although it is always less abundant than plagioclase. It appears to be absent from rocks of higher metamorphic grades. The commonest form is orthoclase microperthite with rods, strings and beads of exsolved plagioclase. Slightly dusky orthoclase is the next most abundant type, commonly as elongate subhedral prisms. Microcline and microcline microperthite are present in some rocks and large volcanic sanidine grains were reported from sandstones in Walton Mountains by Edwards (1980*c*).

Micas are the most widespread mafic mineral in sandstones. *Biotite* is present in most thin sections of sandstones as large flakes up to 1 mm in length, which are often bent around more resistant quartz and feldspar grains. Where least altered, it shows strong pleochroism in shades of red-brown to pale brown, but it is frequently partly bleached and weakly pleochroic in shades of pale brown to colourless. Most grains show loss of birefringence to low greys under X-nicols, and this appears to be the first stage in alteration to chlorite, that occurs as thin sheets growing parallel to the biotite cleavage. Complete pseudomorphs of biotite by chlorite may be indistinguishable from *detrital chlorite*, and some bent chlorite flakes, coexisting with slightly altered biotites, are almost certainly of detrital origin. The latter are generally pleochroic in shades of pale green and show anomalous blue and brown birefringence colours suggestive of penninitic composition. *Muscovite* is subordinate to biotite, which it resembles in its occurrence as large, often bent or broken flakes. The only alteration observed was the occasional growth of thin lenses of prehnite parallel to the cleavage.

Detrital hornblendic *amphibole* is present in approximately one-third of the thin sections studied, sometimes occurring as subhedral prisms up to 0.6 mm long. There is evidence for at least two distinct sources of detrital hornblende: grains with green and brown pleochroism (α = pale brown, β = brown, γ = brownish green to olive green) can be traced to phenocrysts in clasts of fine grained volcanic rocks (p. 18), whereas grains that are pleochroic in green and blue-green (α = pale green, β = yellowish green or brownish green, γ = blue-green) are similar to amphibole that is found in plutonic or high grade metamorphic fragments with quartz, biotite, sphene and plagioclase (p. 20). Both types can be seen as detrital grains, and in fragments of their host rocks in specimens KG.1388.1 and KG.1385.1.

Pyroxene is not an abundant detrital mineral and was recorded from only 18% of thin sections studied. Confusion with colourless epidote can arise, however, and distinction between these two minerals may not always be possible. Clinopyroxene occurs as colourless or very pale green fragments, or more rarely as subhedral prisms. It closely resembles the augite present as phenocrysts in some volcanic fragments (p. 18), and is probably of volcanic parentage.

Detrital *epidote* is present in most sandstones although unequivocal distinction from the authigenic form is often difficult. Large subrounded grains, often composite, are clearly of detrital origin. Colourless and pleochroic yellow-green varieties are equally abundant.

Twenty-one per cent of thin sections studied contain a dark brown accessory mineral of moderate to high relief, sometimes occurring as subhedral prisms. In most cases this was thought to be *allanite*. Pleochroism is strong (β = dark red-brown or chocolate brown, γ = pale brown) and birefringence is moderate to high but masked by the colour of the mineral. Parallel extinction of some grains denies the possibility of them being *brown amphibole* or *Ti-augite* in most cases, but the latter two minerals may be present in small quantities in some sandstones.

Zircon is a common accessory mineral and usually occurs as slightly eroded colourless euhedra with pyramidal terminations. Colourless to pinkish brown *sphene* is present in most sandstones, and is often particularly abundant and conspicuous. Lozenge-shaped euhedra sometimes occur, but subangular to subrounded grains are more common. Interference figures gave a small positive 2V that is sometimes effectively uniaxial. Other less abundant heavy minerals are *garnet, tourmaline* and *apatite*. Garnet was seen in only 14% of thin sections, but may have been to some extent overlooked because of its small size. It generally occurs as subangular to subrounded grains < 0.3 mm across. Sieve structure, with numerous quartz inclusions in some grains, suggests derivation from a metamorphic terrain. Tourmaline was only recorded in two thin sections (specimens KG.1975.4 and KG.1397.1) where it occurs as prisms and broken grains showing colour zoning and strong pleochroism in shades of yellow-brown, green and sky blue. Small elongated euhedra of apatite were occasionally observed.

2. *Secondary mineralogy*

Secondary minerals are widely developed in sedimentary rocks of the LeMay Group. Sericite, calcite, epidote, prehnite, biotite, magnetite and sphene have been described by Bell (1973*b*, 1974) and Edwards (1980*c*). Other minerals encountered during the present investigation are zeolites, pumpellyite, actinolite, stilpnomelane and garnet. No biotite of undisputed regional metamorphic origin was observed, but it is common as a product of contact metamorphism adjacent to plutons (p. 43). The most common alteration, and that which is present to varying degrees in most sandstones, is the replacement of detrital feldspar and certain rock fragments by sericite, calcite, epidote, prehnite and chlorite, and the growth of these minerals in patches and veins. Original detrital components can usually be identified with reasonable confidence in textural zones 1–2 (p. 34) but where alteration is extreme, feldspars, rock fragments and any detrital matrix present become indistinguishable.

Prehnite typically occurs as spongy, ragged patches up to 1.5 mm across, usually replacing parts of detrital plagioclase grains. Occasionally it forms optically continuous patches up to 5 mm across in which 'float' detrital quartz grains. In a second type of occurrence it forms lenses replacing detrital biotite or muscovite (e.g. specimens KG.2203.1 and KG.2204.1) and has a conspicuously lower relief than the spongy prehnite described above. Prehnite commonly occurs in irregular veins with quartz, calcite or analcime (the latter only in rocks of the zeolite facies).

Pumpellyite occurs most commonly as high relief granules and tiny 0.01-mm prisms which aggregate into dense masses and patches up to 0.3 mm across. It is often associated with epidote, and tends to grow in and marginal to detrital plagioclase, but can usually be distinguished by its pleochroism ($\alpha = \gamma =$ colourless, $\beta =$ delicate blue, green or strong blue-green) although a colourless variety also occurs. Other distinguishing features are a small positive 2V, characteristic undulose extinction and anomalous blue and brown birefringence colours. Occasionally pumpellyite is found as dense masses or small prisms in veins, accompanied by prehnite and quartz.

Epidote is present in small quantities in most metasedimentary rocks as small (0.02–0.04 mm) pleochroic green or colourless granules and large ragged aggregates. The colourless variety (probably clinozoisite) has low anomalous birefringence colours and a positive 2V, whereas the green variety has a negative or very large undeterminable 2V. Although (?)clinozoisite is most abundant in some greenschist facies rocks it is by no means restricted to this facies. Pleochroic epidote is most abundant in the prehnite-pumpellyite facies.

Zeolites are rare in LeMay Group sandstones and largely restricted to cataclastically deformed rocks in Debussy Heights and south-west Elgar Uplands. Analcime, the commonest type, occurs chiefly as a vein mineral together with prehnite, calcite or quartz, in sandstones and cherts, but it also forms irregular replacement patches in crushed areas. An optically negative zeolite, tentatively identified as laumontite, occurs as mosaic patches in inclusions within (?) tectonic mélange (p. 51) at station KG.2432. An optically positive zeolite, possibly heulandite, occurs as similar mosaic patches in crushed sandstones on the south side of Bartok Glacier (Fig. 14) and also in a runic pattern replacing plagioclase in specimen KG.2212.9. Both these zeolites display two good cleavages close to 90° apart.

Chlorite is found as tiny flakes, larger irregular patches and in veins. It is also commonly derived by alteration of detrital biotite and amphibole. Pale green varieties predominate, but more strongly blue-green types occur in some greenschist facies rocks.

In rocks up to and including the prehnite-pumpellyite facies of metamorphism, *albite* is largely restricted to veins, often accompanied by prehnite, chlorite, quartz and analcime (the latter in the zeolite facies only). Water-clear or

FIGURE 14
A coarse mosaic of zeolite in cataclastically deformed arkosic arenite (KG.2212.1; X-nicols; ×99).

slightly dusky grains, often with simple twinning, occur in semischists and fine grained schists of the pumpellyite-actinolite facies. In coarser schists of the greenschist facies large (0.3 mm) albite grains probably represent albitized clastic plagioclase, while smaller (0.01–0.04 mm) grains occur in quartz segregations.

In sandstones and semichists of textural zones 1–2, *white mica* occurs as small sericite flakes ($<$0.01–0.02 mm), mainly as an alteration product of plagioclase. Mica flakes in textural zone 3 are aligned parallel to the foliation, and in textural zone 4, large muscovite flakes (up to 0.8 mm) define the foliation in micaceous layers.

Stilpnomelane is generally restricted to semischists and schists where it forms radiating aggregates of flakes up to 0.12 mm long. It displays strong pleochroism (α = straw yellow or golden yellow, $\beta = \gamma$ = dark reddish brown or dark chocolate brown).

Actinolite, or more correctly, a member of the tremolite-actinolite series is found chiefly in semischists and fine grained schists and is less widespread than stilpnomelane. It varies in form from tiny (0.02 mm) needles to stout prisms almost 1 mm long. Colourless and weakly pleochroic varieties (α = pale green, β = green, γ = pale blue-green) are present. Fringes of pale or colourless metamorphic amphibole sometimes rim detrital grains of stronger hornblendic amphibole (Fig. 15). Large weakly-coloured grains probably represent detrital *hornblende* which has equilibriated with the new Al-poor metamorphic product.

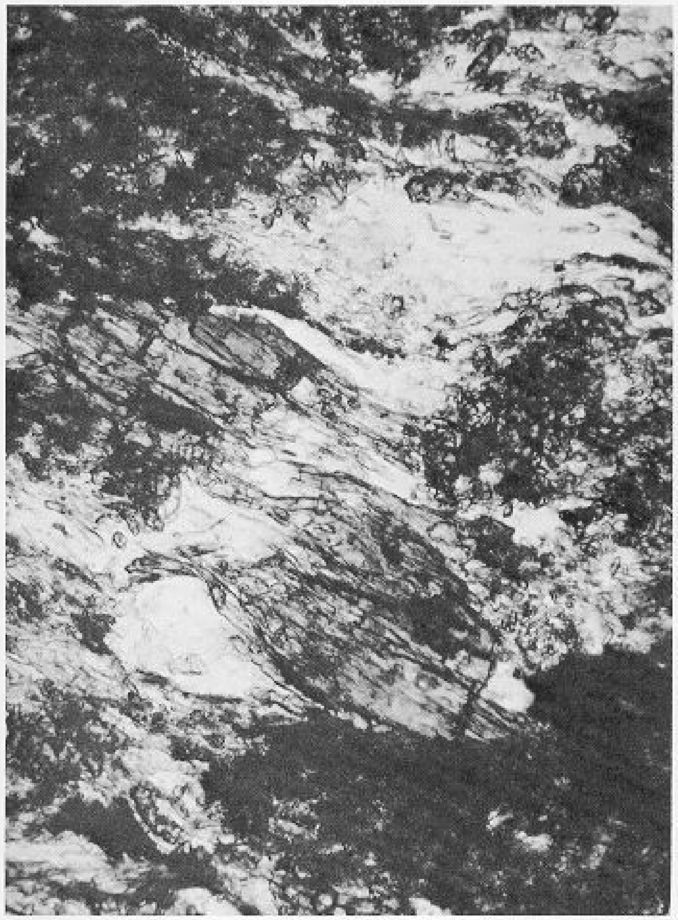


FIGURE 15

Overgrowth of colourless metamorphic amphibole needles on the broken ends of a strongly-coloured detrital amphibole grain in semischist (KG.1562.1; plane-polarized light; ×133).

Occurrences of metamorphic *garnet* from rocks collected *in situ* were noted in only three thin sections of quartz-muscovite schists from northern Douglas Range (p. 36). In specimen KG.1977.4 garnets reach 0.7 mm in diameter, their large size, irregular shape and restriction to micaceous layers clearly indicating a metamorphic origin. Adie (1954) described similar garnets in quartz-mica schists from glacial detritus in ice cliffs on the north-east coast of the island.

Calcite, sphene and *opaque minerals* are widely distributed through all the metasedimentary rocks. Sphene occurs as tiny granules, dusky streaks and patches, and occasionally forms over-growths on detrital sphene. It is also found as an alteration product of ilmenite and leucoxene. A detailed identification of opaque minerals was not attempted. They are found in most metasedimentary rocks as scattered granules, ragged patches and occasional euhedra, and are evidently mostly secondary in origin. Alteration to leucoxene and sphene indicates the presence of ilmenite, and pyrite was identified in a number of rocks.

3. *Lithic fragments*

Lithic fragments typically constitute 1–40% of sandstones. Bell (1973*b*, 1974) described the lithic fraction as consisting mainly of quartzite, quartz-mica schist, basic volcanic material and rare plutonic fragments. Edwards (1980*c*) reported a preponderance of extrusive and pyroclastic volcanic detritus in addition to clasts of quartzite, quartz-mica schist, quartz-epidote schist, and slate, in sandstones and rudites from central Alexander Island. Types of rock fragments in pebbly sandstones from northern and southern Alexander Island are shown in Table IV.

Acid volcanic rocks, probably of dacitic and/or rhyolitic composition are present in most sandstones from northern and southern Alexander Island, and Edwards (1980*c*) described abundant rhyolitic material in sandstones from the central part of the island. They consist of subhedral plagioclase (oligoclase) phenocrysts up to 0.5 mm long, and partly resorbed quartz phenocrysts in a fine grained ground mass of quartz and untwinned alkali feldspar (Fig. 16). Chlorite pseudomorphs after mafic phenocrysts are sometimes present. Most clasts of fine grained polycrystalline quartz probably also represent felsic volcanic rocks, although a positive distinction from chert may not be possible in the absence of phenocrysts. The broken appearance of quartz and feldspar in some clasts suggests a pyroclastic origin.

Detrital grains consisting of bundles of fibres up to 0.4 mm long with straight or nearly straight extinction (Fig. 17) were tentatively identified as zeolite by Care (1980). However, it is now apparent that they are parts of quartz/potash feldspar spherulites from acid volcanic rocks, since they take up a yellow stain in thin sections etched and stained with sodium cobaltinitrite, and they are occasionally seen within acid volcanic fragments.

Clasts of *intermediate volcanic rocks* are often altered and their textures obscured. Most are fine grained and consist of a felted mass of feldspar laths with granules of opaque ores or pyroxene. Phenocrysts up to 0.7 mm in length of anhedral

TABLE IV
Rock fragment contents of some pebbly sandstones from the LeMay Group
(expressed as percentages of the total number of phenoclasts or rock fragments counted in each rock)

Rock type		*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
Volcanic	felsic	21.4	33.3	–	3.1	–	–	20.0	–	9.2
	lathwork, microlitic vitric	14.3	11.1	15.8	12.5	25.1	18.2	5.0	–	7.8
	tuff	–	–	–	–	–	–	5.0	16.7	4.6
Polycrystalline quartz		14.2	–	–	3.1	8.3	9.1	25.0	33.3	20.4
Plutonic and gneissose		–	–	–	6.3	–	–	5.0	–	2.3
Sedimentary	siltstone and mudstone	28.6	33.3	15.8	46.9	50.0	45.4	15.0	25.0	20.4
	sandstone	21.4	22.2	5.3	28.1	8.3	27.3	25.0	–	20.4
	chert	–	–	10.5	–	–	–	–	–	2.3
Low grade metamorphic		–	–	10.5	–	8.3	–	–	25.0	9.1
Unidentified		–	–	42.1	–	–	–	–	–	4.5
Total clasts counted		14	9	19	32	12	41	20	12	44

1. KG.2183.1, western Elgar Uplands.
2. KG.2175.2, western Elgar Uplands.
3. KG.2215.2, south-western Elgar Uplands.
4. KG.2418.1, Debussy Heights.
5. KG.2341.1, Rothschild Island.
6. KG.2344.1, Rothschild Island.
7. KG.55.3, Mount Umbriel.
8. KG.1397.1, Themis Nunatak.
9. KG.1738.2, Mount Umbriel.

FIGURE 16
Resorbed quartz phenocryst in acid volcanic clast; gravelstone (KG.2418.1; X-nicols; ×32).

FIGURE 17
Clastic grain consisting of part of a quartz-potash feldspar spherulite, probably from an acid volcanic rock; pebbly sandstone (KG.2344.1; X-nicols; ×142).

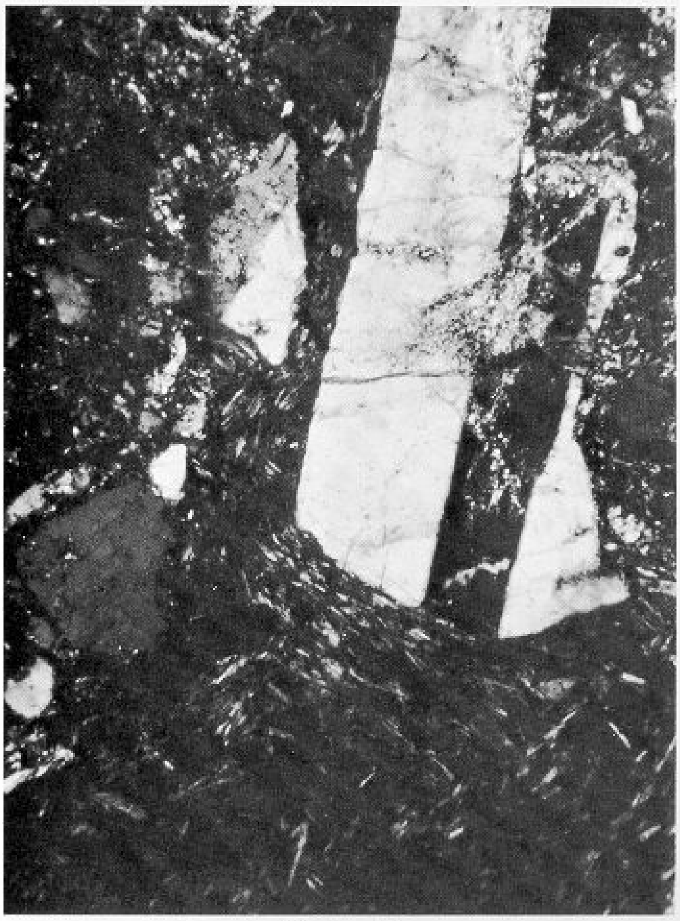


FIGURE 18
Part of an andesitic volcanic fragment consisting of a euhedral, twinned, andesine phenocryst in a fine-grained trachytic groundmass; arkosic arenite (KG.2297.4; X-nicols; ×137).

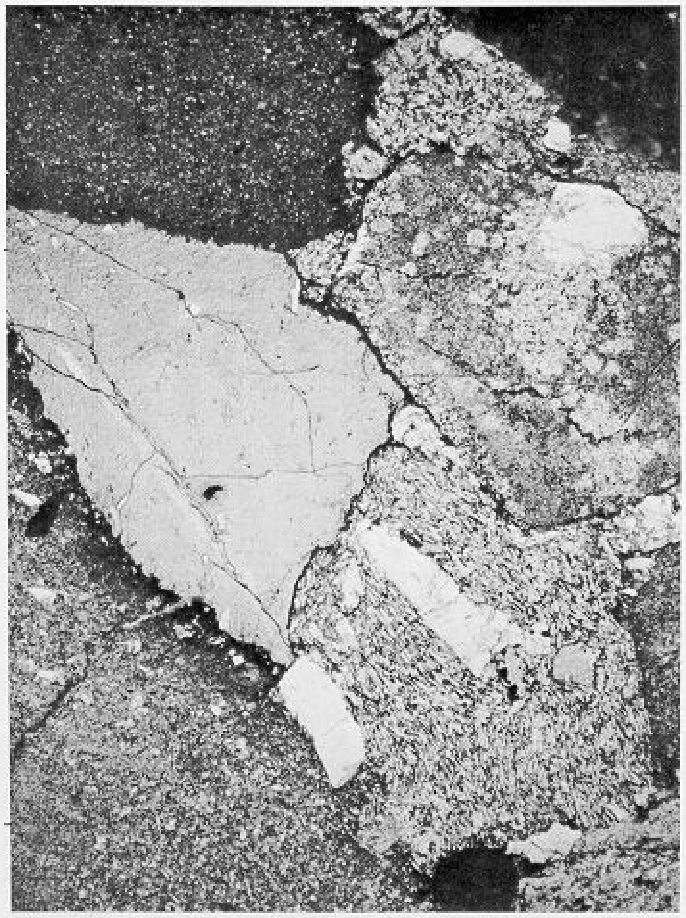


FIGURE 19
Gravelstone rich in volcanic fragments. The clast in the lower right consists phenocrysts of plagioclase and pyroxene in a trachytic groundmass. The on in the centre left contains sparse feldspar microlites in a pale green matr of non-vesicular glass (KG.2418.1; plane-polarized light; ×36).

plagioclase and subhedral pyroxene or hornblendic amphibole are common (Figs. 18 and 19). Where determinable, the composition of plagioclase phenocrysts lies between An_{33} and An_{55}, suggesting a dominantly andesitic composition. Pyroxene phenocrysts are colourless or very pale green augite, with a small to moderate optic axial angle ($2V_{\gamma} \simeq 30\text{–}40^{\circ}$). Pigeonite phenocrysts have been tentatively identified in fine-grained volcanic clasts in central Alexander Island (Edwards, 1980*c*). Vitric fragments are abundant in some sandstones (e.g. specimens KG.2428.2, KG.2423.2) and consist typically of flow-aligned feldspar microlites in a pale green devitrified glass groundmass (Fig. 19). Many volcanic clasts, particularly in southern Alexander Island, have been altered to dusky fine grained material, perhaps the only indication of a volcanic origin being a vaguely defined trachytic texture or an occasional phenocryst. These fragments probably represent devitrified and altered glassy material.

Clasts of rocks identifiable as *tuffs* are rare, although many chlorite-rich siltstones are likely to be volcanic in origin. Two types of tuff were observed: (a) fine grained vitroclastic tuffs with small quartz and feldspar fragments and cuspate shards (replaced by quartz) in a fine grained siliceous matrix, and (b) fine grained crystal-lithic tuffs with abundant gree microlitic fragments, sericitized plagioclase and rare silicifie shards. These fragments are not abundant and appear to b largely restricted to the area near Mimas Peak, souther Alexander Island.

No foliated gneissic clasts, apart from flattened aggregate of polycrystalline quartz were observed, but much of th material described below could have been derived fro either a plutonic or a metamorphic terrain. These *plutoni high-grade metamorphic* fragments consist of granular inter growths of combinations of quartz, orthoclase (frequentl perthitic) microcline and twinned plagioclase of albite t andesine composition. Occasionally biotite or amphibole i also present. Types rich in quartz and potash feldspar ar clearly of acid composition, but quartz-poor clasts containin andesine (commonly with myrmekitic rims) epidote an chlorite probably represent an intermediate parentage. Les common types of clearly acid composition include micro graphic quartz-alkali feldspar intergrowths and porphyriti microgranite.

'Chess-board' albite or oligoclase is sometimes foun intergrown with quartz, microcline or microperthite (Fi 13). This type of twinning is believed to result from sodiu metasomatism in pegmatites, plutonic rocks and keratophyres (Smith, 1974, p. 287). In view of the absence of spilitic volcanic material in the sandstones, a plutonic or pegmatitic origin is most likely. Although replacement of potash feldspar by chess-board albite is known in rocks of the chlorite and biotite zones of regional metamorphism (Starkey, 1959), a post-depositional metamorphic origin for chess-board plagioclase in the LeMay Group is unlikely since there is no correspondence between its distribution and variations in metamorphic grade.

The most abundant *low-grade metamorphic* clasts are unfoliated metasiltstones and fine-grained metasandstones consisting of polygonized mosaics of quartz, with accessory minerals including epidote, amphibole, chlorite and biotite. Granular intergrowths of silt-sized quartz and epidote are evidently the source of much of the detrital epidote in the sandstones. Tectonites are less numerous, and are limited to fine-grained schists and semischists. Quartz-muscovite schists are the commonest type, and sometimes possess a crenulation cleavage. Quartz-biotite and quartz-amphibole schists (Fig. 20) were occasionally seen.

Angular to rounded *penecontemporaneous siltstone* and *mudstone* clasts are present in most sandstones. The unlithified state of these clasts when deposited is clearly indicated by the way that more resistent grains are impacted into them. Some fine-grained sandstone fragments have similar indented outlines, but other rounded and subrounded *sandstone* clasts appear to represent previously lithified rocks. Well-sorted quartz-rich arkosic arenites are chief among these. Other types include poorly sorted arkosic arenites (similar to many LeMay Group sandstones), lithic arenites (some containing abundant microlitic material) and quartz-rich wackes. *Chert* fragments are difficult to distinguish from felsic volcanic material, but some clasts of fine-grained mosaic quartz (<0.01 mm) without phenocrysts, and lacking internal refractive index contrasts are almost certainly chert. A rare example in specimen KG.2215.4 contains radiolarian remains. Clasts interpreted as chert generally have a finer-grained, more regular texture than the felsic volcanic rocks, and some have a pale pinkish colour.

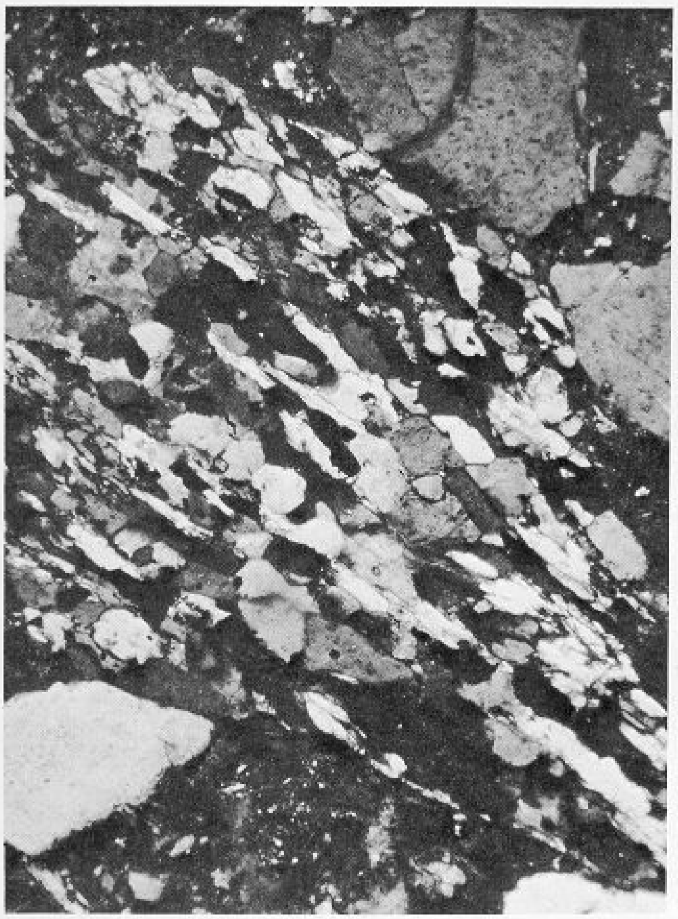


FIGURE 20

Clast of quartz-amphibole schist in lithic (volcanic) arenite. The rock consists of polygonized quartz, aligned pale blue-green amphibole, and opaque grains (KG.2423.1; X-nicols; ×187).

B. DETRITAL CHARACTERISTICS

1. *Modal analyses*

Modal analyses of twenty sandstones from northern Alexander Island are shown in Table V. Thin sections were etched in hydrofluoric acid and stained with sodium cobaltinitrite to enable confident distinction between untwinned plagioclase, K-feldspar and quartz. Growth of secondary minerals, particularly sericite, prehnite, pumpellyite and epidote, hindered identification of detrital minerals. Where secondary minerals were present, but the original mineral could be identified with reasonable confidence, the effects of alteration were 'mentally reversed' and the grain counted as a detrital component. Since detrital and authigenic epidote could not in all cases be distinguished all epidote was counted together under the same category along with other alteration minerals. Determination of detrital matrix also posed a problem in point-counting these rocks. Only intergranular material <0.03 mm which appeared to be of detrital origin was counted as matrix. Alteration and indeterminate material of dubious origin was either counted with the other secondary minerals or as 'other minerals'. As a result of this procedure, detrital matrix may have been somewhat *underestimated*. However, detrital matrix is well below 15% in most thin sections and it appears that arenites rather than wackes are the dominant textural sandstone type.

The majority of the sandstones point-counted are feldspathic (ratio of total feldspar to total lithic fragments >3) and quartz content ranges between 9.6% and 49.4%. Polycrystalline quartz is sometimes an important constituent and the ratio of polycrystalline quartz to total quartz ranges from 0.02 to 0.4. Plagioclase predominates over K-feldspar, the ratio of plagioclase to total feldspar ranging from 0.59 to 0.99. When the analyses are plotted on a triangular QFL compositional diagram (Fig. 21) they fall within the arkosic arenite field of Pettijohn and others (1972). Although the data are sparse, it appears that there may be some significant regional variations in composition. The rocks from Douglas Range, Elgar Uplands and Nichols Snowfield have low contents of lithic fragments and rather more feldspar than quartz. The four samples from Charcot Island and the three from north of Mount Umbriel also have low lithic contents but are rather richer in quartz. They also have somewhat

TABLE V
Modal analyses of LeMay Group sandstones*

	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*	*19*	*20*	*21*	*22*	*23*
Polycrystalline quartz + chert	0.5	7.8	6.5	4.3	6.0	7.0	2.3	1.8	4.7	7.8	3.3	8.0	1.3	3.8	2.3	2.8	8.5	6.2	6.0	6.0	36.7	49.4	39.6
Monocrystalline quartz	28.2	17.3	13.8	24.0	20.5	28.0	19.4	25.3	21.7	26.3	24.5	18.8	9.5	5.8	11.8	18.3	38.3	30.7	26.8	39.3			
Plagioclase	40.9	43.3	40.3	32.0	34.0	40.8	36.2	42.3	26.4	30.5	44.3	31.8	25.8	23.0	25.0	21.3	21.8	26.0	32.0	18.5	19.4	17.2	28.9
K-feldspar	9.9	6.3	0.3	10.8	9.5	6.0	8.5	0.8	8.7	3.8	5.0	12.0	5.5	3.8	8.5	11.3	15.3	4.0	5.3	9.5	15.6	14.2	20.4
Biotite	6.4	2.5	3.3	4.0	0.8	1.8	2.5	9.5	1.8	1.8	4.3	2.8	2.0	0.5	1.0	2.5	1.5	3.0	6.5	3.3	14.9	6.0	4.4
Muscovite	0.3	0.5	tr	0.5	0.5	tr	tr	0.5	tr	–	0.8	–	–	tr	–	0.2	tr	0.5	0.5	0.5	1.6	0.4	–
Amphibole	–	–	tr	tr	0.3	0.5	–	0.3	–	0.3	tr	–	–	0.8	tr	–	1.0	0.3	1.3	1.0	–	–	–
Pyroxene	–	–	tr	–	–	–	–	tr	–	–	tr	–	–	1.0	–	tr	–	–	tr	–	–	–	–
Sphene	tr	0.5	0.8	0.3	0.3	1.3	–	tr	0.8	0.5	tr	tr	0.5	0.3	tr	0.2	tr	tr	tr	tr	†	†	†
Zircon	tr	–	tr	–	tr	tr	tr	tr	tr	tr	tr	–	–	tr	tr	0.2	tr	0.3	tr	tr	†	†	†
Garnet	–	tr	–	–	tr	–	–	tr	–	tr	–	0.3	–	tr	–	–	tr	tr	tr	tr	†	†	†
Secondary minerals‡	5.3	13.0	19.8	6.3	12.0	8.8	8.5	10.5	2.4	13.0	5.5	3.3	10.5	5.5	6.3	4.8	8.8	4.0	7.8	9.0	–	4.5	2.8
Rock fragments																							
Acid volcanic	1.3	1.8	2.3	1.5	4.3	tr	0.3	1.3	0.3	2.3	2.8	4.3	1.0	8.5	5.5	8.0	tr	1.2	0.3	–	–	–	–
Intermediate volcanic	–	–	–	0.3	0.3	–	1.0	0.5	–	0.3	–	0.8	28.5	24.3	22.3	10.5	–	–	–	–	–	–	–
Plutonic + gneissose	–	3.5	4.5	0.8	6.3	3.5	1.0	0.5	0.5	2.0	1.3	2.5	3.5	3.0	2.5	3.3	1.3	4.5	1.8	0.8	11.7	10.2	3.8
Low grade metamorphic	–	0.3	tr	0.3	–	–	tr	–	0.3	–	–	–	–	0.8	–	–	0.8	0.3	tr	0.8			
Sedimentary	–	tr	tr	–	0.3	–	0.8	0.3	0.5	0.8	0.3	1.0	1.0	4.5	1.3	1.0	1.0	0.5	tr	1.3	†	†	†
Matrix	1.5	1.8	6.3	11.0	1.5	2	17.8	3.5	23.7	8.5	7.0	12.8	7.5	12.0	9.1	10.8	1.8	16.6	9.8	1.3	†	†	†
Other	5.6	1.3	2.5	4.3	3.8	–	1.8	3.3	8.2	2.5	1.3	2.0	3.5	2.8	4.5	5.0	0.3	2.2	2.3	9.0	–	–	–
Co-ordinates of triangular diagrams																							
Q	35.5	31.1	30.0	38.3	32.7	41.6	31.2	37.2	41.9	46.3	34.2	33.9	14.1	12.3	17.7	27.5	53.9	50.3	45.5	59.5	44.0	54.3	42.7
F	62.9	62.1	60.0	58.0	53.7	54.4	64.5	59.3	55.7	46.6	60.6	55.4	41.1	34.6	42.4	42.6	42.7	40.9	51.7	36.8	42.0	34.5	53.2
L	1.6	6.8	10.0	3.7	13.6	4.1	4.4	3.5	2.4	7.1	5.2	10.8	44.8	53.1	39.9	29.8	3.5	8.8	2.8	3.6	14.0	11.2	4.1
V	100.0	32.1	33.8	62.1	42.2	–	56.5	78.3	27.3	56.5	68.3	67.1	89.4	89.6	91.8	84.9	–	20.0	14.3	–	†	†	†
M	–	5.4	–	10.3	–	–	–	–	27.3	0.0	–	–	–	2.2	–	–	38.1	5.0	–	50.0	†	†	†
P	–	62.5	66.2	27.6	57.8	100.0	43.5	21.7	45.5	43.5	31.7	32.9	10.6	8.2	8.3	15.1	61.9	75.0	85.7	50.0	†	†	†
Ratios																							
Polycrystalline quartz + chert: total quartz	0.02	0.31	0.31	0.15	0.23	0.20	0.11	0.07	0.18	0.23	0.12	0.3	0.12	0.4	0.16	0.13	0.18	0.17	0.18	0.13	†	†	†
Plagioclase: total feldspar	0.81	0.87	0.99	0.75	0.78	0.87	0.81	0.98	0.75	0.89	0.90	0.73	0.82	0.86	0.75	0.65	0.59	0.87	0.86	0.66	0.55	0.55	0.59

tr Trace.
* All figures as percentages.
† Not included in analysis.
‡ Includes prehnite, pumpellyite, zeolite, epidote, chlorite, calcite, sericite.

1. KG.1969.2 Arkosic arenite, eastern Toynbee Glacier.
2. KG.2025.1 Arkosic arenite, western Douglas Range.
3. KG.2028.1 Arkosic arenite, western Douglas Range.
4. KG.2115.1 Arkosic arenite, Mahler Spur.
5. KG.2116.1 Arkosic arenite, Mahler Spur.
6. KG.2137.2 Arkosic arenite, Nichols Snowfield.
7. KG.2212.1 Arkosic wacke, south-west Elgar Uplands.
8. KG.2173.2 Arkosic arenite, western Elgar Uplands.
9. KG.2214.5 Arkosic wacke, south-west Elgar Uplands.
10. KG.2241.1 Arkosic arenite, Nichols Snowfield.
11. KG.2242.1 Arkosic arenite, Nichols Snowfield.
12. KG.1522.1 Arkosic arenite, Dorsey Island.
13. KG.1526.1 Lithic arenite, Giovanni Peak.
14. KG.2423.1 Lithic arenite, Debussy Heights.
15. KG.2428.2 Arkosic arenite, Debussy Heights.
16. KG.2297.4 Arkosic arenite, Rothschild Island.
17. KG.2200.2 Arkosic arenite, Charcot Island.
18. KG.2201.1 Arkosic wacke, Charcot Island.
19. KG.2203.1 Arkosic arenite, Charcot Island.
20. KG.2204.1 Arkosic arenite, Charcot Island.
21. KG.57.1 Arkosic arenite, north of Mount Umbriel (Horne, 1968, Table I).
22. KG.57.6 Arkosic arenite, north of Mount Umbriel (Horne, 1968, Table I).
23. KG.55.1 Arkosic arenite, north of Mount Umbriel (Horne, 1968, Table I).

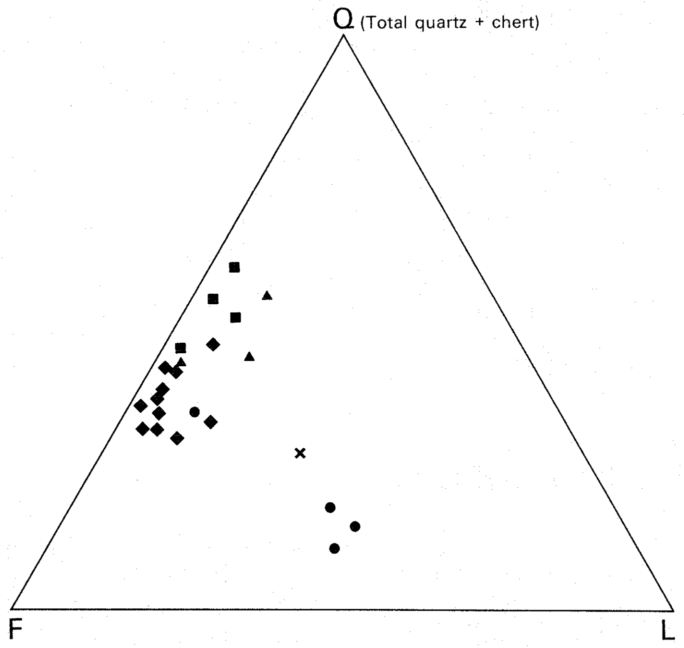


FIGURE 21
QFL diagram showing composition of LeMay Group sandstones.
◆ Elgar Uplands, Nichols Snowfield and Douglas Range.
● Debussy Heights, Giovanni Peak and Dorsey Island.
× Rothschild Island.
■ Charcot Island.
▲ North of Mount Umbriel (Horne, 1968; table I).

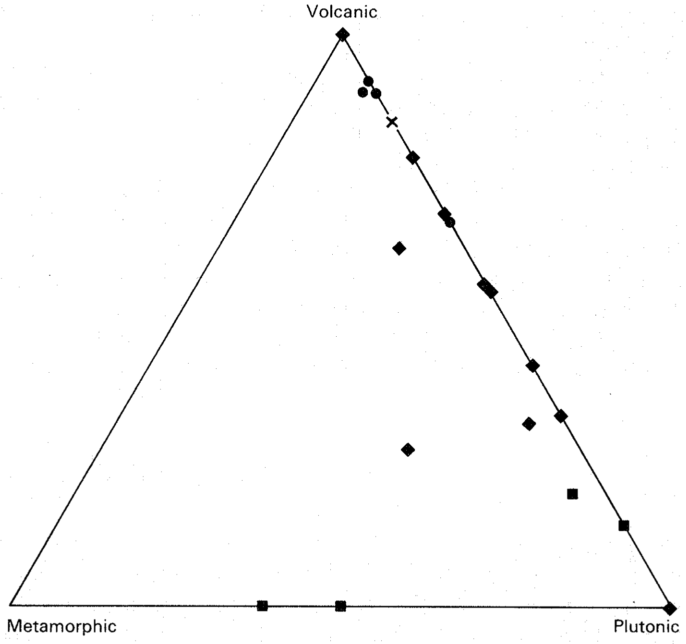


FIGURE 22
Triangular diagram showing composition of the lithic fraction in LeMay Group sandstones. Symbols as for Fig. 21.

lower plagioclase to total feldspar ratios (0.55–0.87) than the rocks from other areas. Sandstones from Debussy Heights, Giovanni Peak and Dorsey Island are much richer in lithic fragments and are transitional to lithic arenites (Pettijohn and others, 1972). They also have markedly lower quartz contents.

Volcanic, plutonic, metamorphic and sedimentary lithic fragments are present in the sandstones. Since the sedimentary category contains both clasts eroded from lithified sedimentary rocks, and intraformational material (which are difficult to tell apart under the microscope) the volcanic, plutonic and low-grade metamorphic categories are used as coordinates for a triangular VPM diagram to show variation in lithic content of the sandstones (Fig. 22). The diagram appears to support the geographical variations suggested above from the QFL diagram. Rocks from Elgar Uplands, Douglas Range and Nichols Snowfield contain sub-equal amounts of volcanic and plutonic material, but few metamorphic fragments. Charcot Island is characterized by mainly plutonic and metamorphic clasts and a very low volcanic contribution. The higher lithic content of rocks from Giovanni Peak, Debussy Heights and Dorsey Island is almost entirely made up of volcanic material. Table V shows that in these rocks intermediate volcanic fragments generally predominate over those of acid composition, in contrast to the other areas where acid types prevail.

Sphene is the most commonly counted heavy material, zircon, garnet and allanite are usually present in trace amounts, and apatite is rare. Allanite appears to be absent from sandstones from Charcot Island.

2. *Provenance*

The lithic fragment content of the sandstones and conglomerates indicates that detritus was supplied from a mixed terrain of volcanic, plutonic, metamorphic and sedimentary rocks, as recognized by Grikurov (1971), Bell (1973*b* and 1974) and Edwards (1980*c*). Volcanic lithic clasts are of acid and intermediate type. Clastic grains of subhedral oligoclase-andesine (and occasionally labradorite), clinopyroxene and green/brown amphibole represent typical andesitic detritus, whereas quartz with resorbed outlines and locally euhedral sanidine (central Alexander Island) probably represent dacitic to rhyolitic material. Textural and mineralogical differences between the volcanic lithoclasts and the pillow lavas within the LeMay Group are outlined on p. 34 and it is concluded that the clastic material is mostly epiclastic, and related to the extrusion of the basic pillow lavas only in the Lully Foothills. This is the only area where material of obvious pyroclastic origin has been identified, as shards in shallow water volcaniclastic sediments interbedded with lavas. In southern Alexander Island, volcanic arenites are associated spacially with lavas near Mimas Peak, but in northern Alexander Island, volcaniclastic rocks occur in a zone that includes Dorsey Island, Giovanni Peak and Debussy Heights and which is 10–15 km west of the main belt of pillow lavas.

In addition to plutonic rock fragments, clastic mineral grains of myrmekitic plagioclase, micrographic quartz-alkali feldspar intergrowths, microperthite, chess-board plagioclase and blue-green amphibole are also of acid–intermediate plutonic or high-grade metamorphic origin. The presence of the heavy minerals sphene, zircon, apatite, allanite and garnet is also typical of such a source. No basic plutonic material or associated heavy minerals (such as rutile or chromite) have been found in the sandstones. Other metamorphic fragments include aggregates of elongated quartz grains, metasiltstones and fine-grained foliated schists and semischists. The sedimentary contribution is represented by various types of quartzose and arkosic arenites and wackes, and occasional chert.

Thus, the type of landmass most likely to have supplied all the detrital elements found in the LeMay Group was either a mature island arc, with crystalline metamorphic basement, or an andean-type continental margin. Little is known of the time span over which the sediments were deposited so that any explanation of the variations in detrital characteristics detected within the LeMay Group can only be speculative. It is likely that the belt of volcaniclastic rocks represents an increase in activity at the postulated arc during the accumulation of the sediments which now constitute the LeMay Group. Abundant volcanic material was supplied to sediments in central Alexander Island during the Triassic, as indicated by the Triassic neritic fauna contained within the volcaniclastic sediments of the Lully Foothills Formation. The Lully Foothills Formation may represent a fore-arc basin supplied with abundant pyroclastic and epiclastic material from the arc, while lesser amounts of epiclastic detritus reached a trench in which the rest of the sediments of the LeMay Group accumulated. This possibility is discussed further on p. 57.

IV. PILLOW LAVAS AND ASSOCIATED ROCKS

Sequences of lavas, pillow lavas and tuffs within the LeMay Group have been described from southern Alexander Island by Bell (1973*b*) and from central Alexander Island by Edwards (1980*c*) and Grikurov (1971). The author found lavas and metabasic rocks of uncertain origin (termed greenstones in this report) often associated with red and green cherts in the vicinity of Nichols Snowfield and Gilbert Glacier, northern Alexander Island, and weakly foliated greenstones in southern Colbert Mountains, central Alexander Island. It appears that these rocks are mostly contained in a belt trending approximately north–south through the centre of the island (Fig. 23).

A. Field Relations

Dark grey and black pillow lavas and basalts associated with tuffaceous sandstones crop out over an area of approximately 500 km^2 around Mimas Peak in southern Alexander Island (Bell, 1973*b*). The total thickness of lavas is estimated to be in excess of 1000 m. The lavas occur in flows up to 10 m thick composed of flattened pillows mostly about 30 cm by 10 cm but occasionally up to 100 cm by 20 cm. These rocks are strongly deformed and cut by 'cleavage planes and narrow bands of greenschist' (Bell, 1973*b*).

Grikurov (1971) reported 'intensely folded and cataclastically deformed metavolcanics of basic composition intercalated with quarzites and greywacke sediments' in western LeMay Range and eastern Lully Foothills. The Lully Foothills Formation has been defined (p. 8) to include the sequence of lavas and volcaniclastic rocks which occupy a 5-km-wide north–south zone in western Lully Foothills (Edwards, 1980*b* and 1980*c*). This zone appears to be separated by faults from early Tertiary volcanic rocks to the west, and other metasedimentary rocks of the LeMay Group with minor occurrences of volcanic rocks to the east. Individual flows attain thicknesses of 10 m or more and are dark grey or green in hand specimens. Tuffaceous sediments occur between the flows and a neritic fauna has been described from one such bed (Edwards, 1980*b* and 1982). The presence of volcanic bombs and (?) welded tuffs suggests that some of the volcaniclastic rocks are of subaerial origin.

Restricted occurrences of metabasic rocks are present in LeMay Range, Walton Mountains (Edwards, 1980*c* and 1982) and southern Colbert Mountains. Pillow lavas and foliated metabasic rocks (some containing blue amphibole) are associated with chert and red and green schists in north-western LeMay Range. In Walton Mountains lavas occur with cherts and cataclastically deformed sedimentary rocks. A rock tentatively identified as a serpentinite by Edwards has on re-examination been recognized as a highly altered basic lava. Electron microprobe analysis identified pumpellyite as the main alteration product (personal communication from G. Hyden). The foliated greenstones of the southern Colbert Mountains, some of which contain high-pressure mineral assemblages, are massive, dark green and red in colour, and possess a platy foliation which controls the shape of the outcrop. In parts they have a crude lineation in the form of a coarse mullion structure. Lenses of nodular jasper are associated with metabasic rocks at station KG.2477.

In northern Alexander Island, the main outcrops of lavas lie within a 10-km-wide belt trending north–west through the south-western ridges of Elgar Uplands (Fig. 23). Thicknesses of up to 150 m of subvertical lavas, some displaying pillow structure (Fig. 24) occur between Bartok and Sullivan Glaciers, and up to 500 m of highly deformed greenstones crop out among the group of nunataks in the mouth of Bartok Glacier. Small outcrops of greenstones in the north-eastern Lassus Mountains may represent a continuation of the same belt. Pods of crushed and altered lava and (?) dolerite occur in a belt of (?) tectonic mélange passing through eastern Debussy Heights (p. 51). In the south-western Elgar Uplands, individual subvertical flows form ridges 3–4 m wide. Pillows are mostly 20–50 cm in diameter, occasionally up to 2 m, and are invariably slightly flattened parallel to the margins of the flow. Radial and concentric jointing together with an arrangement of amygdales are common. Frequently, however, pillows are not discernible, and the lavas are so strongly deformed and altered as to show little trace of their igneous origin. They vary in colour from black, olive green and dark maroon to jasper-red. The green parts are commonly rich in chlorite which imparts a crude schistosity, wrapping around boudin-like bodies of less altered rock. (The intense cataclastic deformation seen at some greenstone localities is discussed on p. 49.) Most

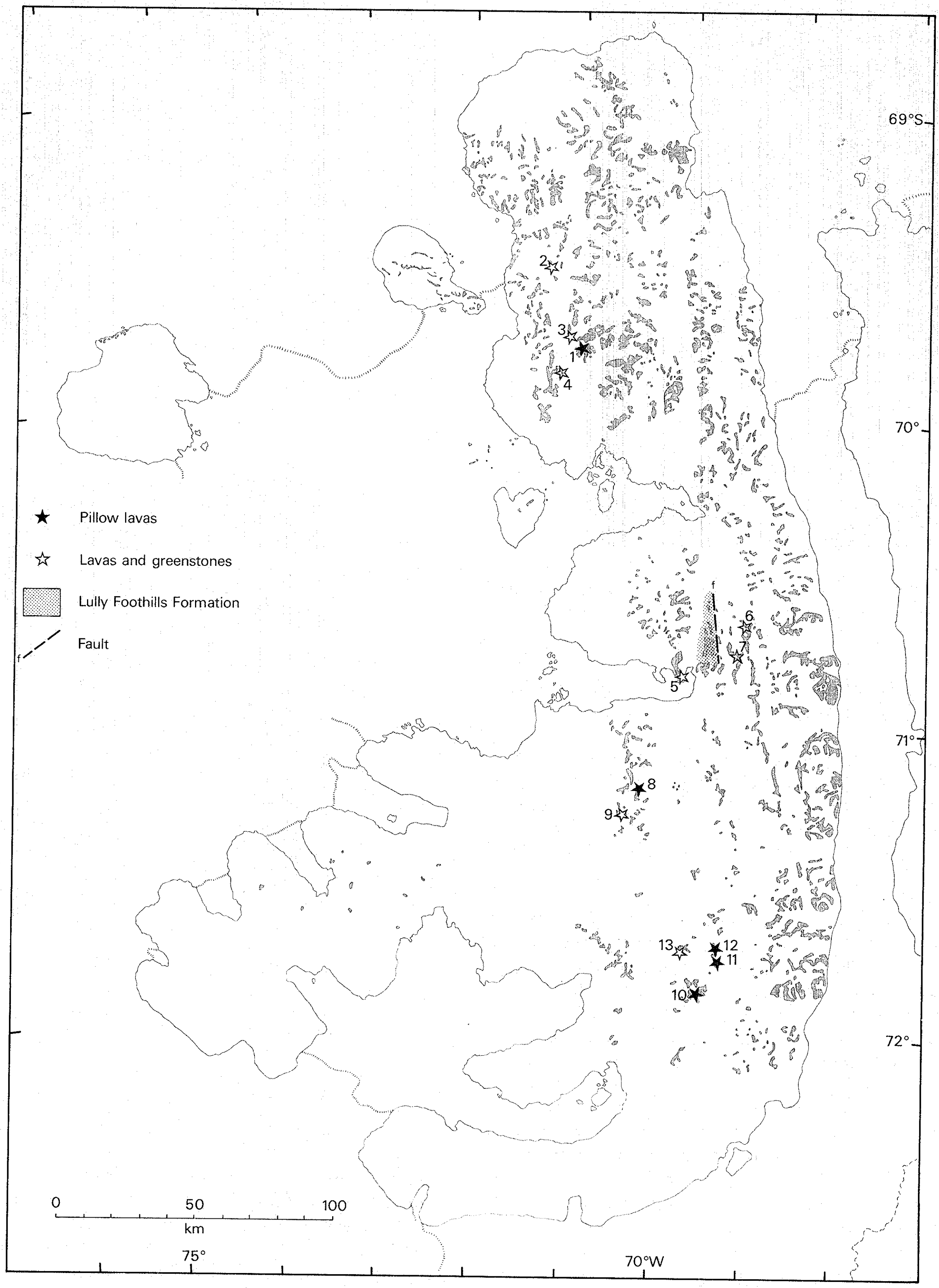


FIGURE 23

Sketch map showing distribution of basic volcanic rocks on Alexander Island. Additional information: Walton Mountains (Edwards, 1980*c*; enc. 4), Lully Foothills (Edwards, 1980*b*; fig. 1), southern Alexander Island (C. M. Bell, unpublished field notes). 1. South-western Elgar Uplands; 2. Nichols Snowfield; 3. Appalachia Nunataks; 4. Eastern Debussy Heights; 5, Southern Colbert Mountains; 6. Snick Pass; 7. North-western LeMay Range; 8. South-eastern Walton Mountains; 9. South-western Walton Mountains; 10. Mimas Peak; 11, 12 and 13. Nunataks north of Mimas Peak.

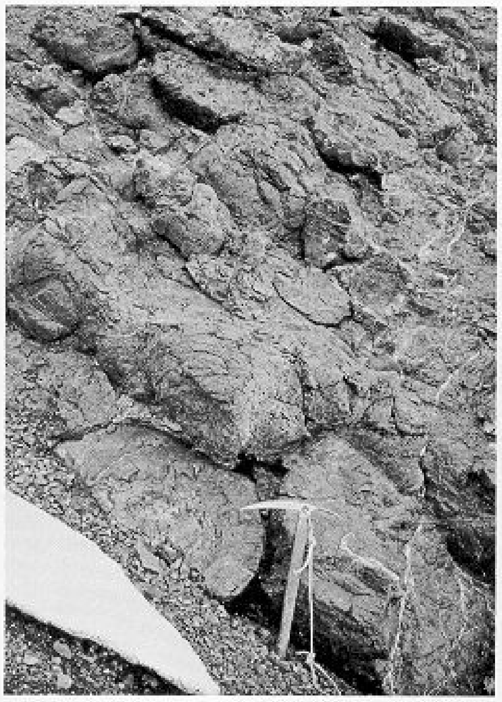


FIGURE 24
Well-formed pillows in part of a 150-m thick sequence of basalts with subsidiary sedimentary rocks, southern Bartok Glacier (station KG.2212). The ice-axe shaft is 55 cm long.

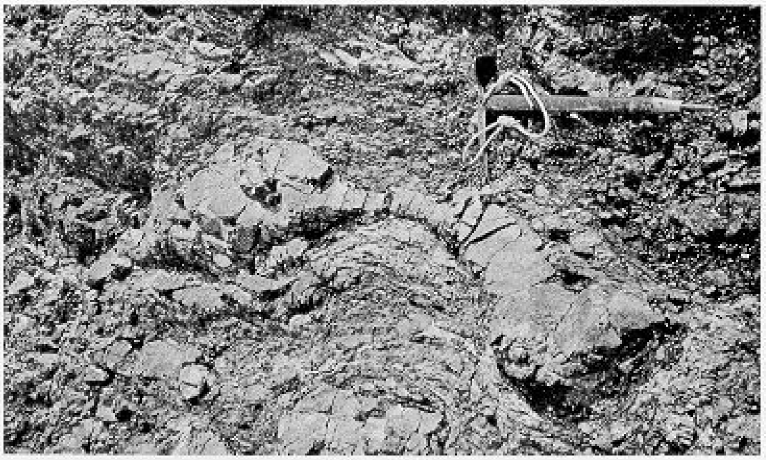


FIGURE 25
Intense cataclastic deformation in bedded arenite, chert, argillite within lava sequence, southern Bartok Glacier (station KG.2212). The ice-axe shaft is 55 cm long.

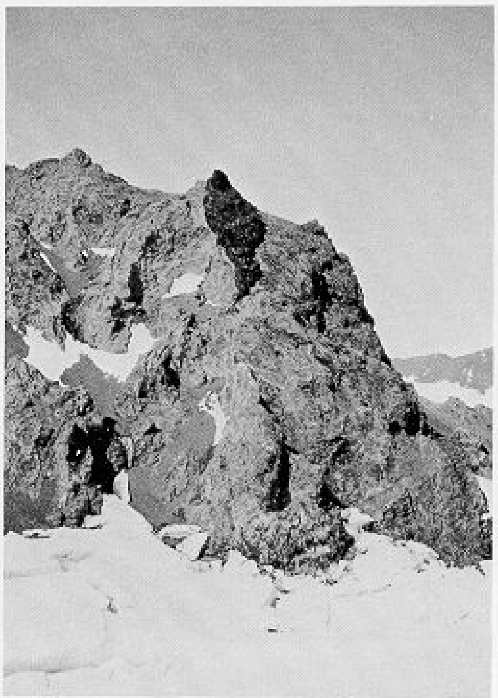


FIGURE 26
Pod of fine grained basalt within shattered, veined sedimentary rocks adjacent to lava sequence, southern Bartok Glacier (station KG.2212). The pod is 5 m thick at its widest point.

outcrops are cut by a fine network of white calcite and zeolite veins. Intervening sediment is sparse but consists of:

i. Units up to 2 m thick of thinly bedded black mudstone and graded sandstone which lap against pillows.
ii. Units up to several metres thick of bedded red and green radiolarian chert (20–50 cm), shattered green and black argillite and medium grained sandstone (20–50 cm).

The thinly bedded graded sandstones young to the north-east and are rich in dark (?) volcanic clasts, probably derived locally and reworked by bottom currents and/or distal turbidites. However, the thicker sandstones within the bedded chert-argillite sequences are no richer in volcanic lithic clasts than arkosic arenites from elsewhere in the LeMay Group. All the sediments within and adjacent to the lava sequences show intense shattering, contortion and boudinage (Fig. 25) similar to that of the broken formation described on p. 50 and are veined by calcite, analcime and other zeolites. Several lense-shaped bodies of lava up to 5 m thick (Fig. 26) were observed within the shattered sedimentary rocks adjacent to the main lava sequence at station KG.2212.

B. PETROLOGY

1. *Lavas and greenstones*

a. *Igneous petrology*. The pillow lavas are porphyritic and non-porphyritic basalts, frequently containing amygdales filled with calcite (sometimes stained pink by haematite), or chalcedonic silica. Specimen KG.2212.15, a porphyritic pillow lava from south-western Elgar Uplands, has a groundmass composed of 0.03–0.3-mm plagioclase (An_{60}) intergrown with granules and frondescent growths of colourless clinopyroxene, and anhedral 0.01-mm granules of opaque (?) magnetite. Khaki-coloured non-pleochroic patches up to 0.3 mm across composed of 0.01-mm length-slow fibres probably represent devitrified glass. Phenocrysts of plagioclase (An_{66}) and colourless augite are abundant and up to 1.5 mm across. Glomerophenocrysts consisting of groups of several large plagioclase and pyroxene grains, displaying subophitic texture are rather common (Fig. 27).

FIGURE 27
Glomorophenocryst of labradorite laths and augite in basaltic pillow lava, showing sub-ophitic texture (KG.2212.15; X-nicols; ×33).

This rock is one of the freshest lavas studied, secondary quartz, calcite, chlorite, zeolite and pyrite being largely restricted to thin veins. An amygdaloidal pillow lava from south-western Elgar Uplands (specimen KG.2222.2) consists of a lathwork of 0.02–0.1-mm plagioclase laths (An_{37}) with interstitial 0.01-mm granules of colourless augite. Phenocrysts of plagioclase (also An_{37}) and subhedral augite are rather rare. Amygdales up to 2 mm across are filled with chlorite, calcite, and radially arranged fibrous chalcedony. Alteration is restricted to veins and patches of chlorite, calcite, and fine-grained alteration of plagioclase. Numerous other fine-grained basic rocks in northern and southern Alexander Island are similar texturally and mineralogically to the pillow lavas. Plagioclase composition in the lavas varies from nearly pure albite (e.g. specimens KG.2192.3, KG.1339.4) to An_{60}, but is mostly between An_{50} and An_{60} in northern Alexander Island and ranges from An_{30} to An_{40} in southern Alexander Island; Edwards (1980*c*) reported a plagioclase composition of An_{37} in a lava from the Lully Foothills. However, insufficient plagioclase determinations were possible to be able to ascertain if the plagioclase in lavas from northern Alexander Island is significantly more calcic than those from central and southern parts of the island. Pyroxenes in lavas from northern, central and southern Alexander Island appear to be similar, usually a colourless or slightly pinkish augite with $2V_\gamma$ of 30°–40°. Electron microprobe analyses of relict pyroxenes in a greenstone from southern Colbert Mountains are given in the Appendix and are discussed on p. 33. Subsidiary pigeonite has been tentatively identified in one lava from the Lully Foothills (Edwards, 1980*c*). The only notable petrographic difference within the lavas is that those from the Lully Foothills Formation are rather coarser grained and have a subophitic texture, whereas lavas from northern and southern Alexander Island, Walton Mountains and eastern Lully Foothills have a fine grained, sometimes glassy groundmass and subophitic texture is only present in the glomerophenocrysts of pyroxene and plagioclase.

Although fine-grained rocks of volcanic aspect are the most abundant basic igneous rocks in the LeMay Group, some medium to coarse-grained rocks may have a plutonic or hypabyssal origin. Specimen KG.2214.4 is from a 20–30-m thick body of greenstone that is associated with radiolarian cherts in south-west Elgar Uplands. It consists of a coarse intergrowth of slightly sericitized plagioclase (An_{52}) up to 35 mm long with subhedral prisms of blade-like colourless to greenish brown augite up to 1.5 mm. Some of the pyroxene forms a complex intergrowth with plagioclase, slivers of optically continuous pyroxene being included within a single large plagioclase grain. Elongate ilmenite laths up to 0.5 mm are partly altered to sphene and leucoxene. The chief secondary minerals are sericite and pyrite. The rock has undergone considerable cataclastic deformation and is cut by branching zones of intense granulation. Specimen KG.2432.1 is a medium grained basic rock of doleritic aspect from a pod in a belt of (?) tectonic mélange passing through eastern Debussy Heights (p. 51). It has undergone severe crushing and is heavily veined by calcite. However, colourless to pale green augite grains up to 1.5 mm long still display a subophitic texture towards wide laths of plagioclase (An_{53}). Ragged patches of opaque pyrite and (?) magnetite are abundant, and some are secondary in origin, being concentrated along zones of granulation.

b. *Secondary mineralogy*. The most highly metamorphosed metabasic rocks are the weakly foliated greenstones of central Alexander Island, some of which contain high-pressure mineral assemblages. Frequently, the only evidence of an igneous origin shown by these rocks is the abundance of pale pink augite. Its form and distribution suggest that it may have once displayed a subophitic texture towards plagioclase which is now totally altered to a fine grained mass of chlorite, epidote, sericite and pumpellyite forming much of the matrix. The augite usually shows marginal alteration to a grass-green mineral (Fig. 28) for which electron microprobe analyses yielded compositions ranging from sodic augite to aegerine-augite (see Appendix). Similar rims of green sodic pyroxene around primary pyroxene have been described from metabasalts in other blueschist terranes, notably in California (Essene and Fyfe, 1967) and New Caledonia (Black, 1974). However, in both the latter examples the sodic pyroxenes are of chloromelanite or omphacite composition. Alignment of chlorite and streaks of sphene in the matrix define a foliation which manifests itself as a moderate to strong platyness in hand specimens. Blue amphibole

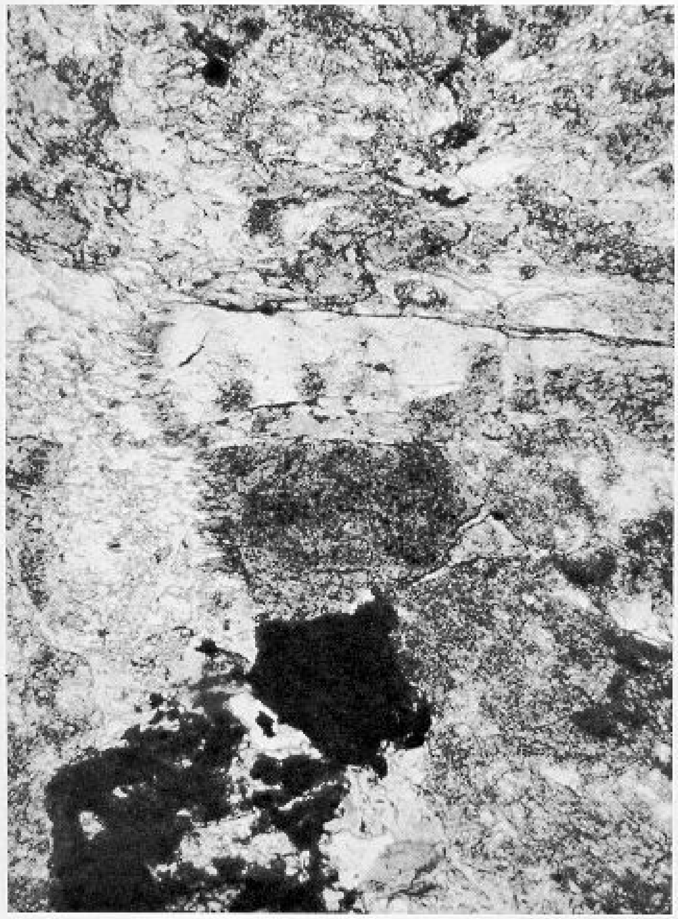


FIGURE 28
Relict phenocryst of augite (top centre) in weakly foliated greenstone, showing alteration to strongly coloured sodic pyroxene (lower centre). A fringe of small crossite needles is developed along the left edge of both grains (KG.2476.1; plane-polarized light; ×88).

FIGURE 29
Tablets of lawsonite in quartz vein cutting foliated greenstone (KG.2477.3; X-nicols; ×135).

(which electron microprobe analyses showed to be transitional between crossite and riebeckite (Appendix) in specimen KG.2476.1) occurs chiefly as fringes of acicular needles up to 0.04 mm long around pyroxene grains (Fig. 28). Pleochroism is strong and of the typical glaucophane type (α = colourless, β = lavender blue, γ = bright blue).

Lawsonite was detected in only one thin section (specimen KG.2477.3) a rock of uncertain origin from a schistose zone within weakly foliated greenstones. The rock consists largely of a mass of alteration products, including (?) pumpellyite, chlorite and aligned muscovite flakes. Haematite occurs as lenses up to 2 mm by 3 mm. The lawsonite forms narrow prisms and tablets up to 0.3 mm long (Fig. 29), scattered through a quartz vein. The prisms are length-fast, display low birefringence, and occasionally show lamella twinning. Identification was confirmed by electron microprobe analysis (see Appendix).

In the lower grade zeolite and prehnite-pumpellyite facies rocks of northern and southern Alexander Island, original igneous textures and mineralogies are normally preserved. Pyroxene is typically fresh, but plagioclase invariably shows alteration to sericite, chlorite and calcite. Refractive index comparisons show that plagioclase in some lavas is almost pure albite, but anorthite contents as high as An_{33} (in southern Alexander Island) and An_{66} (in northern Alexander Island) indicate that albitization is incomplete. Albite frequently occurs with quartz as a vein mineral. Blue-green pumpellyite and yellow-green epidote were found occasionally as small granules, or in veins, but prehnite is rare in metabasic lithologies. Chlorite is a common product of ground mass alteration and also occurs pseudomorphing mafic minerals and in veins. Other abundant secondary minerals include calcite, sphene and pyrite. Ilmenite occurs in various stages of alteration to sphene and leucoxene. Less common vein minerals include an optically positive zeolite (e.g. specimen KG.2212.15) and garnet (specimen KG.1381.2).

2. *Volcaniclastic rocks and tuffs*

Volcaniclastic sediments which occur in southern Alexander Island in close association with pillow lavas (Bell, 1973*b*) and also in northern Alexander Island (where they are not associated with lavas) can be classified as volcanic arenites (cf. Pettijohn and others, 1972). Texturally they are similar to the arkosic arenites which are volumetrically the most important rock type in the LeMay Group. The volcanic arenites examined by the author in northern Alexander Island show the same flysch-type sedimentary structures as are seen in the arkosic arenites. The volcanic fragments, which may constitute up to 70% of the rock, are of two main types (described in more detail on p. 18):

i. Felsic fragments, with or without quartz and/or oligoclase phenocrysts.
ii. Porphyritic, microlitic and glassy andesites, characterized by phenocrysts of andesine, pyroxene and amphibole.

Some volcanic arenites in southern Alexander Island are virtually devoid of non-volcanic lithic fragments (e.g. specimen KG.1576.1) whereas those in the north usually have small amounts of sedimentary, plutonic and metamorphic clasts (e.g. specimen KG.2423.1; Table V). Authigenic minerals include prehnite, blue-green pumpellyite, chlorite, sericite, epidote, sphene and calcite.

Tuffaceous sediments were collected from the north-east coast of Alexander Island by Adie (1954), three thin sections of which were studied in this investigation. Specimen E.145.1A is a strongly foliated rock composed of very poorly sorted, tectonically flattened volcanic fragments up to 4 mm across. The fragments mostly have a microlitic trachytic texture with plagioclase (andesine-oligoclase) phenocrysts. A small number of felsic volcanic, acid hypabyssal and acid plutonic fragments are also present, along with clastic grains of plagioclase (also oligoclase-andesine) and quartz (rather scarce). Specimen E.144.5 is a very fine-grained sandstone in which obscure dusky volcanic fragments constitute about 50% of the rock. The remainder is made up of subangular plagioclase with accessory detrital biotite and zircon. Authigenic minerals in both of these rocks include sericite, chlorite, prehnite, epidote and (?) pumpellyite. Specimen E.144.7 is probably an altered fine-grained volcaniclastic rock, but has been almost completely replaced by a mass of spongy prehnite with subsidiary sericite, epidote, sphene and pumpellyite. The few remaining unprehnitized areas consist of a fine-grained cherty quartz mosaic (0.01 mm) with scattered angular (?) detrital quartz and albitic plagioclase. The similarity between the volcanic content of these rocks and that in LeMay Group volcanic arenites, together with a comparable degree of alteration, suggests that they may be part of a volcanigenic sequence within the LeMay Group, rather than an older (?) early Palaeozoic volcanic terrain, as was suggested by Adie (1954).

The only rocks in the LeMay Group to contain material of undisputed pyroclastic origin are the shallow-water sediments and tuffs of the Lully Foothills Formation. One of these, in which a neritic invertebrate fauna was found (Edwards, 1980*b* and 1982) was described as a grey vitric tuff, containing well-sorted angular and slightly rounded devitrified shards and vesicular pumice. Other constituents were quartz, plagioclase (oligoclase-andesine), detrital augite and rounded fragments of fine-grained basalt.

3. *Chert*

In thin section the red and green cherts consist of a cryptocrystalline or microcrystalline quartz mosaic (<5–$10\,\mu$m). Irregular patches of recrystallization are composed of coarser mosaic quartz and fibrous length-fast chalcedony. All the cherts are cut by an extremely fine network of veins such that the largest vein-free area is rarely more than a few millimetres across. Early veins are commonly offset by later ones. The chief vein minerals are quartz, calcite and analcime, less commonly chlorite, prehnite and albite.

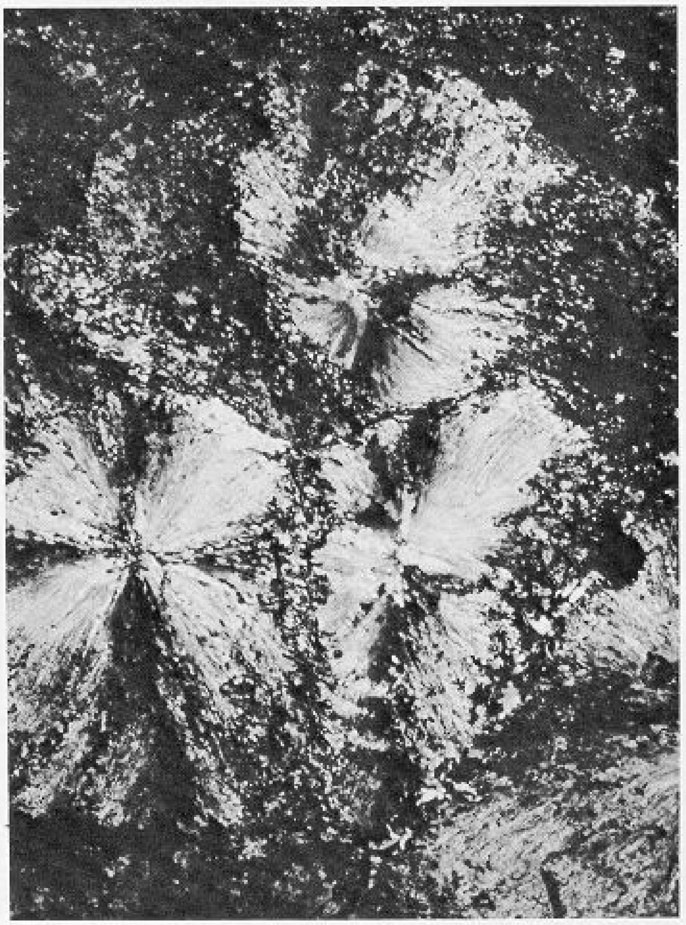


FIGURE 30
Quartz spherulites in a (?) metachert associated with blueschist facies rocks in southern Colbert Mountains (KG.2477.2; X-nicols; ×39).

Radiolarian remains are present in most of the thin sections examined, and consist of 0.03–0.06-mm circular bodies replaced by mosaic quartz or fibrous chalcedony. Part of the radial structure may be preserved. An assemblage with mid-Cretaceous affinities has been extracted from a chert from the east side of the Gilbert Glacier (p.7).

A nodular jasper associated with foliated blueschist facies greenstones in southern Colbert Mountains consists of 0.3-mm spherulitic structures of length-slow quartz fibres, stained red by haematite. A recrystallized mosaic of 0.01-mm quartz grains overprints part so the spherulites, and radially arranged cracks reminiscent of septarian nodules are filled by mosaic quartz (Fig. 30). The interstices between spherulites are filled by ragged haematite and bright green fibrous pumpellyite.

C. GEOCHEMISTRY

1. *Geochemistry of the lavas and greenstones*

Seven samples of lavas and greenstones were analysed for twenty-six major and trace elements (Table VI). Trace element analyses only are available at the present time for a

TABLE VI
Chemical analyses of lavas and greenstones from the LeMay Group of Alexander Island

	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
SiO_2	46.6	51.4	50.5	46.3	47.7	. .	. .	45.3	. .	46.0
TiO_2	1.68	1.78	1.24	1.73	3.27	. .	. .	2.07	. .	1.24
Al_2O_3	12.2	14.3	14.1	12.6	14.7	. .	. .	13.8	. .	12.1
Fe_2O_3†	14.34	11.29	10.60	9.20	17.36	. .	. .	12.81	. .	9.17
MnO	0.2	0.13	0.1	0.1	0.2	. .	. .	0.2	. .	0.2
MgO	16.0	8.6	6.7	5.8	5.1	. .	. .	7.1	. .	7.7
CaO	7.51	8.90	12.8	13.9	7.27	. .	. .	11.17	. .	13.89
Na_2O	1.2	2.9	2.5	2.1	3.5	. .	. .	2.9	. .	2.4
K_2O	–	0.45	0.09	1.55	1.52	. .	. .	0.05	. .	0.29
P_2O_5	0.14	0.15	0.07	0.18	0.43	. .	. .	0.17	. .	0.11
Total	99.87	99.90	98.70	93.46	101.05			95.57		93.10
Trace elements (ppm)										
Cr‡	396	205	205	61	84	196	166	224	136	181
Ni	908	84	88	34	70	81	100	106	71	72
Zn	108	95	87	75	155	109	121	88	114	61
Ga	13	19	14	17	23	18	22	19	17	12
Rb	2	13	2	30	17	4	6	2	15	6
Sr	306	359	117	198	164	170	121	126	105	224
Y	19	20	30	33	42	30	31	28	26	22
Zr	75	85	57	99	214	141	153	119	132	68
Nb	9	7	4	7	25	13	14	14	15	7
Ba	32	265	37	620	145	90	106	79	111	77
La	4	6	3	5	26	13	18	12	11	7
Ce	11	16	10	18	54	33	34	29	31	17
Nd	9	10	8	14	32	20	22	18	18	12
W	32	112	87	47	22	51	38	39	10	28
Pb	3	–	–	6	4	–	5	3	2	2
Th	–	4	3	5	7	–	–	3	3	0.7
Fe*/Mg	1.04	1.52	1.84	1.84	3.95			2.09		1.38
K/Rb		287	374	429	742			208		401
Rb/Sr	0.01	0.04	0.02	0.15	0.10	0.02	0.05	0.02	0.14	0.03
Ba/Sr	0.10	0.74	0.32	3.13	0.88	0.53	0.88	0.63	1.06	0.34
Y/Nb	2.11	2.86	7.50	4.71	1.68	2.31	2.21	2.00	1.73	3.14

– Below detection limit.
. . Not determined.
* Total iron as Fe^{2+}.
† Total iron as Fe_2O_3.
‡ Values rounded to nearest 10 ppm (not corrected for V interference).

1. KG.2214.1 Greenstone, south-western Elgar Uplands.
2. KG.2214.4 Greenstone, south-western Elgar Uplands.
3. KG.2212.15 Pillow lava, south-western Elgar Uplands.
4. KG.2432.2 Greenstone pod in (?) tectonic mélange, eastern Debussy Heights.
5. KG.1937.4 Basalt, central western Lully Foothills.
6. KG.1933.15 Lava, northern Lully Foothills.
7. KG.1933.23 Lava, northern Lully Foothills.
8. KG.1945.2 Basalt, northern Lully Foothills.
9. KG.1936.2 Basalt, central Lully Foothills.
10. KG.1953.1 Pillow lava, south-western Walton Mountains.

further three samples. The analyses were carried out at the Department of Geological Sciences, University of Birmingham, using a Philips PW 1450 automatic X-ray spectrometer. Although all the rocks are altered to some extent, the freshest available samples were used in this study. None of the rocks analysed is believed to have undergone metamorphism exceeding the prehnite-pumpellyite facies. Pyroxenes are generally fresh, but feldspars show variable degrees of alteration to secondary minerals including sericite, chlorite and pumpellyite. Albitization was not apparent in thin section. Secondary quartz does not appear to be widespread, but two samples (KG.1953.1 and KG.2432.2) contain substantial amounts of calcite. The same two samples have low major ion totals (Table VI) but are included in this discussion since so little chemical data are available on these rocks. The error is considered most likely to be in the Al_2O_3 or SiO_2 determination.

The analysed rocks are all basalts, with SiO_2 in the range 45–52 wt%. They fall in the tholeiitic field on the AFM diagram (Fig. 31a) and appear to show a marked iron-enrichment trend. On a plot of ($Na_2O + K_2O$) versus SiO_2 (cf. MacDonald and Katsura, 1964) they spread across the divide between alkali and tholeiitic fields. Owing to the mobility of silica during weathering and metamorphism, abundances of certain less mobile trace elements (e.g. Ti, Zr, Y, Nb, Ce) are probably a more reliable basis for the classification of altered volcanic rocks. The ratio Y/Nb provides a convenient divide of tholeiitic and alkali basalts (Pearce and Cann, 1973; Floyd and Winchester, 1975). When this ratio is plotted against TiO_2 (Fig. 31b) the

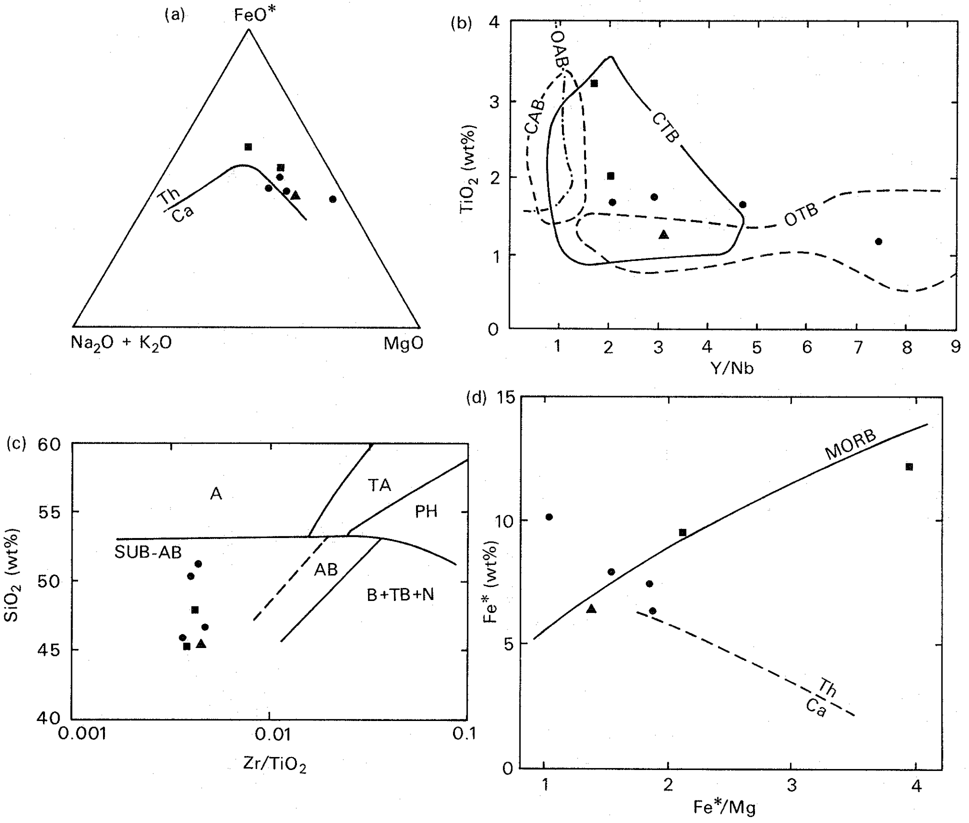


FIGURE 31

a. Triangular AFM diagram for lavas and greenstones from the LeMay Group.
FeO* = total iron as FeO.
Tholeiitic (Th) and calc-alkali (Ca) fields from Irvine and Barager (1971).

b. Plot of TiO$_2$ versus Y/Nb for lavas and greenstones from the LeMay Group. Fields for oceanic tholeiitic basalts (OTB), continental tholeiitic basalts (CTB), continental alkali basalts (CAB) and oceanic alkali basalts (OAB) after Floyd and Winchester (1975).

c. Plot of SiO$_2$ versus Zr/TiO$_2$ for lavas and greenstones from the LeMay Group. Fields for magma types (after Floyd and Winchester, 1978):
A = andesites
AB = alkali basalts
Sub-AB = subalkali basalts
B + TB + N = basanites, trachybasalts, nephelinites
TA = trachyandesites
PH = phonolites

d. Plot of Fe* versus Fe*/Mg for lavas and greenstones from the LeMay Group.
MORB = Fractionation trend for mid-ocean ridge basalts after Saunders and others (1979). Line separating tholeiitic (Th) from calc-alkali (Ca) fields after Miyashiro (1973*b*).
● Northern Alexander Island.
■ Lully Foothills.
▲ Walton Mountains.

Alexander Island rocks fall within the field of continental and oceanic tholeiites, showing considerable spread of Y/Nb values but generally rather low TiO$_2$. A plot of the ratio Zr/TiO$_2$ against SiO$_2$ also clearly shows the sub-alkaline nature of these rocks (Fig. 31c).

In altered rocks, the ration Fe*/Mg (where Fe* is total iron expressed as Fe^{2+}) is believed to be a more reliable indicator of fractionation than SiO$_2$ owing to the mobility of the latter (e.g. Saunders and others, 1979). The increase in Fe* with Fe*/Mg (Fig. 31d) but lack of significant variation in SiO$_2$ (Fig. 32a) is an indication of tholeiitic rather than calc-alkali fraction. Both Zr and TiO$_2$ show positive correlation with Fe*/Mg and plot within or close to the fields for ocean-floor basalts (cf. Saunders and others, 1979).

Considerable effort has been made recently to devise methods of discriminating chemically between basalts of different tectonic settings. Such methods rely on the statistical and graphical treatment of large numbers of published analyses of rocks whose tectonic settings are known. Pearce (1976) has described a method of visual identification of basalts from five different tectonic settings using discriminant analysis of their major element chemistry. Pearce's discriminant functions F$_1$ and F$_2$ for the Alexander Island rocks are shown in Fig. 32c. Three analyses plot in the field of ocean-floor basalt, while the remaining four plot in the within-plate basalt field. A second plot of discriminant functions F$_2$ and F$_3$ (Fig. 32d) places the same three analyses in the ocean-floor basalt field, but the remainder are spread

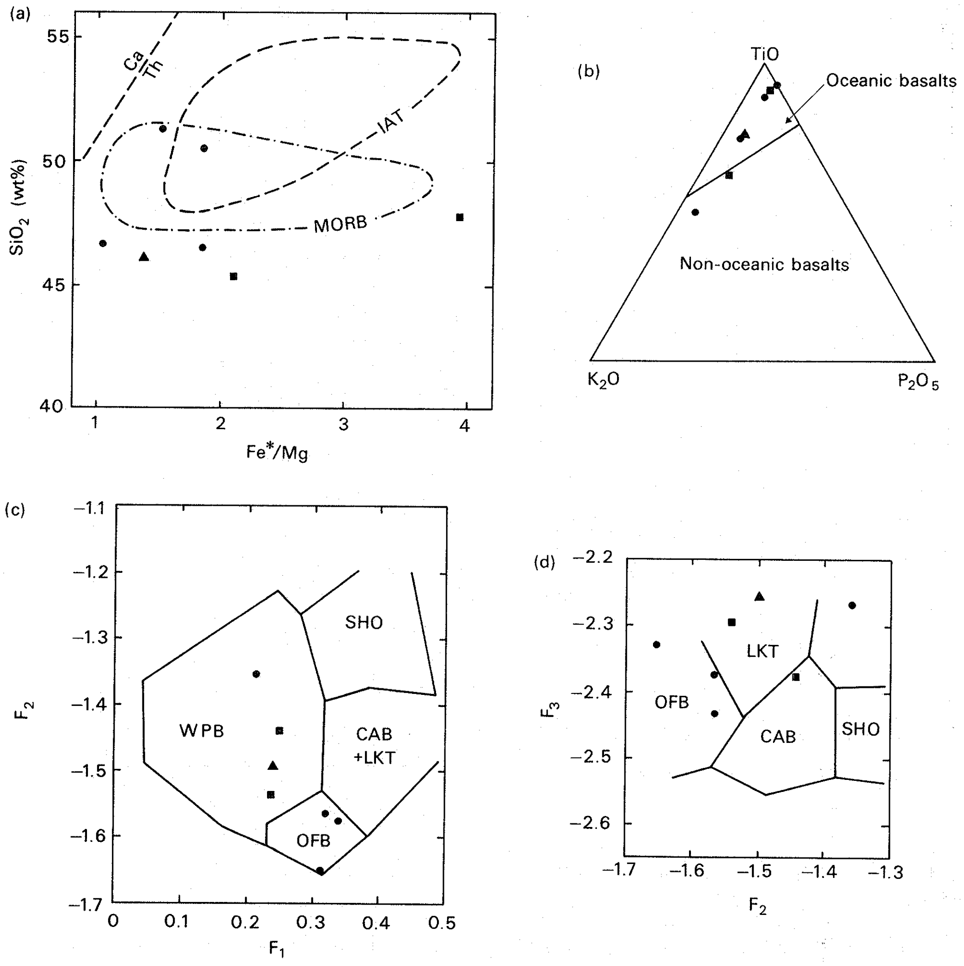


FIGURE 32

a. Plot of SiO_2 versus Fe*/Mg for lavas and greenstones of the LeMay Group. Fields for mid-ocean ridge basalts (MORB) and island arc tholeiites (IAT) after Saunders and others (1979). Line separating tholeiitic (Th) from calc-alkali (Ca) fields after Miyashiro (1973*b*).

b. Triangular TiO_2–K_2O–P_2O_5 diagram for lavas and greenstones from the LeMay Group. Dividing line between oceanic basalts and non-oceanic basalts after Pearce and others (1975).

c. Plot of discriminant functions F_1 versus F_2 (after Pearce, 1976) for lavas and greenstones from the LeMay Group.
$F_1 = +0.0088\,SiO_2 - 0.0774\,TiO_2 + 0.0102\,Al_2O_3 + 0.0066\,FeO - 0.0017\,MgO - 0.0143\,CaO - 0.0155\,Na_2O - 0.0007\,K_2O$.
$F_2 = -0.0130\,SiO_2 - 0.0185\,TiO_2 - 0.0129\,Al_2O_3 - 0.0134\,FeO - 0.0300\,MgO - 0.0204\,CaO - 0.0481\,Na_2O + 0.0715\,K_2O$.
Fields shown for ocean floor basalts (OFB), low potassium tholeiites (LKT), calc-alkali basalts (CAB), within plate basalts (WPB) and shoshonites (SHO).

d. Plot of discriminant functions F_2 versus F_3 (after Pearce, 1976) for lavas and greenstones from the LeMay Group.
$F_3 = -0.0221\,SiO_2 - 0.0532\,TiO_2 - 0.0361\,Al_2O_3 - 0.0016\,FeO - 0.031\,MgO - 0.0237\,CaO - 0.0614\,Na_2O - 0.0289\,K_2O$.
Symbols as for Fig. 31.

across the fields of low potassium tholeiite and calc-alkaline basalts. These results should be interpreted with care owing to the small number of analyses and the fact that several major ion parameters are known to be mobile under conditions of weathering (submarine and subaerial) and low-grade metamorphism. It may be significant, however, that the least altered samples plot in the ocean-floor basalt field in both diagrams. Discriminant function F_2 is most sensitive to K_2O, Na_2O, CaO, MgO, and the observed spread of points away from the ocean-floor basalt field parallel to the F_2 axis on both diagrams could be accounted for by increase in K_2O, or loss of one or more of the other parameters. There is little thin-section evidence for increase in potash in these rocks.

Pearce and Cann (1973) constructed diagrams involving the less mobile elements Ti, Zr, Y in an attempt to characterize basalts from different tectonic settings. The Alexander Island rocks plot in the fields of within-plate-basalts and low potassium tholeiites + ocean-floor basalts + calc-alkaline basalts on the Ti–Zr–Y triangle (Fig. 33a). Separation of the two latter types can be achieved by plotting Zr against Ti (Fig. 33b). The three samples from field B of Fig. 33b plot in fields B and D of Fig. 33b, suggesting an ocean-floor origin. Only one of these samples, however, is common to the three possible ocean-floor basalts recognized on the basis of major ion chemistry.

Pearce and others (1975) have proposed a method of discrimination between oceanic and non-oceanic basalts using a triangular TiO_2–K_2O–P_2O_5 diagram. On this plot all except two of the analyses lie in the oceanic field (Fig. 32b). The two samples plotting in the non-oceanic field owe their position to their rather high K_2O values.

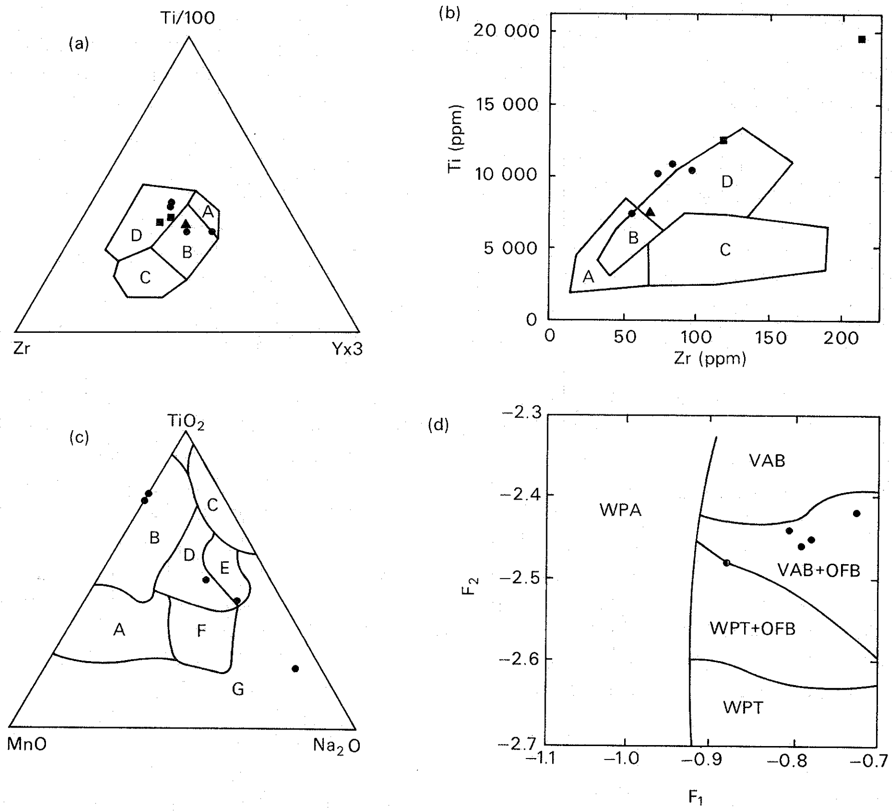


FIGURE 33

a. Triangular Ti/100–Zr–3Y diagram for lavas and greenstones from the Lemay Group. Fields after Pearce and Cann (1973):
A Low potassium tholeiites.
B Low potassium tholeiites + ocean floor basalts + calc-alkali basalts.
C Calc-alkali basalts.
D Within-plate basalts.
Symbols as for Fig. 31.

b. Plot of Ti versus Zr for lavas and greenstones from the LeMay Group. Fields after Pearce and Cann (1973):
A Low potassium tholeiites.
B Low potassium tholeiites + ocean floor basalts + calc-alkali basalts.
C Calc-alkali basalts.
D Ocean floor basalts.
Symbols as for Fig. 31.

c. Triangular TiO_2–MnO–Na_2O diagram for pyroxene from specimen KG.2476.1. Fields after Nisbet and Pearce (1977):
A Volcanic arc basalts.
B Ocean floor basalts.
C Within-plate alkali basalts.
D All.
E Volcanic arc basalts + within-plate tholeiitic basalts + within-plate alkali basalts.
F Volcanic arc basalts + within-plate alkali basalts.
G Within-plate alkali basalts.

d. Plot of discriminant functions F_1 vesus F_2 (after Nisbet and Pearce, 1977) for pyroxenes from specimen KG.2476.1.
VAB Volcanic arc basalts.
OFB Ocean floor basalts.
WPT Within-plate tholeiitic basalts.
WPA Within-plate alkali basalts.
$F_1 = -0.012\,SiO_2 - 0.0807\,TiO_2 + 0.0026\,Al_2O_3 - 0.0012\,FeO^* - 0.0026\,MnO + 0.0087\,MgO - 0.0128\,CaO - 0.0419\,Na_2O.$
$F_2 = -0.0469\,SiO_2 - 0.0818\,TiO_2 - 0.0212\,Al_2O_3 - 0.001\,FeO^* - 0.01435\,MnO - 0.0029\,MgO + 0.0085\,CaO + 0.0160\,Na_2O.$

Few conclusions can be drawn from the study of such a small number of altered samples. The rocks are basalts and show some evidence of tholeiitic fractionation. Since Na_2O is not excessively high (less than 3.5 wt %) and albitization is not widespread the rocks cannot be classified as spilites. Attempts to recognize tectonic setting from major and trace element abundances are inconclusive and somewhat conflicting, but the rocks appear to have affinities with ocean-floor basalts and within-plate basalts.

2. *Clinopyroxene composition and tectonic setting*

Five electron microprobe analyses were made on relict primary pyroxene in specimen KG.2476.1, a blue amphibole-bearing metabasic rock from the southern Colbert Mountains (see Appendix). These phenocrysts resemble in appearance and optical properties many other lavas in southern, central and northern Alexander Island, but have rims of metamorphic grass-green sodic pyroxene of sodic augite to aegerine-augite composition. The primary pyroxenes plot in the augite field of the Di–Wo–Fs triangle.

Nisbet and Pearce (1977) have suggested that fresh pyroxene compositions in altered basic rocks may offer scope for identification of the magma type of the host lava. A plot of Nisbet and Pearce's discriminant functions F_1 against F_2 (Fig. 33d) shows that all the analyses lie in the field of ocean-floor basalts plus volcanic-arc basalts. In a triangular plot of TiO_2–MnO–Na_2O (Fig. 33c), two analyses plot in the ocean-floor basalt field, while the other three are scattered towards the Na_2O corner, suggesting that the analyses are partly influenced by the sodic rims of the phenocrysts.

It is interesting to note that the pyroxene analyses from pillow lavas of the Trinity Peninsula Group in northern Graham Land lie mostly in the field of within-plate alkali basalts on the F_1/F_2 plot (Hyden and Tanner, 1981), implying a different magma type to that of the LeMay Group lavas. Hyden and Tanner noted similarities between their analyses and those from fracture zones and suggested that the lavas in the Trinity Peninsula Group originated at a fracture zone in an oceanic plate.

D. ORIGIN OF THE VOLCANIC ROCKS AND GREENSTONES

It has been suggested that the tuffaceous sandstones in southern Alexander Island were products of contemporaneous volcanism, which also accounted for the extrusion of the pillow lavas with which they are associated (Bell, 1973*b*). However, there are important compositional and textural differences between the volcanic content of the volcaniclastic sandstones in both northern and southern Alexander Island, and the pillow lavas:

i. Volcanic clasts in the sandstones represent andesitic to rhyolitic debris, whereas the pillow lavas are basalts.
ii. The volcanic lithic fragments in the sediments typically have a glassy or trachytic texture and are often porphyritic. By contrast the pillow lavas contain non-orientated plagioclase laths with intergranular pyroxene, and glomerophenocrysts which display subophitic texture.

Furthermore, volcaniclastic sediments occur without associated pillow lavas on Rothschild Island and Debussy Heights, while pillow lavas may occur within arkosic arenites deficient in volcanogenic material (e.g. in south-west Elgar Uplands). Pyroclastic material (e.g. shards or pumice) is not found in the volcaniclastic rocks of northern and southern Alexander Island. It is therefore probable that the volcanic content of the sediments was derived from a source which was different from that responsible for the extrusion of the pillow lavas and was epiclastic in origin. As discussed on p. 24, erosion of a volcanic arc is likely to have supplied much of the volcanic material in the sandstones.

The volcanic and metabasic lithologies within the LeMay Group have been referred to as 'non-sequence type' ophiolites (Edwards, 1982). This terminology was used by Miyashiro (1973*a*) to describe occurrences of pillow lava and pyroclastic rocks that are usually associated with serpentinite bodies and blueschist metamorphism, contained within highly deformed clastic sequences. Such assemblages have been interpreted as slivers of oceanic crust, tectonically emplaced during subduction (e.g. Karig and Sharman, 1975), although the thinness of some of the lava units in such situations and the paucity of ultrabasic rocks have been taken as evidence against an allochthonous origin. In northern Alexander Island, the intense cataclastic deformation of parts of the lava units and the rocks marginal to them, the apparent absence of feeder dykes and the incorporation of greenstones in (?) tectonic mélange certainly advocate an origin by tectonic emplacement in a subduction complex. It follows that there is a strong possibility that these rocks represent oceanic crust, and the limited amount of geochemical data available are compatible with such an interpretation. Although the lavas in northern Alexander Island crop out within a zone at least 10 km long, they do not necessarily constitute a single sheet, but may consist of several tabular bodies associated with a zone of thrusting. No ultrabasic rocks are known from the LeMay Group. This could perhaps be explained by accretion being restricted to thin slivers of layer two of the oceanic crust. Despite evidence for an oceanic derivation, the possibility of extrusion *in situ* during sedimentation followed by subsequent deformation within the trench fill cannot entirely be dismissed, although the author knows of no modern examples of submarine lavas amongst deep sea fan or trench sediments.

The volcanic rocks of the Lully Foothills Formation appear to have somewhat different setting from those described above, in that they are clearly intercalated with shallow water sediments and tuffs, and are apparently not associated with extreme cataclasis. Such an environment accords well with an origin in a fore-arc basin, possibly floored by part of the subduction complex (p. 57).

V. METAMORPHISM

The rocks of the LeMay Group have undergone regional low- and very low-grade metamorphism broadly coeval with folding and the intermittent development of a tectonic fabric. In northern Alexander Island, a north-eastward increase in metamorphism is recognized in the metasediments from zeolite and prehnite-pumpellyite facies sandstones, through pumpellyite-actinolite facies semischists, to muscovite-garnet schists of low greenschist facies. Some metabasic rocks in central Alexander Island contain blueschist facies mineral assemblages.

A. TEXTURAL ZONATION

Variations in the degree of deformation and recrystallization in the low grade metasedimentary rocks of the LeMay Group can be denoted using a scheme similar to that

FIGURE 34
Typical prehnite-pumpellyite facies arkosic arenite of textural zone 1, with abundant prehnite derived from alteration of detrital plagioclase (KG.2175; X-nicols; ×90).

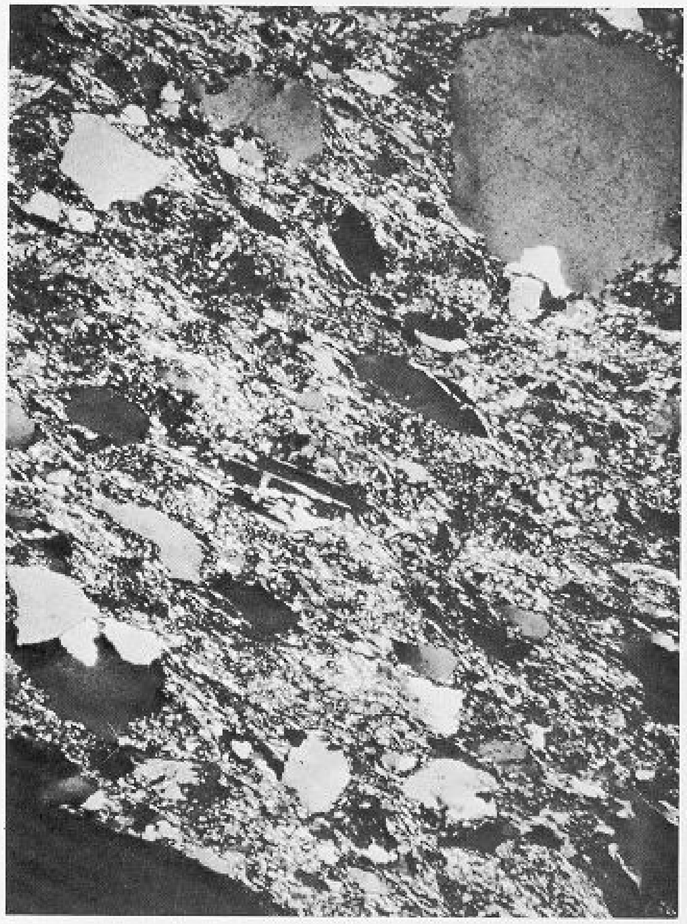


FIGURE 35
Pumpellyite-actinolite facies semischist of textural zone 2, showing flattening of detrital quartz grains and development of a finely recrystallized matrix largely of aligned white mica and actinolite (KG.2094.1; X-nicols; ×38).

introduced by Turner (1935) and Hutton and Turner (1936) for mapping textural subzones (chlorite 1 to chlorite 4) in the chlorite zone of the New Zealand Geosyncline. The four textural zones mapped in the LeMay Group are outlined below. They are virtually identical to Hutton and Turner's chlorite zones except that the initial rock in the case of the LeMay Group was a moderate to poorly sorted arenite, not a greywacke.

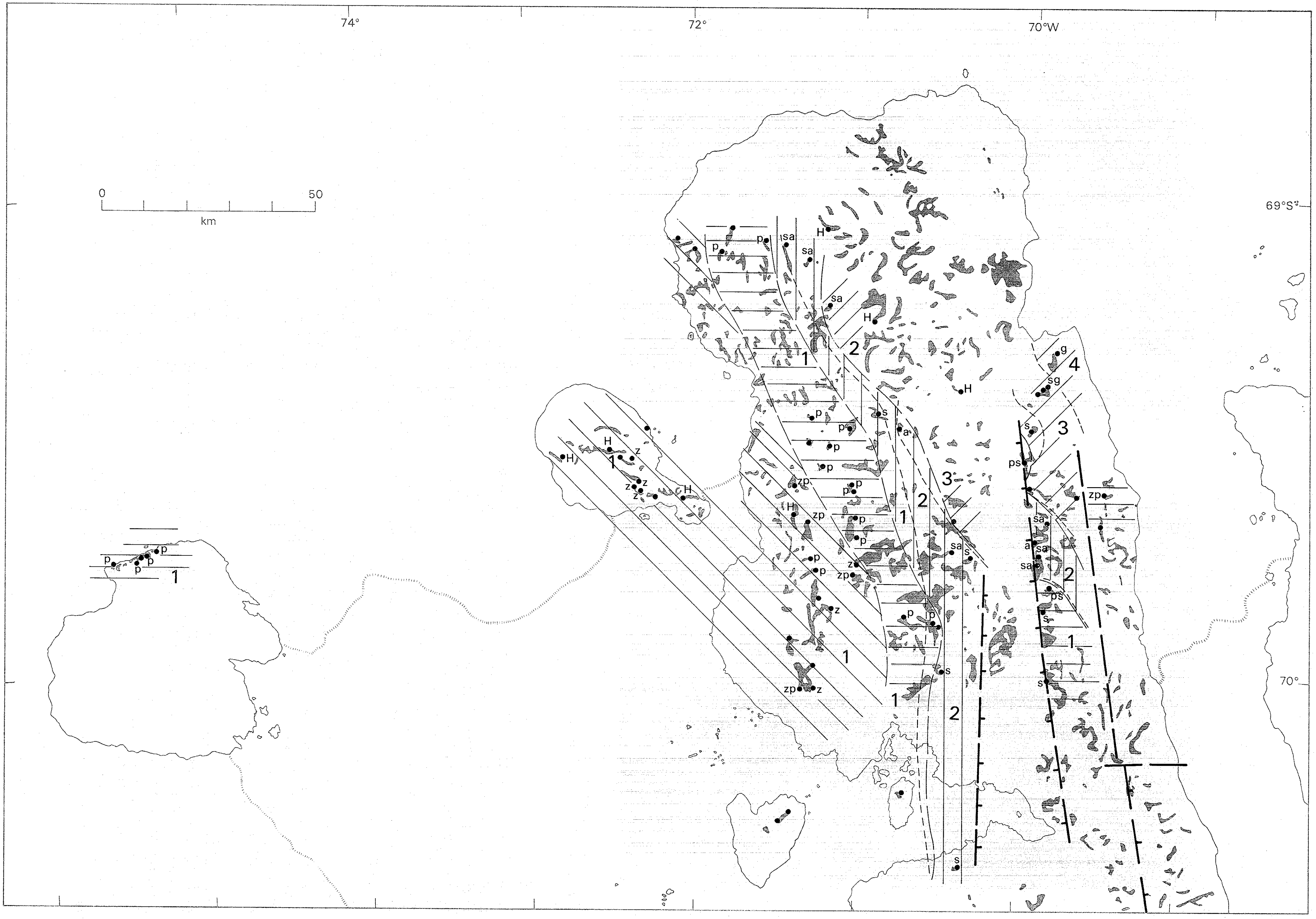
Textural zone 1. Sandstones retain their initial texture (Fig. 34) except for slight cataclasis of quartz and feldspar grains, and bending of mica flakes. The rocks are commonly veined irregularly with quartz, calcite and prehnite. Slaty cleavage begins to appear in pelites.

Textural zone 2. Quartz and feldspar become extensively recrystallized and flattened. Recrystallization and alignment of fine-grained alteration products after feldspar and certain rock fragments give rise to a foliated matrix. These rocks are foliated sandstones or semischists.

Specimen KG.2094.1 (Fig. 35) is a typical pumpellyite-actinolite facies semischist from this zone. It consists of detrital quartz, plagioclase (not albitized), muscovite, sphene and various rock fragments, in a finely recrystallized (<0.2 mm) groundmass of quartz, white mica, pumpellyite and actinolite. No segregation laminae are present, but flattening of detrital quartz and alignment of mica and amphibole in the matrix result in a strong planar fabric.

Textural zone 3. Sandstones have been converted to completely recrystallized, fine-grained, well-foliated schists, with only a few persisting relict clastic grains. Some rocks show incipient segregation of quartz and albite into lenses and laminae parallel to the foliation. A crenulation cleavage is commonly developed parallel to axial planes of mesoscopic folds and a lineation may be present parallel to their axes in the form of corrugations in foliation surfaces, or grain elongation.

Specimen KG.2070.2 (Fig. 36) is a greenschist facies quartz-muscovite schist of textural zone 3. Discontinuous segregation laminae up to 3 mm thick consist of a 0.02–0.2-mm mosaic of strained quartz and albite. Grain margins are mostly sutured, but some are partly polygonized. A few relict clastic grains of quartz, albitized plagioclase, muscovite, sphene and allanite remain. Alignment of muscovite flakes up to 0.3 mm long and minor amounts of chlorite define a strong foliation.



74°
72°
70°W
69°S
70°
0
50
km
1
2
3
4
p
sa
H
s
a
z
zp
ps
sg
g

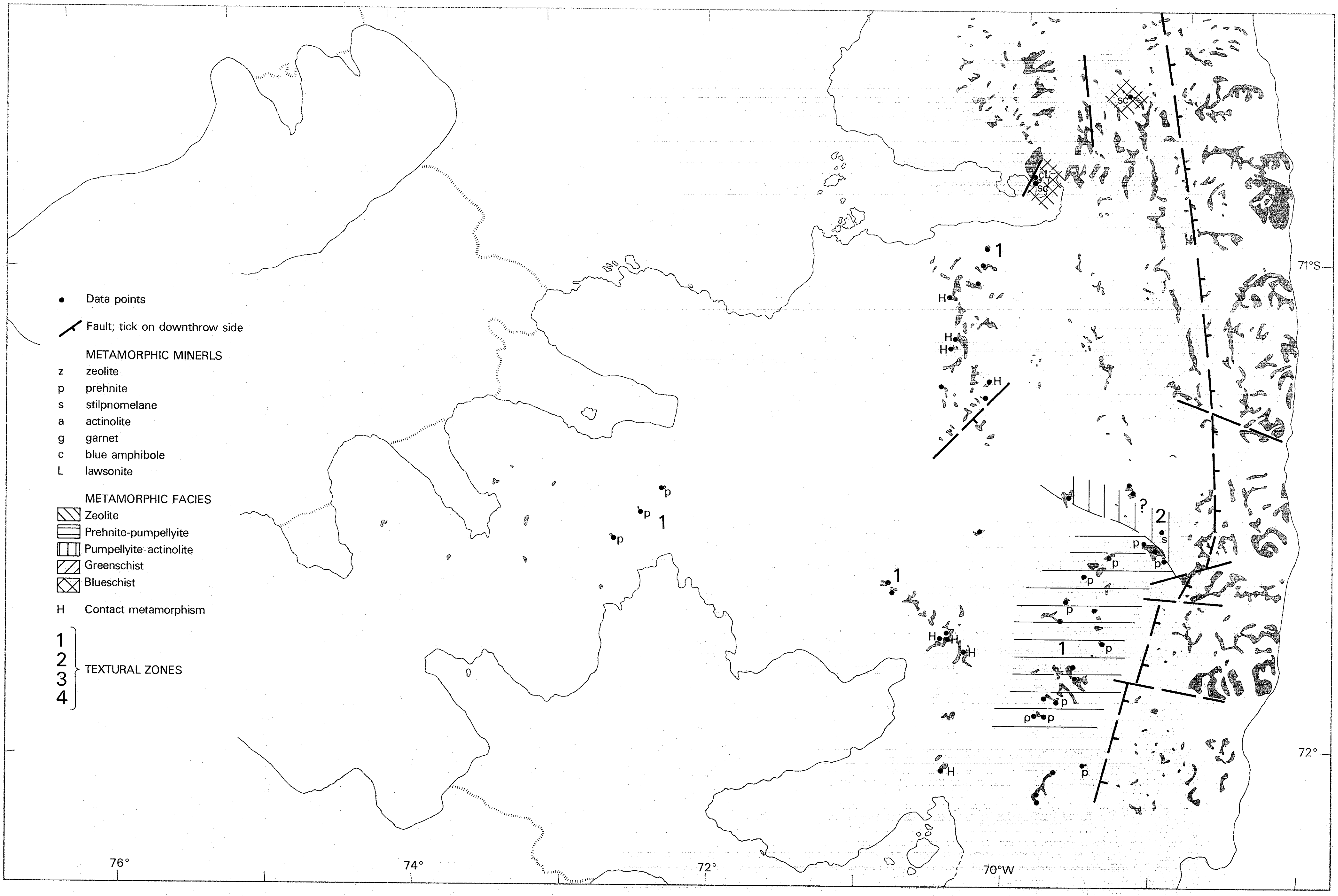


FIGURE 38a and b
Maps showing distribution of textural zones and metamorphic facies within the LeMay Group.

FIGURE 36
Greenschist facies quartz muscovite schist of textural zone 3 containing a few relict detrital quartz and albitized plagioclase. The strongly foliated groundmass which includes quartz, muscovite and chlorite, shows F_4 microfolds (KG.2070. 2; X-nicols; ×33.

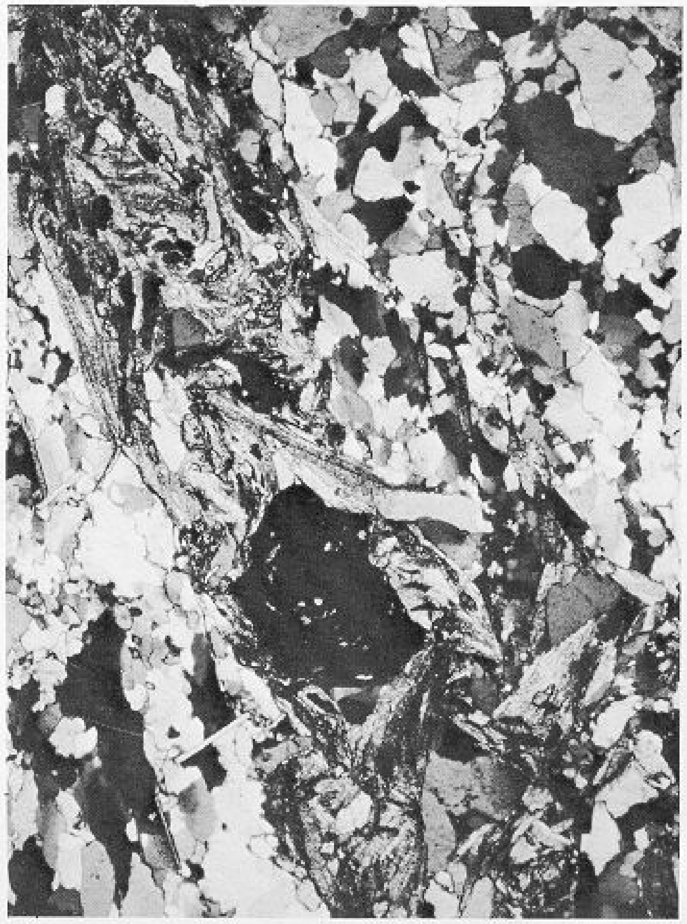


FIGURE 37
Greenschist facies quartz-muscovite-garnet schist of textural zone 4. The rock consists of micaceous layers of muscovite, chlorite and occasional garnets (left centre) alternating with quartz-albite segregations (KG.1977.4; X-nicols, ×46).

Textural zone 4. Sandstones have been fully reconstituted to coarse-grained foliated and lineated schists, with segregation laminae of quartz and albite up to 8 mm thick, parallel to the main foliation. No trace of original sedimentary texture remains.

Specimen KG.1977.4 (Fig. 37) is a typical greenschist facies quartz-muscovite schist from textural zone 4. Quartz-albite segregations are well developed and are up to 4 mm thick; they consist of an irregular mosaic of 0.1–0.5-mm sutured quartz and clear untwinned albite. Quartz grains tend to be flattened parallel to the foliation. Between the quartzose layers are micaceous layers up to 3 mm thick consisting chiefly of coarse aligned muscovite flakes up to 0.7 mm long with subsidiary chlorite, prisms of colourless epidote, sphene and occasional garnet porphyroblasts up to 0.7 mm.

The distribution of textural zones is shown in Fig. 38. Lines between zones are isotects joining places with equal development of tectonic fabric. They reflect degree of deformation and recrystallization; they are distinct from isograds, although in northern Alexander Island the two are broadly parallel.

B. MINERALOGICAL ZONING AND METAMORPHIC FACIES

1. *Metasedimentary rocks*

In the LeMay Group, sandstones are the most suitable lithology for the study of variations in metamorphism, owing to their widespread occurrence and reasonably uniform composition. In addition, work by numerous authors on low-grade metamorphism in many parts of the world has demonstrated that arkosic sandstones are responsive to metamorphic changes and often contain diagnostic assemblages.

Isograds for the LeMay Group may be drawn on the basis of presence or absence of certain key minerals (Fig. 38). These isograds are: zeolite-out, prehnite-out, pumpellyite-out. It is now widely accepted that these isograds delineate four facies of low grade metamorphism in 'greywackes':

i. the zeolite facies,
ii. the prehnite-pumpellyite facies,
iii. the pumpellyite-actinolite facies,
iv. the base of the greenschist facies.

All of these have been recognized in the LeMay Group of Alexander Island.

The *zeolite facies* was redefined by Coombs and others (1959) 'to include at least all those assemblages produced under physical conditions in which the following are commonly formed: quartz-analcime, quartz-heulandite, quartz-laumontite'. This definition embraces products of diagenesis and hydrothermal activity as well as metamorphism.

Zeolite-bearing rocks are not common in the LeMay Group of Alexander Island, and are restricted to south-west Elgar Uplands, Debussy Heights and eastern Toynbee Glacier (Fig. 38). This rarity of zeolites possibly reflects unsuitability of composition (? lack of volcanic glass) of the host sandstones. It is noteworthy that Boles and Coombs (1977) pointed out that even in the classic zeolite facies terrain of the Southland syncline, New Zealand, zeolites are absent from more than 25% of sandstones and are rare in siltstones.

Fine-grained white mica and sphene are present in most thin sections studied. Vein minerals are calcite, chlorite, prehnite, analcime, other zeolites and albite. Prehnite and pumpellyite are not common and it should be noted that although these minerals occur more frequently in the prehnite-pumpellyite facies, their presence alone is not indicative of that facies (Boles and Coombs, 1977).

The prehnite-pumpellyite facies was originally defined by Coombs (1960) who recognized two subzones: a quartz-prehnite zone in which combinations of quartz, albite, prehnite, pumpellyite, calcite, sphene, orthoclase and muscovite occur and a higher grade prehnite-free subzone in which stilpnomelane and actinolite appeared. Hashimoto (1966) restricted the definition of the prehnite-pumpellyite (schist) facies to Coombs' quartz-prehnite zone and erected a new pumpellyite-actinolite facies corresponding to the upper prehnite-free zone. Hashimoto's restricted definition of the prehnite-pumpellyite facies is used in this report.

Assemblages of coexisting minerals and their frequency of occurrence are shown in Table VII. Vein minerals are calcite, chlorite, prehnite, albite and rarely epidote and pumpellyite. Stilpnomelane and actinolite are present in a few thin sections, rarely in assemblages with prehnite. Albite grains of clearly metamorphic origin are rare, and detrital plagioclase of oligoclase-andesine composition is abundant.

The criteria for recognition of the *pumpellyite-actinolite* facies are the absence of prehnite from greywacke assemblages containing quartz, albite, sericite, chlorite, sphene, actinolite, stilpnomelane and epidote (Hashimoto, 1966; Bishop, 1972). Mineral assemblages in LeMay Formation metasandstones are shown in Table VII.

Despite its common occurrence in rocks of the prehnite-pumpellyite facies, detrital potash feldspar is rare in the pumpellyite-actinolite facies in Alexander Island. This supports the view of Bishop (1972) that potash feldspar breaks down low in the pumpellyite-actinolite facies. Vein minerals recorded are calcite, quartz and epidote.

The onset of the *greenschist facies* is marked by the disappearance of pumpellyite (and lawsonite) (Coombs, 1960), and by the appearance of colourless iron-poor epidote or clinozoisite and the abundance of actinolite in meta-greywackes (Bishop, 1972). Assemblages in LeMay Group metasedimentary rocks are shown in Table VII. Stilpnomelane and actinolite are present in some rocks, but the dominant assemblage is chlorite-epidote. Coloured and colourless epidote are apparently equally abundant. Garnet occurs sporadically in northern Douglas Range. Appearance of garnet without biotite is slightly unusual, and in parts of the Sanbagawa metamorphic belt of Japan it has been attributed to relatively high pressure (Ernst and others, 1970).

2. *Lavas and greenstones*

The distribution of metabasic rocks is too restricted to enable recognition of any mineralogical zoning within this

TABLE VII

Occurrence of selected mineral assemblages in LeMay Group metasandstones from northern Alexander Island
(ep = epidote, ac = actinolite, pr = prehnite, pu = pumpellyite, st = stilpnomelane, gn = garnet, z = zeolite, an = analcime)

Greenschist facies		*Pumpellyite-actinolite facies*		*Prehnite-pumpellyite facies*		*Zeolite facies*	
Assemblage	*Frequency*	*Assemblage*	*Frequency*	*Assemblage*	*Frequency*	*Assemblage*	*Frequency*
ep	4	ep–st–ac–pu	3	ep–pr–pu	10	ep	12
ep–gn	2	ep–st–pu	2	ep–pr	8	ep–an–pr	3
ep–st–gn	1	ep–st–ac	2	ep	4	ep–an–z	3
ep–st–ac	1	ep–ac	2	ac–pr	2	ep–pr	3
ep–ac	1	ep	2	ep–st	2	ep–z	1
ep–st	1	st–ac–pu	1	ep–st–pr–pu	1	z–pr–pu	1
st	1	ep–st	1	ep–st–pu	1	ep–pu	1
		st–ac	1	ep–st–pr	1		
		ac	1	ep–ac–pr	1		
				ep–pu	1		
				st–pu	1		
No. of thin sections	11		15		32		24
Albite, quartz, muscovite and sphene are usually present.		Chlorite, muscovite and sphene are usually present. Other minerals include calcite and albite.		Chlorite, muscovite and sphene are usually present. Other minerals include calcite and albite.		Chlorite, muscovite and sphene are usually present. Other minerals include calcite and albite.	

lithology. In northern Alexander Island, most of the lavas are associated with zeolite facies sandstones. However, zeolites are rare in the lavas and occur only as vein minerals (e.g. specimen KG.2212.15). The most abundant secondary minerals are chlorite, sericite (in plagioclase), calcite, sphene and pyrite. Veins of chlorite, pyrite, albite, quartz and calcite are common. The metabasic rocks in southern Alexander Island occur within the area of prehnite-pumpellyite metamorphism in sandstones. Pumpellyite and prehnite are much less common than in the sandstones, the most frequent alteration minerals being chlorite, sericite and epidote. The existence of plagioclase as calcic as An_{35} indicates incomplete albitization, although albite does occur in veins. Other vein minerals include epidote, chlorite, calcite, pumpellyite (rare) and garnet (rare, specimen KG.1381.2).

The most interesting metabasic rocks from a metamorphic point of view are the weakly foliated blue amphibole-bearing greenstones in central Alexander Island, first described by Edwards (1980*c* and 1982). Assemblages that include high pressure minerals are:

i. Blue amphibole-pumpellyite-epidote-chlorite-stilpnomelane-white mica-sphene-aegerine augite/sodic augite (specimen KG.2476.1).
ii. Blue amphibole-pumpellyite-epidote-chlorite-sphene-aegerine augite/sodic augite (specimen KG.2477.1).
iii. Blue amphibole-pumpellyite-epidote-white mica sphene-stilpnomelane (specimen KG.1872.5).
iv. Lawsonite-pumpellyite-epidote-chlorite-white mica albite (specimen KG.2477.3).

These assemblages may be placed within the blueschist facies of Bailey, Irwin and Jones (1964) which is virtually synonymous with the glaucophane-lawsonite schist facies of Winkler (1965). The presence of lawsonite is critical in both cases. Blue amphibole alone is not diagnostic and can occur in facies transitional to the greenschist facies. The absence of jadeite indicates that the albite $\rightleftharpoons$ jadeite + quartz breakdown temperature was not exceeded during recrystallization.

3. *Distribution of metamorphic facies*

Fig. 38 shows the distribution of metamorphic facies in the LeMay Group. In northern Alexander Island a clearly defined north-eastward increase in metamorphism exists, from zeolite-bearing sandstones around Gilbert Glacier, through prehnite-pumpellyite and pumpellyite-actinolite facies to greenschist facies rocks in northern Douglas Range. A corresponding increase in textural reconstitution takes place across the area. Most zeolite and prehnite-pumpellyite facies rocks lie in textural zone 1, most pumpellyite-actinolite facies rocks are textural zone 2 semischists, whereas well-crystallized lineated schists are characteristic of the greenschist facies. Anomalies occur at the peripheries of the area: zeolite-bearing rocks of textural zone 1 crop out on the eastern side of Toynbee Glacier (specimen KG.1965.1) and prehnite-pumpellyite facies rocks occur on Charcot Island. Volcaniclastic rocks cropping out on the north-eastern coast of Alexander Island appear to be of prehnite-pumpellyite facies (p. 29).

Garnet bearing quartz-muscovite schists from detritus in ice cliffs north of Schokalsky Bay (station E.209) on the north-east coast of the island were interpreted by Adie (1954) as possible evidence for early Palaeozoic or Precambrian crystalline basement on Alexander Island. However, from his description, these rocks appear to be very similar to textural zone 4 greenschist facies rocks in the northern Douglas Range, and it is likely that they are derived from LeMay Group metasedimentary rocks of greenschist facies underlying parts of the Roberts Ice Piedmont.

A less well defined north-eastward increase in metamorphism appears to be present in the metasedimentary rocks of southern Alexander Island, most of which are characterized by prehnite-pumpellyite facies assemblages. In the southern nunataks, lack of prehnite and pumpellyite, together with minimal recrystallization suggests that the zeolite facies has not been exceeded, whereas near Titania Peak, sporadic occurrences of stilpnomelane and textural zone 2 semischists (Fig. 38) probably indicate a higher metamorphic grade. Sandstones near Mount Umbriel, a little further north-east lack prehnite and pumpellyite and show minimal recrystallization, features which suggest again that the zeolite facies has not been exceeded. It is possible that some of these abrupt changes in metamorphism can be attributed to late Cenozoic block faulting which may have juxtaposed rocks from different structural levels.

Much of central Alexander Island has undergone low greenschist facies regional metamorphism (Edwards, 1980*c*) but in the Walton Mountains the effects of low-grade regional metamorphism and contact metamorphism could not be distinguished with confidence. The occurrence of blue amphibole, associated with purple and green schists marks a restricted zone of high-pressure metamorphism along eastern Lully Foothills and western LeMay Range. The blueschist facies rocks of the southern Colbert Mountains are separated from this zone by the much less deformed and metamorphosed volcanogenic rocks of the Lully Foothills. At present it is not possible to ascertain whether these two areas represent parts of the same high-pressure metamorphic belt whose outcrops at the surface are separated by less metamorphosed rocks, or two separate narrow belts of high-pressure metamorphism in central Alexander Island.

C. CONDITIONS OF METAMORPHISM

1. *Metamorphic facies series*

Mineralogical changes in LeMay Group metasedimentary rocks reveal a facies series through zeolite, prehnite-pumpellyite, prehnite-actinolite facies to the garnet-zone of the greenschist facies. It is not clear how the local occurrences of blueschist facies rocks fit into this sequence. A similar facies series is present in the late Palaeozoic–Mesozoic New Zealand geosyncline (Bishop, 1972; Landis and Bishop, 1972) and comparable series lacking high pressure minerals have been described from the Palaeozoic Appalachian Belt of northern Maine (Coombs and others, 1970), the late Palaeozoic Nambucca slate belt of New South Wales, Australia (Leitch, 1975) and the late Palaeozoic–Mesozoic Sanbagawa belt of Japan (Seki and others, 1971). A transition from pumpellyite-actinolite facies to jadeite-bearing blueschist facies rocks is described by Watanabe (1974) from the Sanbagawa belt of Japan.

The pumpellyite-actinolite facies appears to be suppressed in low-pressure/high-temperature facies series where both prehnite and pumpellyite disappear together near to where actinolite first appears (Coombs and others, 1970). Several authors show the pumpellyite-actinolite facies field on pressure/temperature grids intervening between the prehnite-pumpellyite facies and higher temperature greenschist and higher pressure blueschist facies (Seki, 1969; Coombs, 1971; Liou, 1971). Comparisons of LeMay Group mineralogy and metamorphic facies with similar terrains in Japan and New Zealand and crossite-bearing rocks of the South Shetlands Islands are shown in Table VIII.

The Sanbagawa belt at Kii Peninsula shows a progressive increase through zeolite, prehnite-pumpellyite, pumpellyite-actinolite to greenschist facies away from the Pacific coast of Japan (Seki and others, 1971). Although metasedimentary rocks do not display conspicuous mineralogical zoning, the metabasic rocks have parageneses similar to those of the LeMay Group metasediments. Ernst and others (1970) observed progressive metamorphic zones within the Sanbagawa belt in the Shirataki and Oboke districts, where lawsonite and blue amphibole occur. The increase in development of foliation in metasedimentary rocks through zones I′, I, II and III, matched by the appearance of first epidote, then garnet (without biotite) is similar to that seen in the LeMay Group. Pumpellyite and actinolite were not recorded in metasedimentary rocks from that part of the Sanbagawa terrain. The massive or weakly foliated metabasic rocks of zones I′ and I resemble blueschist facies rocks from Alexander Island in that they contain pumpellyite, stilpnomelane, blue amphibole and relict augite. Ernst and others (1970) concluded that the assemblages crossite-chlorite-epidote/pumpellyite in the Sanbagawa metabasic rocks was indicative

TABLE VIII
Comparison of metamorphic mineral assemblages in LeMay Group rocks with those in similar low grade metamorphic terrains

	Alexander Island LeMay Group				New Zealand Torlesse Terrain, Otago (Bishop, 1972)			Japan: Sanbagawa Belt, Kii Peninsula (Seki and others, 1971)				Japan: Sanbagawa Belt, Oboke District (Ernst and others, 1970)			South Shetland Islands Smith and Barlow islands (Clarkson and Smellie, 1975)
Metasediments															
Minerals / *Facies/zones*	Z	P–P	P–A	G	P–P	P–A	G	Z	P–P	P–A	G	I′	I	II	
quartz	—	—	—	—	—	—	—	—	—	—	—	—	—	—	
albite	- -	- -	—	—	—	—	—	—	—	—	—	—	—	—	
prehnite		- —			—										
pumpellyite		- -	- -		—	—									
epidote	- -	- -	- -	- -	- -	- -	—						- -	- -	
Ca amphibole			- -	- -		- -	- -								
Na amphibole												- -			
chlorite	- -	- -	- -	- -	—	—	—	—	—	—	—	—	—	—	
white mica	- -	- -	- -	- -	—	—	—	—	—	—	—	—	—	—	
stilpnomelane		- -	- -	- -	- -	- —				- -	- -	—	—	—	
sphene	- -	- -	- -	- —	—	—						—	—	—	
analcime	- -														
zeolite	- -														
garnet				- -										- -	

	Alexander Island LeMay Group			Japan: Sanbagawa Belt, Kii Peninsula (Seki and others, 1971)				Japan: Sanbagawa Belt, Oboke District (Ernst and others, 1970)			South Shetland Islands Smith and Barlow islands (Clarkson and Smellie, 1975)
Metabasic rocks											
Minerals / *Facies/zones*	Z	P–P	B	Z	P–P	P–A	G	I′	I	II	? transitional between G and B
quartz	- -	- -	- -	—	—	—	—	- -	- -	- -	- -
albite	- -	- -	- -	—	—	—	—	—	—	—	- -
prehnite		- -			—						
pumpellyite		- —	—		—	—		—	- -		
epidote		- -	- —		—	—	—		- —	—	- -
lawsonite			- -					- -			
Ca amphibole			- -			—	—		—	—	
Na amphibole			- -					- -	- -	- -	- -
chlorite	- -	—	—	—	—	—	—	—	—	—	- -
white mica	- -	- -	- -	- -	—	—	—	- -	- -	- -	
stilpnomelane			- -		- -	- -	—	- -	- -	- -	- -
sphene	- -	—	—					—	—	—	- -
analcime											
zeolite	- -			—							
garnet										- -	- -

Abbreviations: Z zeolite facies.
P–P prehnite-pumpellyite facies.
P–A pumpellyite-actinolite facies.
G greenschist facies.
B blueschist facies.

of metamorphism under a lower pressure/temperature regime than terrains such as the Franciscan Complex of California in which blueschist facies metabasic rocks are characterized by glaucophane/crossite-lawsonite-pumpellyite, and metagreywackes contain jadeite-quartz. The local development of high-pressure minerals and increase in the metamorphism of the Sanbagawa belt away from the Pacific Ocean is interpreted as the result of northward subduction of Pacific Ocean crust.

A progressive increase from prehnite-pumpellyite through pumpellyite-actinolite to greenschist facies is present in the Torlesse terrain of the New Zealand geosyncline (Table VIII) (Bishop, 1972), where mineralogical changes in metagreywackes are closely paralleled by those in metasandstones of the LeMay Group. Lawsonite and blue amphibole are restricted to narrow belts on each side of the tectonic contact which separates the Torlesse from broadly contemporaneous volcaniclastic rocks to the south and west. This intermediate to high facies series has been attributed to subduction of the Torlesse beneath a volcanic arc to the west (Landis and Bishop, 1972).

Well-foliated blue amphibole-bearing rocks are present on Smith Island and Barlow Island, South Shetland Islands (Smellie and Clarkson, 1975; Rivano and Cortes, 1976). Those rocks are more coarsely recrystallized than equivalents in the LeMay Group, and they are richer in blue amphibole, which microprobe analysis indicates is riebeckitic (personal communication from G. Hyden). Coexistence of epidote and garnet with blue amphibole was taken by Smellie and Clarkson to indicate conditions transitional to blueschist and greenschist facies. They suggest that blue amphibole-bearing rocks in dredged samples collected near Clarence Island originated within the South Shetland Islands, and that Elephant Island, on which blueschists also occur (Dalziel, 1976), and the serpentinite-dunite on Gibbs Island (de Wit, 1977) may be parts of the same belt of relatively high-pressure metamorphism.

The low grade metamorphism in the LeMay Group appears to be of an intermediate to high-pressure type and generally increasing towards the north-east or east. The small areal extent of blueschist facies rocks and absence of widespread assemblages containing jadeite-quartz, are thought to indicate metamorphism under lower pressures and higher temperatures than the more typical blueschist terrains such as the Franciscan Complex of California.

2. *Paired metamorphic belts*

Smellie and Clarkson (1975) contrasted the physical conditions of the metamorphism undergone by the rocks of metamorphic basement of the South Shetland Islands, and possibly also the South Orkney Islands with the relatively low-pressure, high-temperature metamorphism of the Antarctic Peninsula metamorphic complex. They postulated the existence of a Ryoke-Abukuma/Sanbagawa type paired belt in Lesser Antarctica resulting from eastward subduction of ocean crust beneath a continental margin or island arc situated along the present day Antarctic Peninsula.

Discovery of blue amphibole on Alexander Island (Edwards, 1980*c* and 1982) substantiated the view put forward by Suárez (1976) that the rocks of the LeMay Group were accreted during eastward subduction beneath Palmer Land and that the metamorphic complex thereon represents the roots of the coeval volcanic arc. The confirmation of blueschist facies metamorphism, and the wide extent of intermediate to high-pressure metamorphism on Alexander Island now provide strong evidence for presence of a paired metamorphic belt on Alexander Island and Palmer Land, probably an extension of the one recognized further north in Graham Land and the South Shetland Islands. The Antarctic Peninsula metamorphic complex crops out widely on Palmer Land and southern Graham Land opposite Alexander Island, and consists largely of orthogneisses, with subsidiary paragneisses, and also includes migmatites, amphibolites, quartz-mica-garnet schists and quartz-mica schists (Rowe, 1973; Skinner, 1973; Davies, 1976; Ankorn, 1977; Singleton, 1980; Smith, 1977). Most of the gneisses are thought to have been metamorphosed at least to amphibolite facies. Several authors have noted features in common with the Ryoke-Abukuma high-temperature, low-pressure metamorphic belt of Japan, notably the presence of cummingtonite and high-anorthite plagioclase, the absence of epidote and garnet (Smith, 1977) and the lack of almandine garnet in some metabasic rocks (Ankorn, 1977).

The timing of deformation in the LeMay Group (at least in the Lully Foothills area) is restricted by palaeontological/stratigraphical considerations to post-middle to late Triassic and pre-late Jurassic (p. 7) (Edwards, 1982). No reliable radiometric dates have so far been obtained for the metamorphism of the crossite schists in the South Shetland Islands, but a late Triassic (197 Ma) age given by a five point Rb-Sr isochron from the Miers Bluff Formation (a possible correlative of the LeMay Group on Livingston Island) is thought to indicate the time of deformation or diagenesis (Dalziel, 1972). K-Ar mica ages from schists in the South Orkney islands range between 177 and 189 [181–193] Ma, although a Rb-Sr isochron gave an age of 289 [280] Ma (Rex, 1976) and may indicate an earlier event. Gneisses from Marguerite Bay have yielded a two point Rb-Sr whole-rock isochron age of 200 [207] Ma (Halpern, 1972) and a six point Rb-Sr whole-rock isochron gave 175 [171] Ma (Gledhill and others, in press). K-Ar dating of hornblendes from gneisses near Jason Peninsula, eastern Graham Land, gave ages of 243 [248] Ma and 237 [242] Ma (Rex, 1976). These rather sparse geochronological data appear to indicate that metamorphism of the two parts of the postulated paired belt in the Antarctic Peninsula area was broadly contemporaneous, and took place during a late Triassic to early Jurassic 'Gondwanian' event (p. 43) although the older dates from eastern Graham Land and the South Orkney Islands have been interpreted as evidence for an earlier event (Gledhill and others, 1982).

In other parts of the world, the two parts of paired metamorphic belts are typically separated by a major tectonic dislocation, along which the high-pressure part has been uplifted (e.g. Miyashiro, 1972). It has been suggested (Smellie and Clarkson, 1975) that such a feature may be present along the south side of the South Orkney Islands platform, or in Bransfield Strait, although Dalziel (1982) discussed evidence for such a major tectonic break separating the blueschist facies rocks of northern Elephant Island from low greenschist and (?) amphibolite facies rocks on the remainder of Elephant Island and Clarence Island. The most likely location of such a feature between Alexander Island and Palmer Land is George VI Sound, the size, depth and linearity of which over 300 km strongly implies that major faulting played an important role during its formation (p. 53).

The presence of acid and intermediate plutons intruding the LeMay Group on Alexander Island is apparently anomalous in that such activity is normally restricted to the low-pressure parts of paired metamorphic belts (Miyashiro, 1973*a*). This anomaly is likely to be the result of an early Tertiary westward migration of the volcanic arc which was situated on Palmer Land during the Mesozoic (Suárez, 1976; Burn, 1981).

D. Contact Metamorphism

The acid and intermediate plutonic rocks which intrude the LeMay Group are surrounded by narrow contact metamorphic aureoles with widths of the order of 0.5 km. An estimate of 10 km for the width of the aureole of the Rouen Mountains batholith (Bell, 1974) is probably excessive and arises from a different interpretation of the relative importance of contact and regional metamorphism. Albite-epidote hornfels facies contact metamorphism has been described from the aureoles of plutons at Staccato Peaks (Bell, 1973*b*), Rouen Mountains (Bell, 1974; Care, in press) and Rothschild Island (Care, 1980).

Hornfelses adjacent to the predominantly dioritic intrusions of Staccato Peaks, and the granodiorite of Rothschild Island lack foliation. Assemblages of contact metamorphic minerals include albite, epidote, tourmaline, chlorite, amphibole (in southern Alexander Island only), sphene, biotite, and muscovite. Mildly hornfelsed sediments contain relict detrital plagioclase, potash feldspar, zircon and biotite in a fine-grained recrystallized matrix of 0.01–0.05 mm sutured quartz and albite grains, commonly with finely divided biotite and amphibole (e.g. specimens KG.1312.2 and KG.1321.1). More highly recrystallized rocks (e.g. specimens KG.1326.1, 2 and KG.1335.2) consist of a granoblastic mosaic of 0.05–0.02 mm unstrained quartz and albite with biotite flakes up to 0.7 mm long, chlorite, and sometimes tourmaline. In specimen KG.1310.2 tourmaline occurs in a thin vein accompanied by cassiterite. On Rothschild Island hornfelsed pelites contain spots consisting of a central area of sphene and epidote surrounded by a sericite-rich selvage.

The aureole of the Rouen Mountains batholith (tonalite-granite) differs from that of other plutons in that compositional and mineral fabrics are almost ubiquitous. In western Rouen Mountains the rocks have a thinly banded appearance in hand specimens consisting of alternating quartzose and micaceous layers. They usually display a good mica fabric and sometimes a lineation parallel to minor fold axes (p. 46). The quartzose layers are 1–8 mm thick and consist of 0.03–0.5 mm granoblastic quartz (unstrained), albite and tiny randomly oriented chlorite flakes. Most quartz shows polygonized grain boundaries, although some sutured boundaries are present. The micaceous layers consist chiefly of fine-grained muscovite and occasionally biotite, with scattered granules of epidote and sphene. Relict detrital grains include strained quartz, plagioclase (oligoclase), potash feldspar and allanite. A more highly recrystallized rock from the north-western Rouen Mountains (specimen KG.2289.6) consists of layers of coarse unstrained polygonized quartz up to 1 mm across and large randomly oriented flakes of penninitic chlorite, alternating with a granular intergrowth of 0.05-mm quartz, albitized plagioclase, orthoclase and chlorite. Other minerals include epidote, sphene and calcite.

The foliated hornfelses of Rouen Mountains resemble regional textural zone 3 and 4 schists of northern Douglas Range and eastern Elgar Uplands in the following respects:

i. Their coarsely recrystallized texture,
ii. The development of quartz segregations,
iii. The presence of a foliation which is sometimes folded with development of a lineation parallel to fold axes.

Important differences include the unstrained, regular polygonized nature of the quartz in the hornfelses, random orientation of some chlorite and mica flakes, and the presence of biotite in some aureole rocks. These foliated hornfelses probably represent metasedimentary rocks which underwent recrystallization corresponding to textural zones 3 and 4 during regional metamorphism and were subsequently modified by contact metamorphism. The possibility that the foliation is a contact effect alone, produced during forceful emplacement of the batholith, is improbable since the batholith shows no evidence internally that it was emplaced in this way. As far as is known, it does not contain foliated plutonic rocks.

VI. STRUCTURE

At least some of the rocks of the LeMay Group were deformed in an early Mesozoic event, probably related to the 'Gondwanian orogeny' (du Toit, 1937; Elliot, 1975) recognized in other parts of Lesser Antarctica. Stratigraphical considerations restrict the timing of this deformation in central Alexander Island to post-middle to late Triassic and pre-late Jurassic (Edwards, 1982). However, the recent discovery of probable mid-Cretaceous radiolarians in northern Alexander Island (p. 7) indicates that parts of the LeMay Group were deposited and deformed at a much later time. The age of this later folding is bracketed by the mid-Cretaceous age of the radiolarians and the early Tertiary radiometric dates obtained from the volcanic rocks which unconformably overlie the LeMay Group in northern Alexander Island (Burn, 1981).

The present strikingly linear north–south topography is the result of block faulting, of probable late Cenozoic age. Folding in the LeMay Group is complicated and structural observations are hindered by cataclasis and diagenic/metamorphic effects which sometimes obliterate sedimentary features and later-formed tectonic fabrics. This chapter is a compilation of previous structural work, chiefly that of Grikurov (1971) and Edwards (1980*a* and 1980*c*) in central Alexander Island, Horne (1967) and Bell (1973*b* and 1975) in southern Alexander Island, together with recent studies by B. W. Care and the author in northern Alexander Island.

TABLE IX
Summary of various authors' interpretations of folding in the LeMay Group of Alexander Island

Author	*Bell (1975)*	*Grikurov (1971)*	*Edwards (1980c)*	*Bell (1974a)*	*Burn (this report)*
Region	*Southern Alexander Island*	*Central Alexander Island*	*Central Alexander Island*	*Northern Alexander Island*	*Northern Alexander Island*
Interpretation	Three episodes of folding. Later fold axes have moderate plunges to east-south-east, south, south-west and west.	Major folds with north south axes, locally refolded at the hinge.	Four episodes of folding.	(?) Three episodes of folding. Refolding of axes and axial planes of early folds by one or two later deformations.	Four episodes of folding.
First episode of folding	Large-scale folds overturned to the north.		F_1: isolated intrafolial folds.		F_1: isoclinal folds with axial planar slaty cleavage. Downward facing areas may lie on inverted limbs if F_1 nappes or recumbent folds.
Second episode of folding	Tight folds with axial planar cleavage.		F_2: isoclinal shallow-plunging folds with axial planar crenulation cleavage. Axial planes dip steeply to west or east.		F_2: large-scale upright folds with axial planar fracture cleavage. Axial planes dip steeply to south-west or rarely north-east.
Third episode of folding	Refolding of bedding and cleavage planes.		F_3: open-limbed folds without penetrative fabric. Axes plunge shallowly to south-east in the north-east LeMay Range, but shallowly to the west-south-west in the eastern Lully Foothills.		F_3: small and intermediate-scale folds without penetrative fabric. Variable orientations.
Fourth episode of folding			F_4: refolding of F_3 axial planes, no penetrative fabric.		F_4: small-scale asymmetrical folds with penetrative axial planar crenulation cleavage, and lineation parallel to their axes. Plunges shallow, axial planes dip steeply to south-south-west. Restricted to schists and semischists of textural zones 3–4 in eastern Elgar Uplands and Rouen Mountains.

A. FOLDING

1. *Northern Alexander Island*

After a reconnaissance study, Bell (1974) recognized three episodes of folding (Table IX) but was not able to determine their orientations; from work in the Elgar Uplands and Nichols Snowfield the author recognized four phases of folding (Table IX).

Bedding measurements in northern Alexander Island are plotted on equal area stereonets (Figs. 39 and 40), the region being divided into sub-areas I–X, each of which show some structural homogeneity. These are shown on the structural map of the island (Fig. 41). The predominance of north-west–south-east strikes in Douglas Range, western Elgar Uplands, Nichols Snowfield and Havre Mountains (sub-areas I, IV, VI, VIII) is clearly seen. Strikes swing west-north-west–east-south-east in the vicinity of Sullivan Glacier (sub-area II) and north–south on the east side of Mahler and Puccini spurs and in Rouen Mountains (sub-areas III, VII). Dips are mostly steep south-westerly, but are steep north-north-easterly near Sullivan Glacier (sub-area II). Distribution of poles to bedding in crude partial great circles suggests folding about axes ranging from north-north-west–south-south-east to west-north-west–east-south-east. Poles to bedding on Rothschild Island (sub-area IX) and Charcot Island (sub-area X) suggest folding about south-south-west–north-north-east and west-south-west–east-north-east axes respectively.

a. *F_1 folding.* The earliest recognizable deformation resulted in the formation of a more or less ubiquitous bedding-parallel cleavage (S_1) which manifests itself as a good slaty cleavage (cf. Ramsey, 1967) in most pelitic rocks, and may result in a weak to strong foliation in semischists and schists of textural zones 2–4 (p. 34). Intraformational pelite clasts are sometimes flattened parallel to S_1, but crystalline pebbles are rarely deformed in this way. The S_1 fabric appears to be axial planar to rarely observed isoclinal folds, F_1 (Fig. 42). Too few closures were observed to yield any information concerning the orientation of this episode of folding.

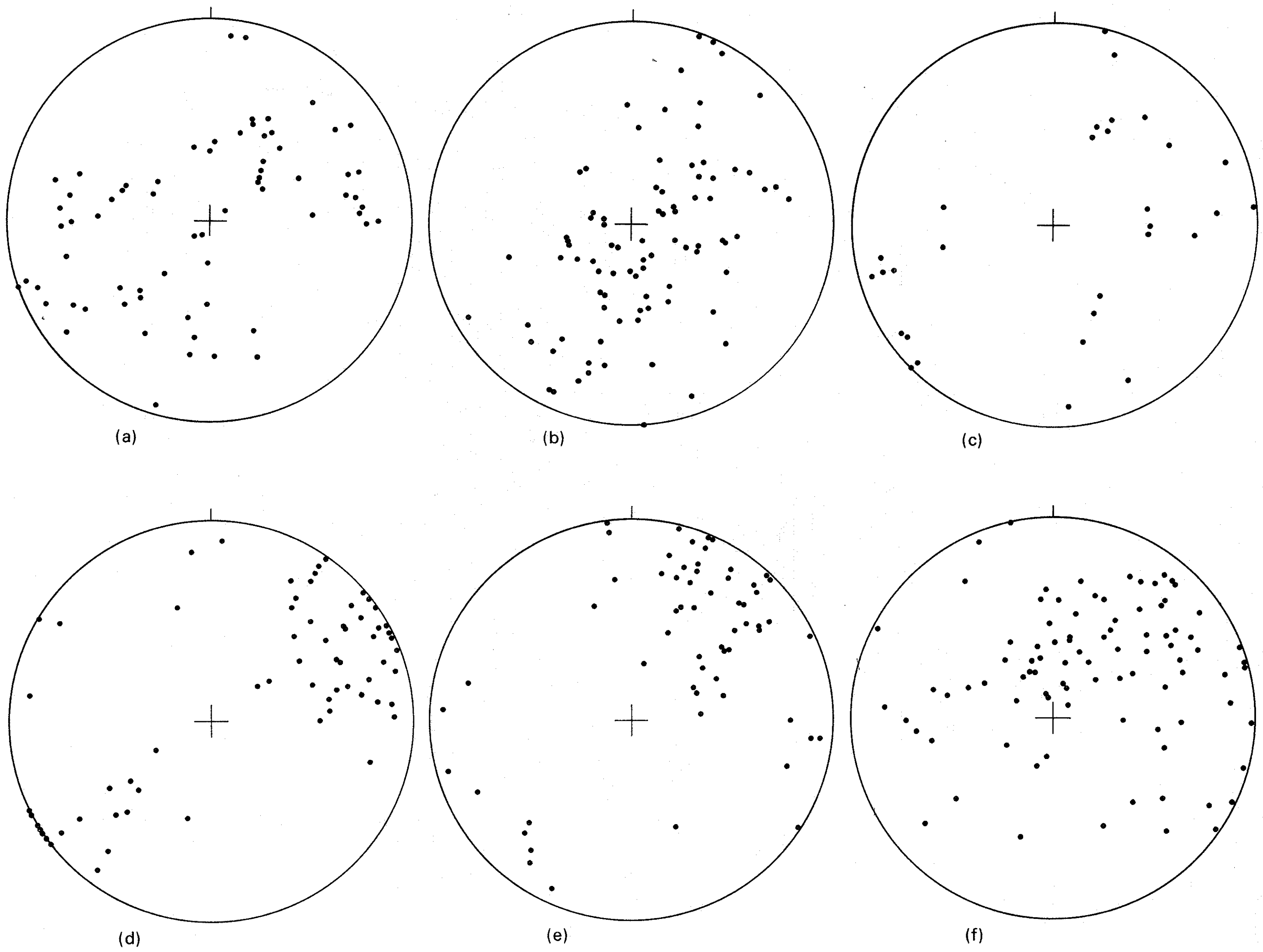


FIGURE 39
Equal area projections of poles to bedding in LeMay Group metasediments in northern Alexander Island.
a. Sub-area I (Douglas Range)
b. Sub-area II (south-eastern Elgar Uplands)
c. Sub-area III (Mahler and Puccini Spurs)
d. Sub-area IV (south-western Elgar Uplands)
e. Sub-area V (Appalachia Nunataks)
f. Sub-area VI (northern Nichols Snowfield)

b. *F_2 folding.* A second cleavage (S_2) overprints S_1 in parts of Nichols Snowfield and Elgar Uplands. Although less penetrative than S_1 it approaches a slaty cleavage in some pelites. More usually it is a fracture cleavage (cf. Ramsey, 1967), consisting of discrete parallel fractures spaced 1–2 mm apart. S_2 is usually aligned at a low angle (3°–10°) to bedding. Cleavage/bedding relationships delineate axial traces of folds, F_2, to which S_2 is axial planar. The distribution of these axial traces is shown in Fig. 41. F_2 folds are large-scale structures and no closures were positively identified. Their axial traces follow the regional north-west–south-east to north-north-west–south-south-east strikes, and their axial planes (indicated by S_2 cleavage) dip steeply to the south-west or rarely to the north-east (Fig. 43a). Plunges, indicated by S_2-bedding intersections, appear to be shallow north-westerly and south-easterly.

c. *F_3 folding.* Most observed small and medium scale fold closures deform an earlier S_1 or S_2 cleavage, and lack a penetrative axial planar fabric, although crenulations are sometimes present in their cores. These folds (F_3) are usually asymmetrical and rather variable in style (Figs. 44–47). No consistent sense of vergence was detected. They often show brittle deformation, beds being sheared and disrupted around the core of the fold (Fig. 47). Plunges and axial planes to F_3 folds are shown in Fig. 43b and c.

In northern Nichols Snowfield and Appalachia Nunataks (sub-areas V and VI) plunges vary from shallow west-north-

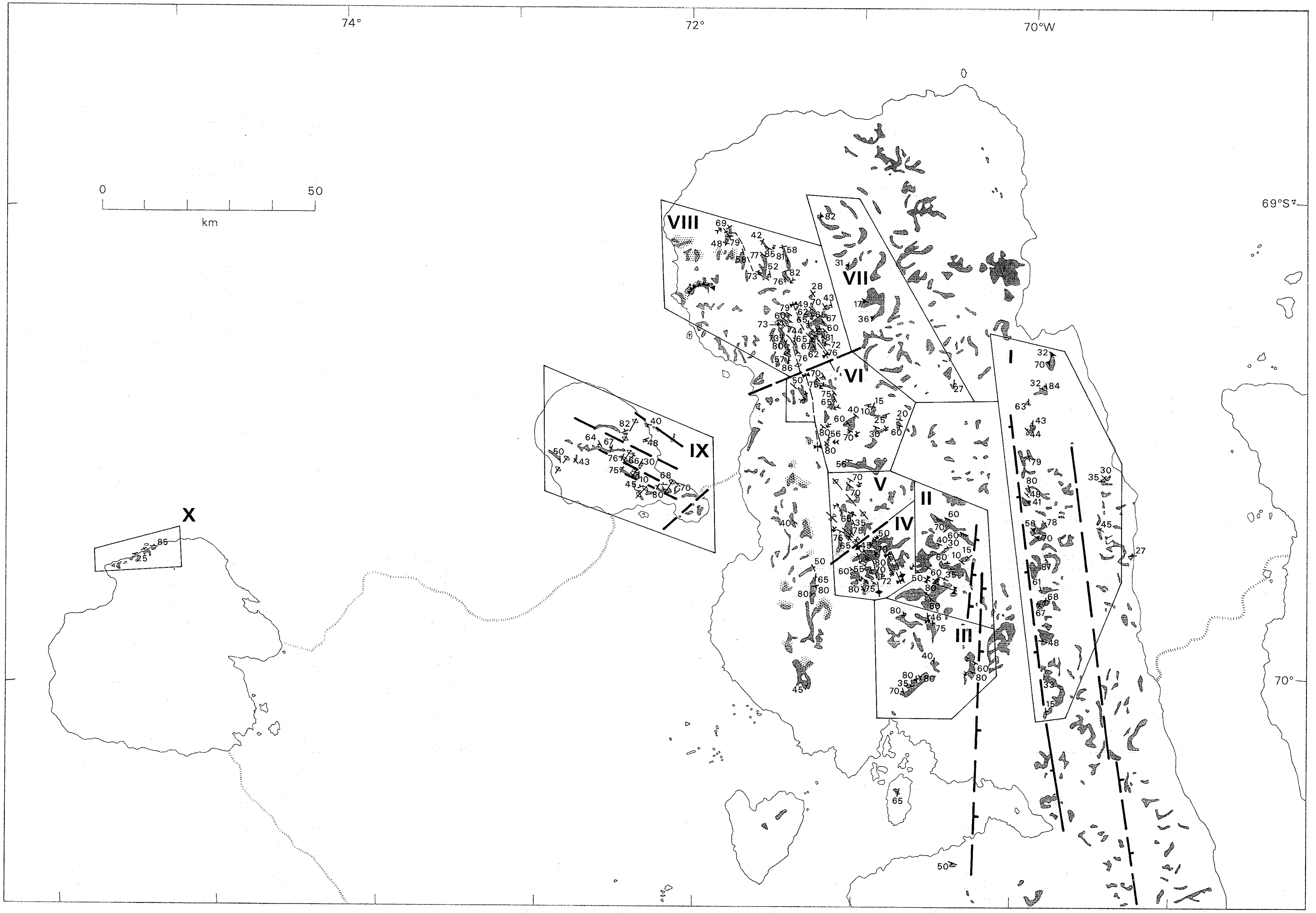

74°
72°
70°W
69°S
70°
0
50
km
I
II
III
IV
V
VI
VII
VIII
IX
X

FIGURE 41a and b
Structural maps of the LeMay Group of Alexander Island. Additional sources: Douglas Range, Rouen Mountains, Havre Mountains (unpublished field data, B. W. Care); Rothschild Island (Care, 1980; fig. 26); Walton Mountains (Edwards, 1980*c*; enc. 4); Lully Foothills and LeMay Range (Edwards, 1980*c*; enc. 3); Southern Alexander Island (C. M. Bell, unpublished field data).

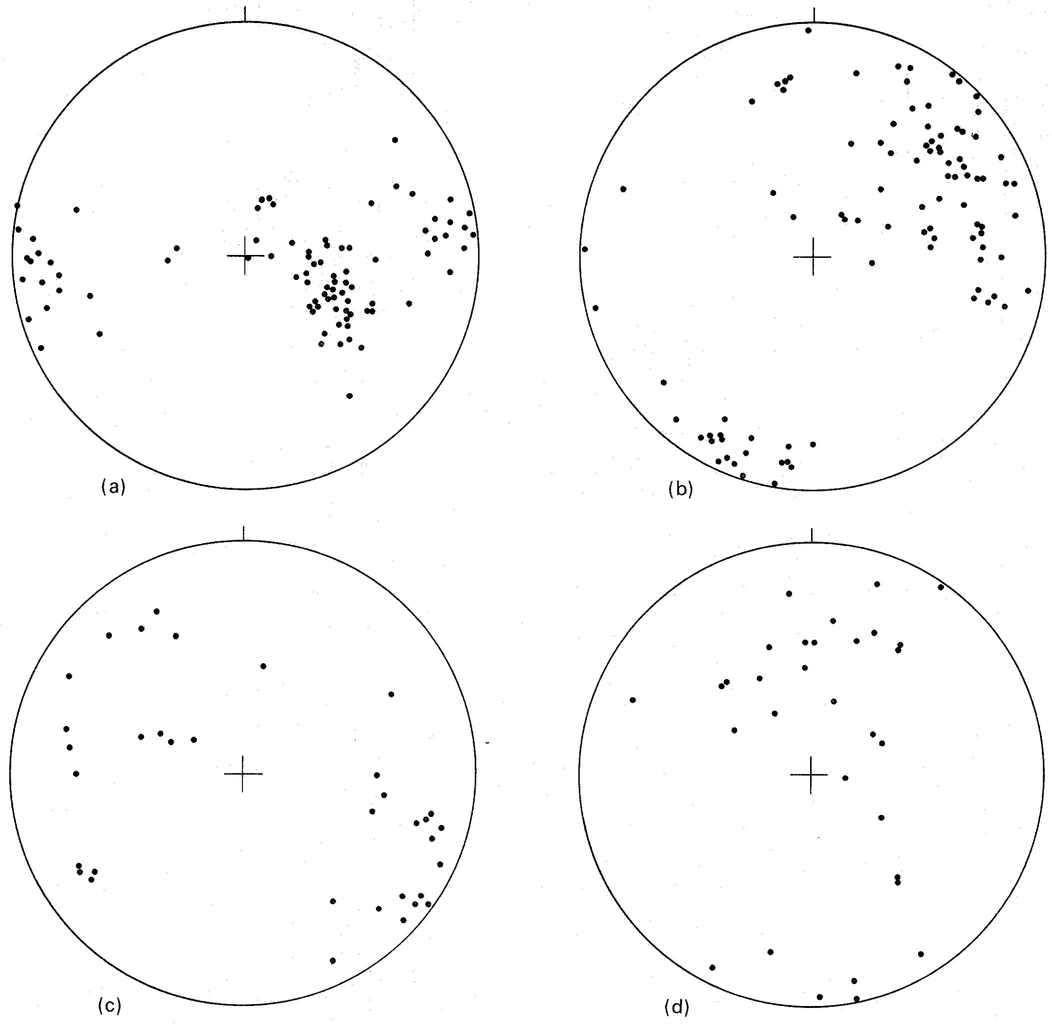


FIGURE 40
Equal area projections of poles to bedding in LeMay Group metasediments in northern Alexander Island.
a. Sub-area VII (western Rouen Mountains)
b. Sub-area VIII (Havre Mountains)
c. Sub-area IX (Rothschild Island: after Care, 1980)
d. Sub-area X (Charcot Island)

west, through moderate south-west to shallow east. Axial planes show much variation. In the vicinity of Bartok and Sullivan Glaciers (sub-areas II and IV) F_3 fold axes are mostly north-west–south-east with shallow, moderate and steep plunges. Axial planes mostly have moderate dips to the north-east.

d. *F_4 folding*. This episode of folding was recognized in the semischists and fine-grained lineated schists of textural zones 2–3 in eastern Elgar Uplands (northern part of sub-area II). In that area small scale asymmetrical folds with a well-developed penetrative axial planar crenulation cleavage (Ramsey, 1967) are abundant (Fig. 48). There is commonly a lineation consisting of millimetre corrugations of foliation surfaces (and grain elongation parallel to the fold axes) which are subhorizontal and trend west-north-west–east-south-east. Axial planes dip steeply to the south-south-west (Fig. 43d). A well-preserved interference figure (Fig. 49) shows that these folds represent at least the fourth episode of deformation in the area, and accordingly the folds and lineations are termed F_4 and L_4 respectively. Folds comparable to F_1–F_3 were not detected in the area, but a bedding parallel foliation or cleavage, possibly equivalent ot S_1 or S_2 is folded by F_4 folds. F_4 structures do not appear to be abundant away from eastern Elgar Uplands and it is evident that the more advanced metamorphism and textural reconstitution of these rocks is accompanied by a more complex structural history.

Tight minor folds, some accompanied by a lineation found in the contact aureole of the Rouen Mountains batholith (B. W. Care, unpublished field notes) resemble F_4 folds and may be attributed to the same episode of deformation. These folds have shallow west-south-westerly plunges (Fig. 43e).

e. *Cleavage/bedding relationships and facing*. F_2 axial traces in northern Nichols Snowfield and south-west Elgar Uplands

FIGURE 42

F_1 isoclinal minor fold closure in thinly bedded flysch, with shattered axial planar S_1 cleavage. The fold has been modified by subsequent deformation. Western Elgar Uplands (station KG.2177). The hammer shaft is 35 cm long.

were mapped by observing the attitude of S_2 cleavage relative to bedding, and by younging criteria supplied by cross laminations, graded bedding and bottom structures. These features also define areas of upward and downward facing (facing being younging direction along S_2 cleavage). The facing of mapped F_2 folds is indicated in Fig. 41. Downward facing occurs over a distance of at least 12 km across strike south from Delius Glacier across axial traces of two F_2 folds, and was also recorded at Puccini Spur. Perhaps the most plausible explanation for the downward facing areas is that they represent parts of the inverted limbs of large-scale recumbent F_1 folds or nappes which have been refolded by more or less upright F_2 folds. Alternatively, changes in facing could be brought about by the refolding of F_2 axial planes by F_3 folds. This is undoubtedly achieved locally by some of the larger F_3 folds in Appalachia Nunataks (Fig. 44) and probably accounts for local anomalies in areas where facing is otherwise consistent. However there is little evidence for F_3 folding on a scale sufficiently large to cause reversals in facing over distances of 10 km or more.

2. *Central Alexander Island*

Along the western foot of LeMay Range, Grikurov (1971) postulated the existence of a north-north-west trending major anticline with local refolding near the hinge. Four major episodes of folding (summarized in Table IX) were recognized from work in LeMay Range, Lully Foothills and Walton Mountains by Edwards (1980*c*), who agreed with Grikurov in the dominance of folding parallel to the Antarctic Peninsula. Large areas of inverted strata crop out in Walton Mountains (personal communication from C. W. Edwards).

3. *Southern Alexander Island*

Bell (1973*b*, 1975) carried out structural observations in southern Alexander Island, where he concluded there were three episodes of folding (Table IX). Axes of the third phase of folding varied between shallow to the east-south-east at Mimas Peak, moderate to the west near Mount Umbriel, and moderate to the south-west near Titania Peak. He found little evidence for the predominance of folding about north-north-west axes in central Alexander Island described by Grikurov.

4. *Overall structural trends in Alexander Island*

Table IX summarizes the interpretation of structure in the LeMay Formation to date. The three phases of folding suggested by Bell (1975 and 1974) for northern and southern Alexander Island are comparable to the author's F_1, F_2 and F_3 in northern Alexander Island. However, Bell did not attribute an axial-planar fabric to the first phase of folding, believing instead that the regional cleavage was related to the second episode. The author agrees with Edwards (1980*c*) in that early isoclinal F_1 folds were refolded by a third phase of rather open folds lacking an axial planar fabric. However, Edwards' F_2 folds differ from those of the author in possessing a crenulation cleavage instead of a fracture cleavage, although their orientations are comparable. In fact the F_2 folds of Edwards closely resemble in style, but not in orientation, the author's F_4.

The structural map of Alexander Island (Fig. 41) shows the predominance of north-west–south-east strikes and steep south-westerly dips in the northern part of the island, and indicates the importance of approximately north–south strikes with steep easterly and westerly dips in the central and southern parts. There is a suggestion of a south-westerly swing in strikes in southern Alexander Island, paralleling the coast of Palmer Land.

The widespread westerly and south-westerly dips in the LeMay Group are not fully consistent with a history of accumulation and deformation in a subduction complex, as proposed on p. 57. Current subduction/trench models (e.g. Seely and others, 1974) envisage moderate landward dips and an oceanward fold vergence, resulting from underthrusting from the oceanward side. However, there is evidence that Alexander Island was the site of subduction not only in the early Mesozoic, but also later in the Mesozoic and up until the middle Tertiary (Suárez, 1976; Burn, 1981). It is not unlikely therefore that the structure of an early Mesozoic subduction complex would have been highly modified and possibly rotated landward as a result of addition of younger sediments by accretion.

B. CATACLASTIC DEFORMATION

Previous workers have commented on the pervasive shearing undergone by some of the rocks in the LeMay Formation, sometimes masking bedding and depositional structures. Bell (1974) recognized the presence of a belt of cataclastic deformation up to 12 km wide, through the

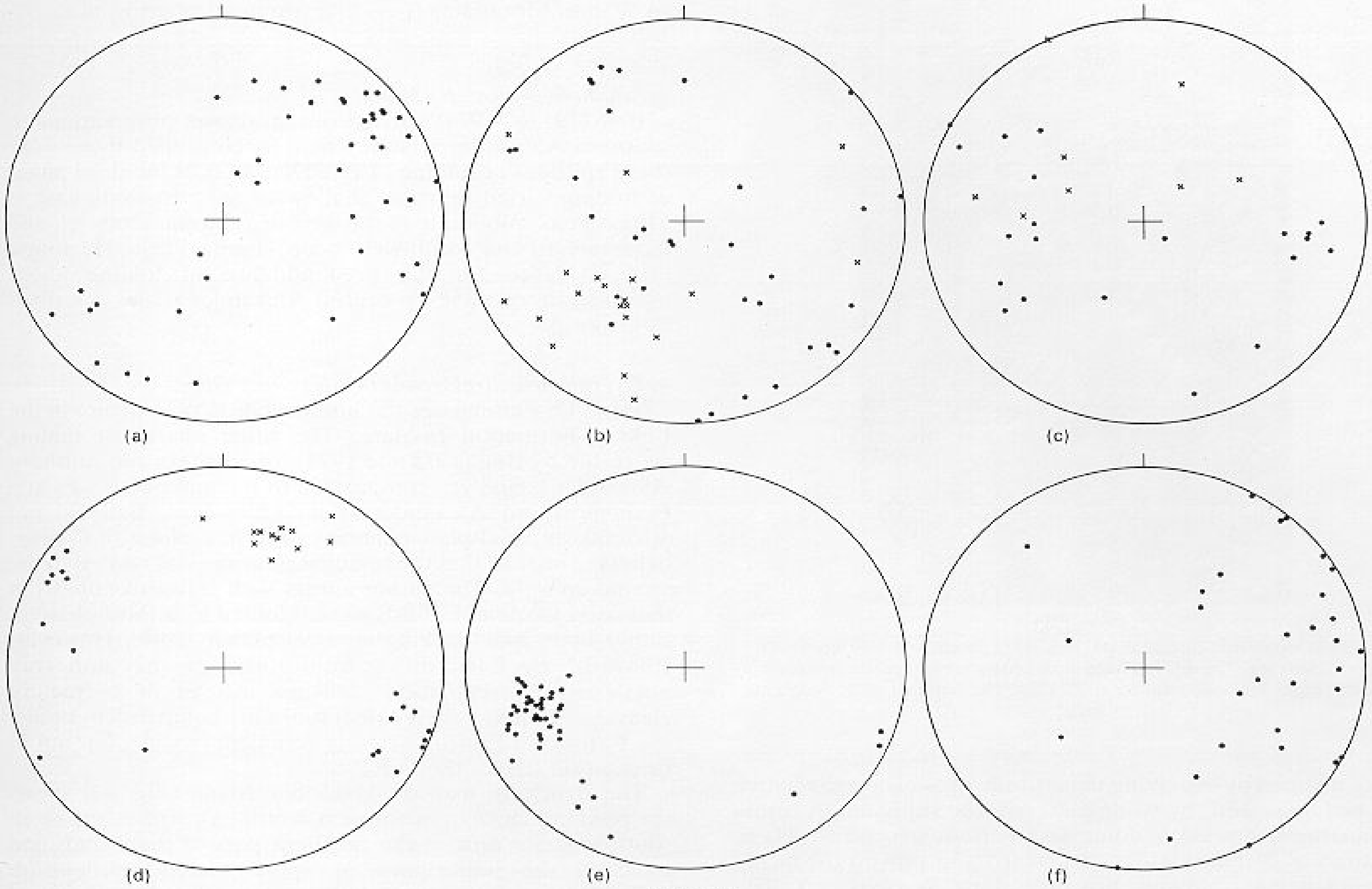


FIGURE 43
Equal-area projections of structural data from northern Alexander Island.

a. Poles to S_2 cleavage.
b. Plunges (●) and poles to axial planes of F_3 folds (×) in sub-areas II and IV.
c. Plunges (●) and poles to axial planes of F_3 folds (×) in sub-areas V and VI.
d. Plunges of F_4 folds and L_4 lineations (●) and poles to S_4 crenulation cleavage (×) in schists in sub-area II.
e. Plunges of minor fold axes and lineations in hornfelsed metasediments, western Rouen Mountains (B. W. Care, unpublished field data).
f. Poles to cataclastic foliation in broken formation in Lassus Mountains and Debussy Heights.

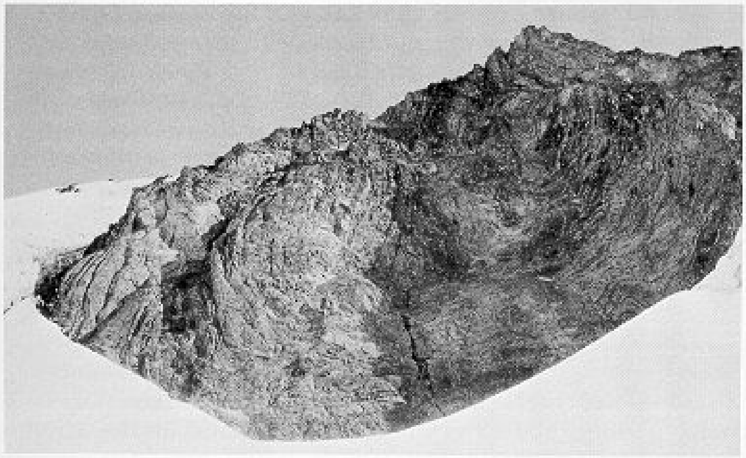


FIGURE 44
Large-scale F_3 overturned synform, Appalachia Nunataks (station KG.2186). The cliff is approximately 70 m high at its highest point.

western part of northern Alexander Island, possibly extending south to the vicinity of Franck Nunataks. Intense cataclasis has also been recognized in association with occurrences of basic volcanic rocks in the eastern Lully Foothills (Grikurov, 1971) and the Walton Mountains (Edwards, 1980c). The following account is based on a study of the cataclastic belt in northern Alexander Island.

1. *Field occurrence and petrography*

In northern Alexander Island there is a complete gradation from relatively coherent strata, showing pinch and swell and some boudinage, to a chaotic distribution of phacoids and tectonically rounded inclusions of competent material (sandstones, less commonly chert) in a matrix of sheared argillite (Figs. 50–52). The inclusions appear to approximate in shape to oblate ellipsoids. Where deformation is most intense, the cross-section of the inclusions becomes circular (Fig. 52) presumably as a result of tectonic rolling, but it was

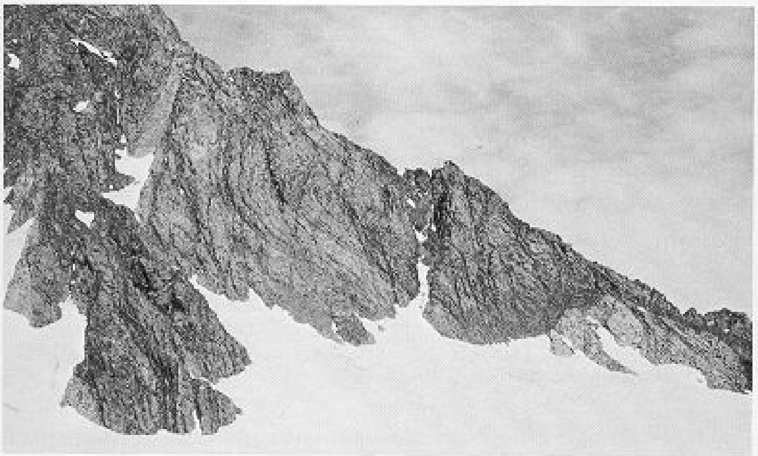


FIGURE 45
Intermediate scale F_3 asymmetric overturned fold, north side of Delius Glacier (station KG.2149). A hornblende-andesite dyke cuts the folded strata at the left of the photograph, and an irregular body of hornblende-feldspar porphyry crops out at the right-hand end of the ridge. The height of the gully in the centre of the photograph is approximately 30 m.

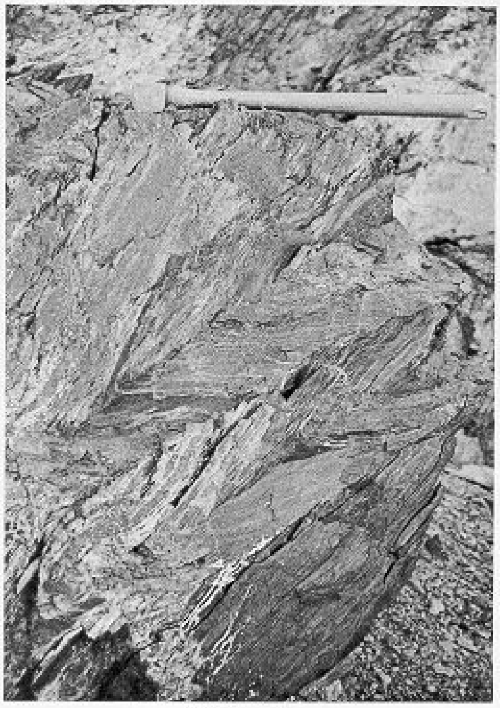


FIGURE 46
S_1 cleavage in mudstone with thin siltstone beds folded by F_3 chevron folds, south-west Elgar Uplands (station KG.2221). The hammer shaft is 35 cm long.

not possible to ascertain whether these bodies are spherical, cylindrical or ellipsoidal shapes in three dimensions. The inclusions are commonly cut by transverse fractures along which offsets of several centimetres may occur and hair-like veins of calcite, quartz, prehnite and zeolites are common throughout matrix and inclusions. A cataclastic foliation is usually defined by the plane of flattening of the inclusions and by an irregular scaly cleavage in the matrix, but measurements of this foliation show little pattern or consistency (Fig. 43f). The style of deformation is similar to that described by Hsü (1974) as broken formation (i.e. 'A body of pervasively sheared strata that contains no exotic elements').

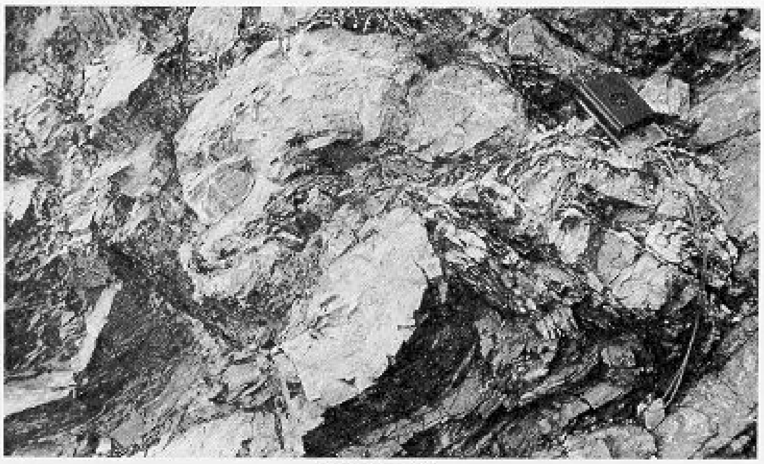


FIGURE 47
F_3 minor fold with disrupted short limb. S_1 cleavage is folded with bedding, western Elgar Uplands (station KG.2177). The compass is 10 cm long.

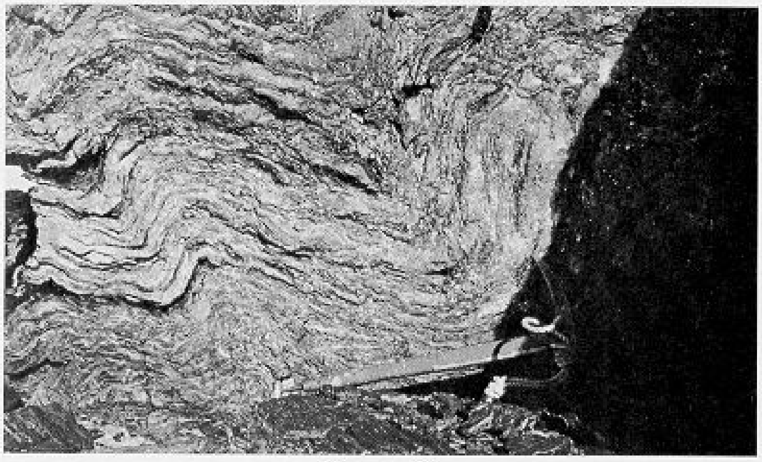


FIGURE 48
Small-scale F_4 fold with axial planar crenulation cleavage (S_4) in textural zone 3 schists, eastern Elgar Uplands (station KG.2070). The ice axe shaft is 55 cm long.

In thin section the matrix is seen to be very fine grained, and may be either effectively isotropic under X-nicols, or composed of finely divided undeterminable birefringent minerals. Variable amounts of tectonically rounded sand and silt-sized quartz and feldspar may be present. Dark streaks, and occasionally stretched quartz grains define the foliation which wraps around the tectonic inclusions. In the sandstone inclusions sedimentary textures are more or less unmodified, except along random and anastomozing zones (usually approximately 1 mm wide) of granulation in which tectonic rounding and reduction in grain size has occurred (see Bell, 1974, fig. 5b).

A 500-m wide vertical north–south orientated zone of highly sheared rocks in eastern Debussy Heights contains pods of greenstone up to 5 m by 1 m (Fig. 53), in addition to intensely crushed sandstone inclusions. Petrographically the greenstones are similar to pillow lavas and (?) dolerite

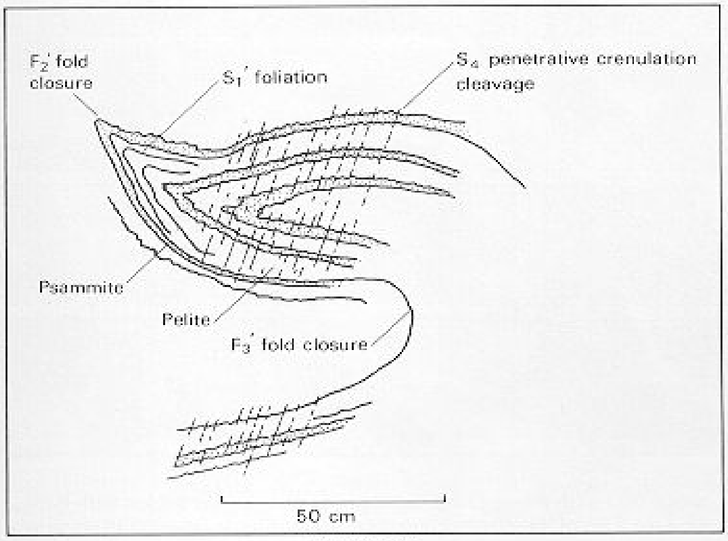


FIGURE 49
Interference figure showing F_4 folding to post-date three previous deformation episodes, eastern Elgar Uplands (station KG.2070). Note: the features S'_1, F'_2, F'_3 in this figure are not necessarily correlated with the structural elements designated S_1, F_2, F_3 described on pages 44–46.

FIGURE 50
Phacoids of arenite in crushed argillite matrix, broken formation, eastern Debussy Heights (station KG.2427). The ice axe shaft is 55 cm long.

FIGURE 51
Streaks and lenses of cataclastically disrupted sandstone and chert in sheared argillite matrix, eastern Lassus Mountains (KG.2248).

FIGURE 52
Tectonically rounded inclusions of sandstones in sheared argillite matrix, broken formation, eastern Debussy Heights (station KG.2427). The ice axe shaft is 55 cm long.

FIGURE 53
Greenstone pod (top right), in matrix of highly sheared green and red argillite, intensely veined by zeolite; (?) tectonic mélange, eastern Debussy Heights (station KG.2432). The compass is 10 cm long.

described on p. 27. It is not clear if these greenstone pods are truly exotic in origin (i.e. tectonically transported from a body of basic igneous rocks elsewhere, or whether they result more or less from disruption *in situ* of a sediment-lava succession. If the former interpretation is correct then this zone can be regarded as a true *tectonic mélange* as defined by Hsü (1974). Poorly exposed cataclastically deformed rocks in the north-west Nichols Snowfield contain phacoids of greenstone (similar petrographically to pillow lavas within the LeMay Formation) in a chlorite-rich matrix. In this section, the matrix is seen to be composed of a very fine-grained pale green, effectively isotropic material, chlorite, and broken and granulated pyroxene crystals, and has evidently been derived by crushing of fine-grained basic rock. A 2 m by 1 m pod of sandstone (Fig. 54) (significantly lacking in volcanogenic material) enclosed in this matrix might be construed as an exotic tectonic inclusion in a mélange. Serpentine, an important constituent of tectonic mélanges elsewhere, has not been found in the cataclastic rocks of the LeMay Group.

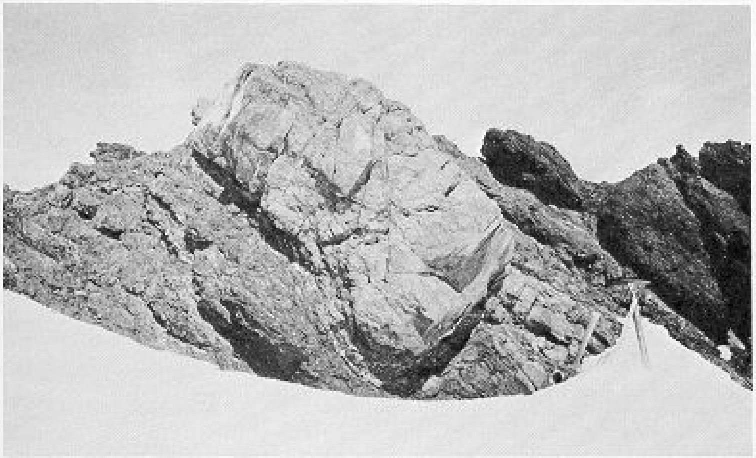


FIGURE 54
Pod of arkosic arenite in sheared chlorite-rich greenstone, north-western Nichols Snowfield (KG.2241). The hammer shaft is 35 cm long.

Fig. 41 shows the linear distribution of broken formation in northern Alexander Island, and the rather sporadic nature of such occurrences. The latter may be due to the presence of slabs of bedded sediment surrounded by pervasively sheared rocks. A similar conclusion was reached by Cowan and Boss (1978) to explain the relationship between coherent and chaotic strata in a similar setting on the Kenai Peninsula, Alaska.

2. *Origin of the cataclastic belt*

Bell (1974) suggested that the cataclasis affecting rocks of the LeMay Group was evidence for an ancient transcurrent fault zone. This explanation is unlikely since the cataclastic deformation in Alexander Island is chaotic and affects large volumes of rock, whereas fault zones are characterized by intense development of mylonite fabrics along narrow zones (e.g. Higgins, 1971).

Despite superficial resemblances of some of the rocks described above to diamictite, gradation between coherent and chaotic strata and the mechanical granulation observed in thin section is unequivocal evidence of a tectonic origin. Since chaotic deformation post-dates cleavage development, and is not restricted to well-defined stratigraphic units, an origin by gravity sliding by semiconsolidated strata can be dismissed. Large areas of broken formation, similar to those within the LeMay Group have only been described from well-documented subduction complexes, including the Franciscan Complex of western California (Hsü, 1974) and the Uyak Complex and Kodiac Formation of Kodiac Islands, Alaska (Connelly, 1978). Connelly described field and petrographic characteristics identical to those described above. The style of deformation in Kodiac Islands is attributed to underthrusting of semi-lithified sediments of the lower trench slope as a result of subduction. A similar origin is likely for the deformation in the LeMay Group.

C. FAULTING

The presence of major faulting in rocks of the LeMay Group can generally only be inferred by topography, unless observable displacements of specific formations are involved. King (1964) and Bell (1974) attributed the striking north–south linearity of mountain ranges in Alexander Island, and the gentle southerly dip of the accordant summit level to late Cenozoic block faulting. Hampton Glacier represents a narrow graben containing downfaulted early Tertiary volcanic rocks, and the fault along its east side, or a closely related one, probably extends south along the western scarp of LeMay Range. Hampton Glacier is a feature of extremely high relief, its base is at least 300 m below sea level in places (British Antarctic Survey unpublished radio echosounding data) and the peaks of Douglas Range immediately to the east rise to nearly 3000 m. It is probably of late Cenozoic origin. The eastern extent of the LeMay Group is bounded by the LeMay Range fault which downfaults the late Jurassic–early Cretaceous Fossil Bluff Formation against it (Bell, 1975; Edwards, 1980*a*). This same fault, or a similar one, probably extends through eastern Douglas Range north of Tilt Rock and either passes into George VI Sound south of Wager Glacier or continues along the eastern wall of Douglas Range to Cape Brown. The known extent of north–south faulting on Alexander Island, and the proven existence of at least one graben indicate that a similar origin is extremely likely, for George VI Sound and other prominent parallel features (e.g. Toynbee Glacier, Nichols Snowfield–Gilbert Glacier). It has been suggested that the LeMay Range fault is the western margin of a large graben which includes the Fossil Bluff Formation of eastern Alexander Island as well as George VI Sound (Edwards, 1980*a*).

There is some evidence for an important set of north-east trending faults in the interior of the island. One such fault downfaults early Tertiary volcanic rocks along the north side of Bartok Glacier, and others occur at the south end of Colbert Mountains (Burn, 1981) and Walton Mountains (Edwards, 1980*c*). Eight small outcrops of late Tertiary alkali basalt volcanics are aligned along a north-easterly trend a few kilometres north of Bartok Glacier, suggesting that some fractures with this orientation were sufficiently deep seated to provide a passage for rising magmas.

Few examples of thrusting have been observed, but the lack of marker horizons may have led to their being overlooked. Near Cape Vostok coherent strata appear to overlie broken formation along a north-easterly dipping thrust (personal communication from B. W. Care), and at a locality in Nichols Snowfield massive sandstones appear to overlie steeply dipping, thinly bedded flysch along a south-westerly dipping thrust.

VII. REGIONAL CORRELATION AND CONCLUSIONS

A. REGIONAL CORRELATION

The LeMay Group has been tentatively correlated with several flysch-type sequences occurring in the Antarctic Peninsula and off-lying islands (Fig. 55) on the basis of similarities in lithology, provenance and structural style (e.g. Grikurov and others, 1967). Unfortunately, the rocks in question are largely unfossiliferous and evidence of their

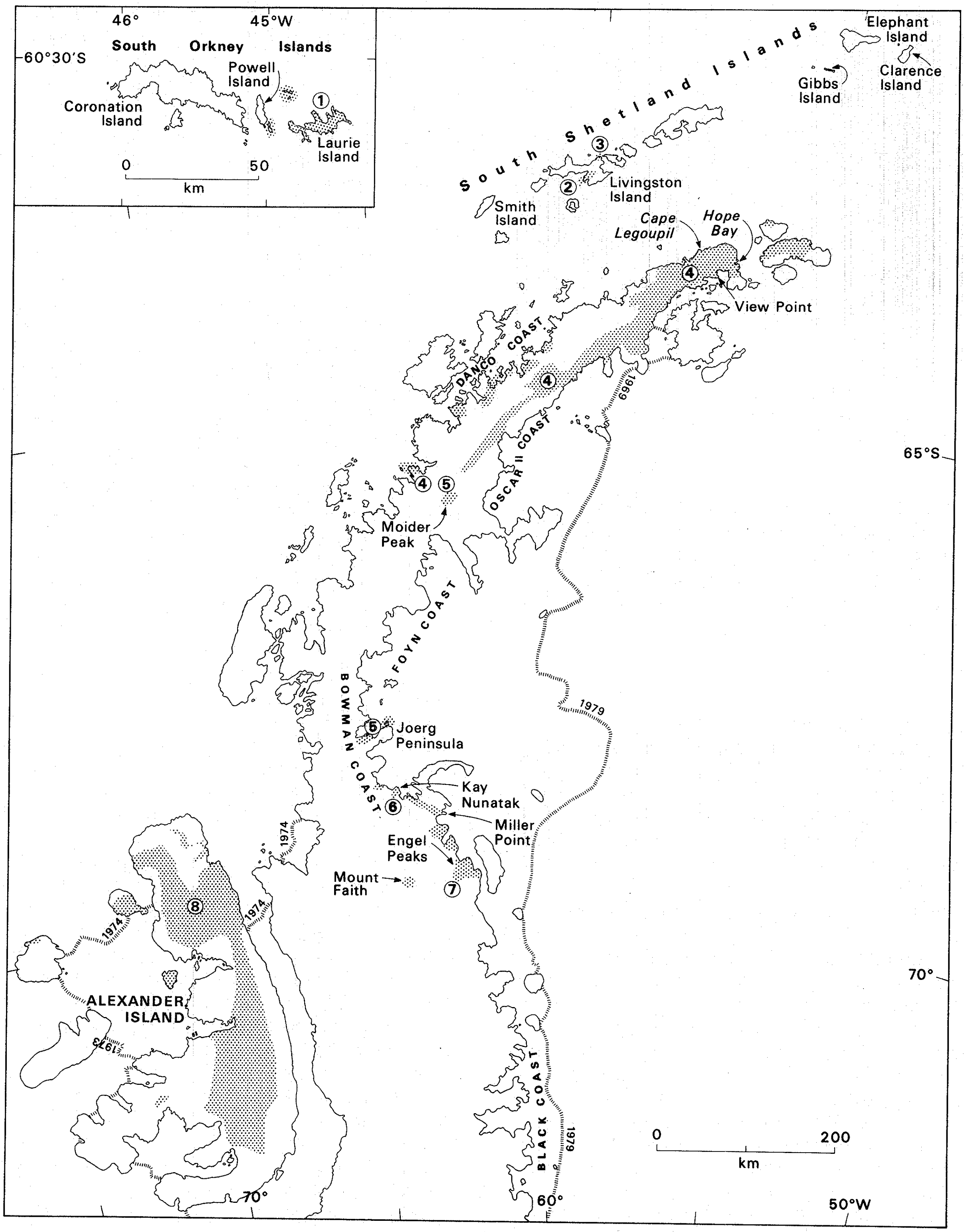


FIGURE 55
Extent of sedimentary sequences possibly of late Palaeozoic–early Mesozoic age. 1 Greywacke-shale Formation; 2 Miers Bluff Formation; 3 Williams Point beds; 4 Trinity Peninsula Group; 5 Sedimentary rock occurrences on Oscar II and Foyn coasts; 6 Sedimentary rock occurrences near Mobiloil Inlet; 7 Metasedimentary and metavolcanic rocks, north-eastern Palmer Land; 8 LeMay Group.

relative ages is sparse and in most cases inconclusive. The LeMay Group itself contains rocks whose ages are as diverse as Triassic and mid-Cretaceous (p. 7). In this section the salient features and age evidence pertaining to these possible correlatives are summarized and comparisons made with the LeMay Group.

Flysch-type rocks in Graham Land were originally assigned to the Trinity Peninsula Series (Adie, 1957) which was renamed the Trinity Peninsula Formation (Thomson, 1982) and subsequently upgraded to the *Trinity Peninsula Group* (Hyden and Tanner, 1981). Three component formations have been recognized in northern Graham Land: the Hope Bay, View Point and Legoupil formations. The Hope Bay Formation contains plant material considered by Croft (in Adie, 1957) as definitely not earlier than Carboniferous in age, and the validity of an early to middle Carboniferous age, based on palynological evidence (Grikurov and Dibner, 1968), was discussed earlier (p. 7). A two-point Rb-Sr isochron for a deformed shale from Hope Bay gave an age of 242 [237] Ma which has been interpreted as the time of diagenesis or deformation of the Trinity Peninsula Group (Dalziel, 1972). The Legoupil Formation has yielded a Triassic bivalve fauna (Thomson, 1975).

Although the sediments of the Trinity Peninsula Group are similar to those of the LeMay Group, two rock types not recognized in the latter are present: limestone (Fleet, 1965), and pebbly mudstone (Aitkenhead, 1975; Elliot, 1965). All three formations of the Trinity Peninsula Group were considered by Hyden and Tanner (1981) to belong to the turbidite facies and were interpreted in terms of a submarine fan environment. It appears that the sandstones differ from those of the LeMay Group in that they are typically wackes with more than 15% matrix (Aitkenhead, 1975). A QFL diagram (Fig. 56) for Trinity Peninsula Group rocks shows a wide variety of sandstone compositions including quartz-rich lithic wackes, lithic wackes, arkosic wackes and arkosic arenites. The source terrain was composed mainly of acid plutonic, hypabyssal and volcanic rocks with lesser amounts of sedimentary and metamorphic material. The presence of chess-board plagioclase and rutilated quartz is a feature in common with the LeMay Group, but the clastic composition of Trinity Peninsula Group sandstones appears to differ in a number of ways:

i. Most of the plagioclase in the Trinity Peninsula Group appears to be less calcic than oligoclase.
ii. Rutile and spinel, heavy minerals typical of basic plutonic rocks, are present in some sandstones.
iii. Acid volcanic fragments dominate over intermediate types (Aitkenhead, 1975; Elliot, 1965, 1966 and 1967).

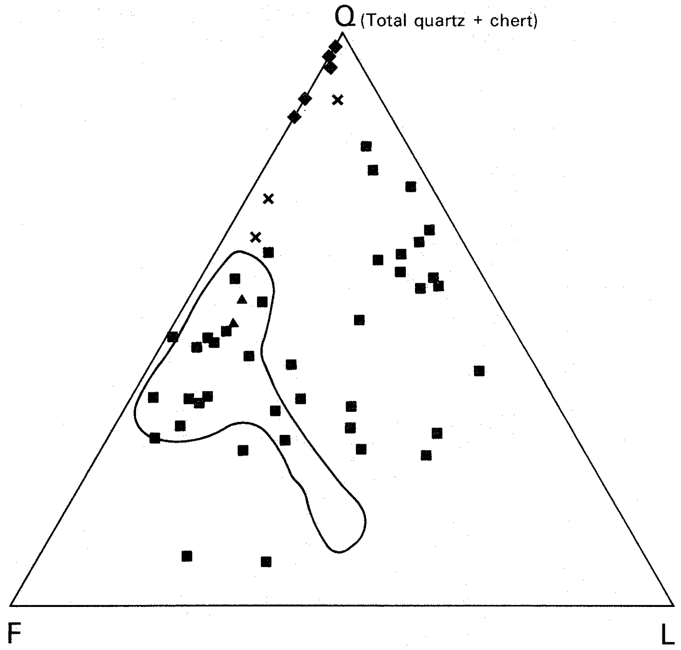


FIGURE 56

QFL diagram comparing composition of sandstones from (?) late Palaeozoic and early Mesozoic sequences in the Antarctic Peninsula region with those from the LeMay complex. The closed line represents the field of LeMay Group sandstones from Fig. 21.

■ Trinity Peninsula Group, northern Trinity Peninsula (Elliot, 1965; table II; Aitkenhead, 1975; fig. 3), and Danco Coast (West, 1974; table II).
▲ Miers Bluff Formation, Livingston Island (Smellie, 1979; table III).
× Legoupil Formation, north-west Trinity Peninsula (Halpern, 1964; table I, averages for 'quartz wacke', 'quartz-feldspathic wacke' and 'arkosic arenite to quartz-feldspathic arenite').
◆ Kay Nunatak and Miller Point sediments, Bowman and Wilkins coasts (Fraser and Grimley, 1972; table III).

The Trinity Peninsula Group in northern Graham Land has undergone deformation comparable to that of the LeMay Group. At least two phases of folding have been recognized, with fold axes dominantly parallel to the trend of the Antarctic Peninsula and with axial planes dipping north-west (Hyden and Tanner, 1981). Broken formation occurs locally. Metamorphism in northern Graham Land is believed to have reached prehnite-pumpellyite facies (Hyden and Tanner, 1981) and locally the rocks have been reconstituted to textural zone 2A of Bishop (1972) (equivalent to part of textural zone 2 of this report). The intensity of metamorphism increases to the south-west, and stilpnomelane, biotite and albite occur in fine grained schists on the Nordenskjöld coast (Elliot, 1966). The Trinity Peninsula Group contains scattered occurrences of pillow lava (Hyden and Tanner, 1981) and metabasic rocks (Aitkenhead, 1975; Elliot, 1966). Pyroxene compositions suggest that the original tectonic setting and magma type was within-plate alkaline basalt, possibly derived from a fracture zone in an oceanic plate (Hyden and Tanner, 1981). In contrast, the pillow lavas within the LeMay Group appear to be subalkaline and possibly of oceanic origin (p. 33).

The *Miers Bluff Formation* of southern Livingston Island, South Shetland Island, contains plant material of probable post-Carboniferous and possible Mesozoic age (Schopf, 1973). A four point Rb-Sr isochron from a cleaved mudstone gave an age of 197 [197] Ma (latest Triassic), which has been interpreted as the time of diagenesis and/or deformation (Dalziel, 1972). The Miers Bluff Formation is lithologically similar to the LeMay Group and is believed to consist mostly of turbidites (Hobbs, 1968). The sandstones are arkosic arenites and wackes. The two modal analyses available are similar in composition to the LeMay Group sandstones in terms of quartz, feldspar and lithic fragments (Fig. 56) but differ in their high content of metamorphic fragments (Fig. 57). Plagioclase composition (oligoclase-andesine) is similar but subhedral grains are rare and the volcanic contribution is considered to be small (Smellie, 1979). The structure of the Miers Bluff Formation is dominated by a nappe-type fold overturned to the south-east, with refolding about north-east–south-west axes (Dalziel, 1972). Very low-grade metamorphism is indicated by slight recrystallization of chlorite and sericite and lack of albitization in plagioclase (Smellie, 1979). Isolated occurrences of basic lava were reported by

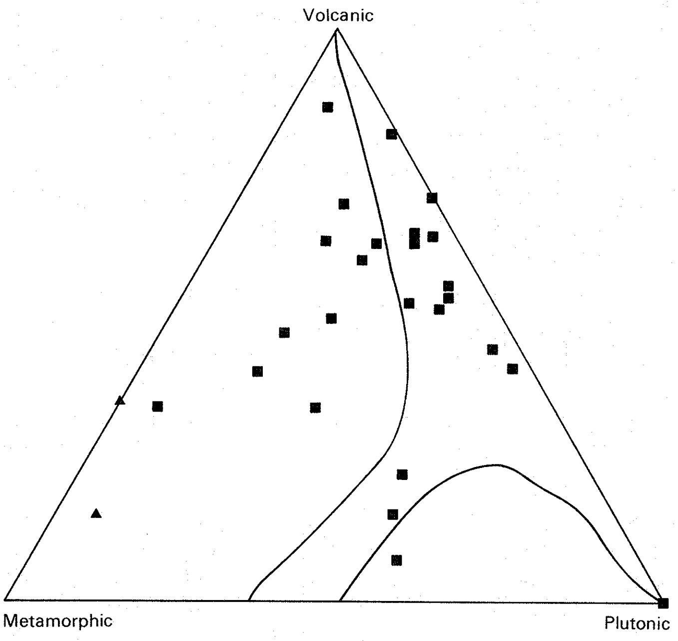


FIGURE 57
Triangular diagram comparing the composition of the lithic fraction in sandstones from the Trinity Peninsula Group and the Miers Bluff Formation, with that in sandstones of the LeMay Group. The closed line represents the field of LeMay Group sandstones from Fig. 22.

- ■ Trinity Peninsula Group, northern Trinity Peninsula (Elliot, 1965; table II; Aitkenhead, 1975; table XI).
- ▲ Miers Bluff Formation, Livingston Island (Smellie, 1979; table III).

Hobbs (1968), but on re-examination these are considered to be sills (Smellie, 1981).

The Greywacke–Shale Formation of the South Orkney Islands has been correlated on lithological grounds with the Trinity Peninsula Group (Adie, 1957). The only geochronological evidence relating to this formation are late Triassic–early Jurassic K-Ar dates obtained from the metamorphic complex of the islands, which may represent the deformation that affected the overlying sedimentary rocks (Miller, 1960; Rex, 1976). Late Triassic Radiolaria have been recovered from a bedded chert on Scappa Rock which appears to be structurally conformable with rocks of the Greywacke–Shale Formation exposed on nearby islands (Dalziel and other, 1981). Texturally the rocks are wackes (although it is not clear how much of the matrix is of diagenetic origin) and they are mainly of arkosic and sub-arkosic composition (Thomson, 1973). The structure of the Greywacke–Shale Formation is complex and has not been described in detail. Pelites have been reconstituted to phyllites with abundant chlorite and sericite (Thomson, 1973).

Several sequences which crop out further south in Graham Land and in Palmer Land have also been correlated with the Trinity Peninsula Group on lithological grounds. These include: feldspathic sandstones on the Danco Coast (West, 1974) and quartzose sandstones and shales on Oscar II and Foyn coasts (Marsh, 1968; Fleet, 1968), Joerg Peninsula (Stubbs, 1968) and near Mobiloil Inlet (Fraser and Grimley, 1972). The sequences on the Foyn and Oscar II coasts and Joerg Peninsula differ from the LeMay Group and the other sequences described above in their high quartz contents, and scarcity of feldspar and lithic fragments. Furthermore the well-sorted mature sediments of the Joerg Peninsula were considered by Stubbs (1968) to be shallow water deposits. Sandstones from sequences at Kay Nunatak and Miller Point, near Mobiloil Inlet, are also quartz-rich (Fig. 56) and contain few lithic fragments (chiefly sedimentary rocks and metaquartzite); plagioclase of oligoclase-andesine composition is a minor constituent.

The sequences discussed above have usually been regarded as being of late Palaeozoic to early Mesozoic age, and therefore possibly contemporaneous with the partly Triassic LeMay Group. However, the recent discovery of radiolarians which are probably of mid-Cretaceous age in cherts from northern Alexander Island opens the possibility that parts of the group may even be coeval with the late Jurassic–early Cretaceous Fossil Bluff Formation of eastern Alexander Island and the middle–late Jurassic Latady Formation of the Black, Lassiter and Orville coasts. These two sequences are discussed briefly below.

Although the Fossil Bluff Formation differs from the LeMay Group in that it consists of dominantly shallow marine and deltaic deposits, the provenance and detrital components of the two sequences are similar, a fact which led Horne (1967, 1968 and 1969) to believe that the LeMay Group was a deep-water facies variant of the Fossil Bluff Formation. However most Fossil Bluff Formation sandstones have lower quartz contents and contain more lithic fragments than those of the LeMay Group (Fig. 58). The volcanic fragments, which are mostly andesitic with some acid and basic types (Horne, 1968; Elliot, 1974) are similar to those of the LeMay Group, but tuffaceous material is

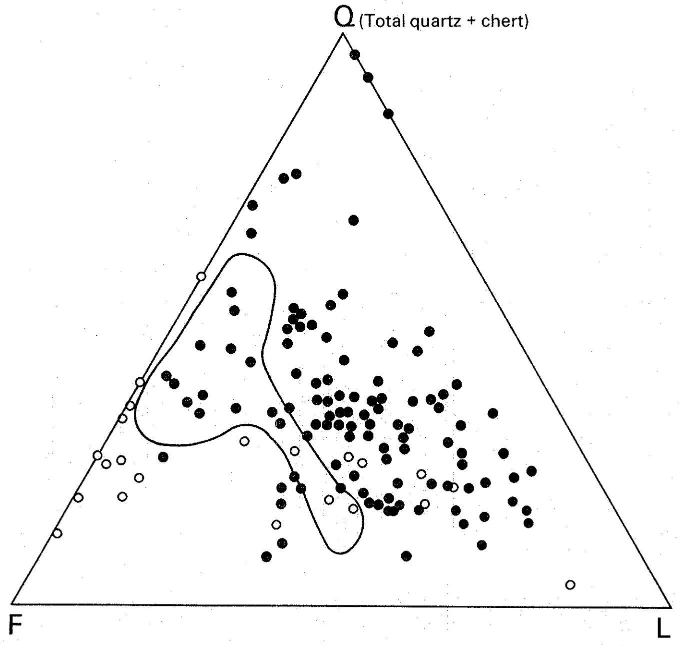


FIGURE 58
QFL diagram comparing composition of sediments from Jurassic–Cretaceous sedimentary sequences in the Antarctic Peninsula region with those of the LeMay Group. The closed line indicates the field for LeMay Group sandstones from Fig. 21.

- ● Latady Formation, Lassiter Coast (Williams and Rowley, 1972) and eastern Ellsworth Land (Laudon, 1972, fig. 5).
- ○ Fossil Bluff Formation, Alexander Island (Horne, 1968, fig. 2a; M. H. Elliott, 1974, fig. 8).

probably more abundant, and shard deposits are widespread. Structurally, the Fossil Bluff Formation is much less complex than the LeMay Group, although two episodes of folding have been recognized in south-eastern Alexander Island (Bell, 1975). The rocks have undergone diagenesis/metamorphism consistent with the zeolite facies (Elliot, 1974). At least part of the LeMay Group was deformed prior to the deposition of the Fossil Bluff Formation since it is unconformably overlain by the latter in central eastern Alexander Island. The two sequences are juxtaposed along the LeMay Range Fault over a considerable distance in eastern Alexander Island. The relationship between the LeMay Group and the Fossil Bluff Formation is discussed later (p. 60).

The Latady Formation of the Lassiter and Black coasts is dominated by siltstones and mudstones but further south, in the Orville Coast area, sandstones predominate. These strata contain middle to late Jurassic fossils and are probably shallow-water deposits (Thomson and others, 1978). At one locality the sequence is capped by 1000 m of dacitic and andesitic lava flows and ash-flows tuffs (Williams and others, 1972). The sandstones are mostly wackes with high quartz to feldspar ratios, and many are more lithic than those of the LeMay Group (Fig. 58). Lithic fragments are mostly volcanic, but sedimentary and metavolcanic clasts are also abundant, and some plutonic material is present. The rocks are tightly folded, with axes parallel to the trend of the Antarctic Peninsula (Williams and others, 1972; Kellogg, 1979). Grikurov (1972) correlated part of the LeMay Group of central Alexander Island (his 'upper terriginous series') with the Latady Formation on the basis of Jurassic–Cretaceous K-Ar dates from rocks in central Alexander Island, and some lithological similarities. Although it cannot be denied that some parts of the LeMay Group may be the same age as Latady Formation, there is no evidence for the type of direct correlation proposed by Grikurov, and it is likely that the two sequences were deposited in different tectonic settings (p. 60).

B. THE TECTONIC FRAMEWORK OF ALEXANDER ISLAND AND THE ANTARCTIC PENINSULA

In this final section, the findings of the preceding chapters are summarized, and a plate tectonic model for the (?) late Palaeozoic to Mesozoic history of Alexander Island and the Antarctic Peninsula discussed. Finally the evolution of the region is discussed within the wider context of the western margin of Gondwana prior to its break-up.

1. *Plate tectonic setting of the LeMay Group*

The predominance of sandy flysch of plutonic, metamorphic and volcanic derivation in the LeMay Group indicates an abundant supply of sediment, probably from the erosion of a mature volcanic arc situated on a crystalline basement. Sedimentary structures and facies associations suggest that much of the sediment was redeposited by turbidity currents or similar mechanisms in a submarine fan environment. The deformation and low-grade intermediate to higher-pressure metamorphism undergone by these rocks suggest that they accumulated in a subduction complex formed by underthrusting of the sediment prism as Pacific Ocean crust was subducted at a trench along the western margin of the Antarctic Peninsula, an idea first put forward by Suárez (1976). The rocks display complex polyphase folding and are locally pervasively sheared and disrupted to form broken formation and possibly tectonic mélange. Pillow lavas and greenstones often associated with this type of deformation may be tectonically emplaced and of oceanic origin, but geochemical evidence for this is inconclusive. The intermediate to high-pressure facies series with local attainment of blueschist facies is consistent with a process of deep burial followed by rapid uplift affecting parts of the complex. In the north of the island, more highly metamorphosed rocks crop out on the eastern side, perhaps indicating that deeply buried and metamorphosed parts of the complex lie on the landward side of (?) more recently accreted, less metamorphosed rocks, a feature to be expected from present understanding of subduction processes (Ernst, 1975). The LeMay Group may represent part of a paired metamorphic belt, the gneisses of Palmer Land constituting the corresponding zone of low-pressure metamorphism.

The volcaniclastic rocks of the Lully Foothills Formation differ from other rocks of the LeMay Group in that they contain abundant vitroclastic material, and clear evidence of shallow-water deposition in the form of a neritic fauna. They appear to have undergone similar polyphase deformation, although cataclastic effects have not been reported. Edwards (1982) suggested that these rocks represent 'the final stages of the infilling of the arc-trench gap and are precursors of the oceanward migration of the volcanic island arc'. Smellie (1981) tentatively suggested that they formed part of an extensive Triassic fore-arc basin. This certainly seems to be the most satisfactory explanation for the apparently anomalous characteristics of the Lully Foothills Formation. Such a fore-arc basin would probably have been floored by subduction complex, since blueschist facies rocks crop out east and west of the Lully Foothills.

The Lully Foothills Formation is the only part of the LeMay Group that is known to be of Triassic age and, if the above interpretation is correct, parts of the subduction complex are of a similar age or slightly older. However, radiolarian evidence indicates that rocks in northern Alexander Island are as young as mid-Cretaceous. It is therefore possible that part of the LeMay Group may belong to a younger subduction complex, and may be partly coeval with the late Jurassic–early Cretaceous fore-arc basin (Thomson, 1982) in which the Fossil Bluff Formation accumulated.

The above interpretation raises questions concerning the timing and significance of deformation in Alexander Island. In central Alexander Island the LeMay Group was folded during an early Mesozoic 'Gondwanian' deformation, whereas in northern Alexander Island, folding took place between mid-Cretaceous and early Tertiary (p. 43). Dalziel (1982) has suggested that the major pre-Upper Jurassic unconformity recognized widely in the Antarctic Peninsula may represent a hiatus in subduction after the Gondwanian deformation, and this assumption has tended to shape recent interpretations of Antarctic Peninsula geology. However, it is clear from the evidence in Alexander Island that subduction, accretion and deformation may have taken place more or less continuously from the late Palaeozoic or early Mesozoic until the mid-Cretaceous or later, although the occurrence of more than one distinct episode of subduction remains a possibility. Unfortunately, owing to structural complexity the relationship between the Cretaceous radiolarian cherts and the rest of the sequence is not clear. Although Thomson and others (1983) suggested that they represent ponded sediment on an older accretionary wedge, the author favours the view that the LeMay Group includes accreted material ranging in age at least from Triassic to mid-Cretaceous and

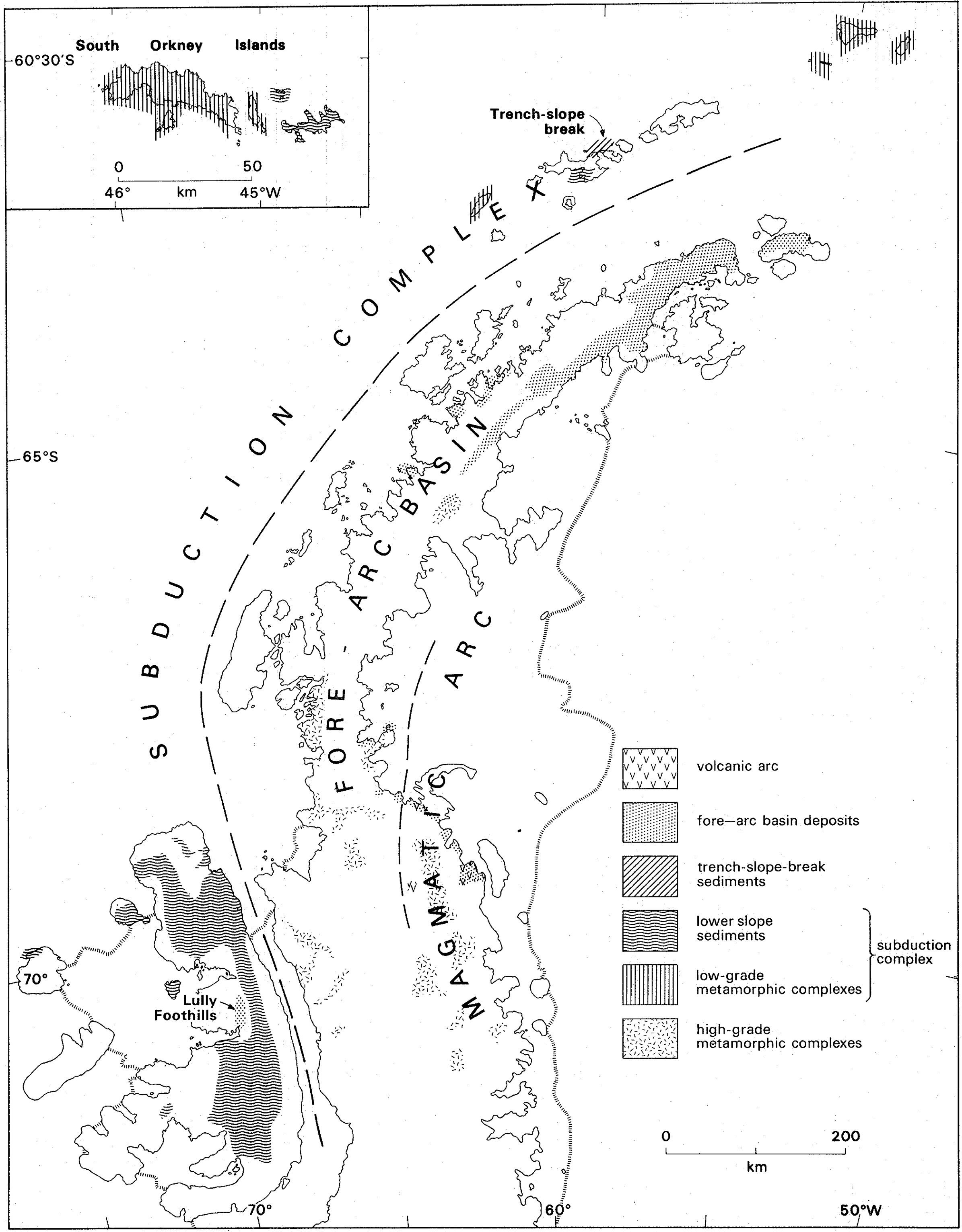


FIGURE 59
Distribution of stratotectonic elements constituting the postulated late Palaeozoic–early Mesozoic arc-trench system in the Antarctic Peninsula, based on Smellie (1981).

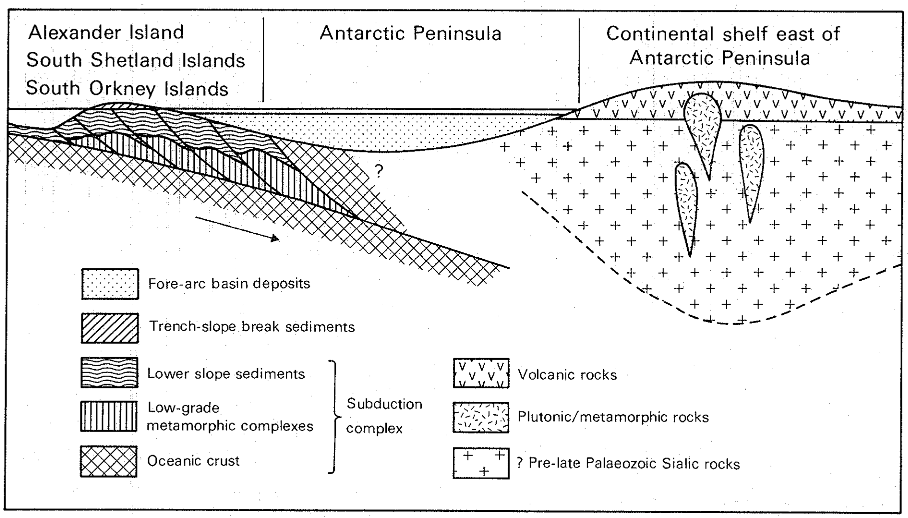


FIGURE 60
Schematic cross-section of the postulated late Palaeozoic–early Mesozoic arc-trench system.

probably later, bearing in mind that subduction west of Alexander Island was probably active well into the early Tertiary (Burn, 1981).

2. *Evidence for a complete arc-trench system in the Antarctic Peninsula region during the late Palaeozoic–early Mesozoic*

The (?) late Palaeozoic–early Mesozoic sedimentary sequences and metamorphic rocks of the Antarctic Peninsula and off-lying islands have been interpreted as a late Palaeozoic–early Mesozoic arc-trench gap assemblage which accumulated off the Pacific margin of Gondwana (e.g. Suárez, 1976; de Wit, 1977; Dalziel, 1982). Smellie (1981) identified four strato-tectonic elements of the assemblage:

i. Subduction complex.
ii. Trench-slope break sediments.
iii. Fore-arc basin.
iv. Magmatic arc.

Furthermore, there is also evidence that some gneisses and plutonic rocks represent a leading edge of continental basement on which the postulated arc was founded. The main points of this interpretation are summarized below, and the distribution of the postulated stratotectonic elements shown in Figs. 59 and 60.

a. *Subduction complex*. The clastic sequences and metamorphic complexes of the South Shetland Islands and South Orkney Islands, together with the LeMay Group of Alexander Island, constitute the subduction complex. Factors pertinent to this interpretation can be summarized:

i. The sequences in question are peripheral to the postulated continental mass of Gondwana.
ii. The rocks have undergone complicated histories of deformation, with low to very low-grade metamorphism locally attaining blueschist facies.
iii. Ultrabasic rocks are associated with blueschists in the Elephant and Clarence islands group, and possibly represent obducted or disrupted oceanic lithosphere.
iv. Thick flysch-type sequences, although not diagnostic of an active trench environment, are the dominant lithologies.
v. As yet there is no evidence for the sequences in question being floored by continental crust.

Smellie suggested that the metamorphic complexes are a 'mélange zone' representing a deeper structural level in the subduction complex, although no deformation approaching that of *tectonic mélange* or *broken formation* (terminology used in this report, p. 51) has been described. The timing of deformation and metamorphism of the subduction complex is not well known (p. 42), but a Rb-Sr isochron of 289 [280] Ma for schists from the South Orkney Islands (Rex, 1976) suggests that the metamorphic complex was in existence by late Palaeozoic times. Although late Precambrian acritarchs have been found in the metamorphic rocks of Clarence Island (Iltchenko, 1972) these may represent material rafted in on a subducted plate rather than part of a Precambrian shield.

b. *Trench-slope break sediments*. The undeformed Triassic alluvial Williams Point beds of Livingston Island (Fig. 55) were interpreted by Smellie as trench-slope break sediments, deposited during uplift of part of the subduction complex to form an emergent island chain.

c. *Fore-arc basin*. The Trinity Peninsula Group of north-eastern Graham Land, and some of its possible correlatives on Foyn, Oscar II and Bowman coasts (p. 56), together with the Lully Foothills Formation of Alexander Island, may constitute parts of a fore-arc basin, partly Triassic in age, and coeval with the subduction complex. Evidence for such an interpretation is not strong, but can be summarized:

i. The sequences in question are situated on the continental side of the subduction complex.
ii The Trinity Peninsula Group is probably floored at least in part by continental crust (Gledhill and others, 1982).

iii. Parts of the Trinity Peninsula Group and its (?) correlatives on the Antarctic Peninsula contain evidence for shallow water deposition, previously regarded as anomalous: limestone within the Trinity Peninsula Group (Fleet, 1965); shallow water features in the Legoupil Formation (Halpen, 1964; Thomson, 1975) and the sediments of Joerg Peninsula (Stubbs, 1968).

iv. The Lully Foothills sequence differs from the rest of the LeMay Complex in containing a shallow water fauna and an abundance of vitric pyroclastic material (p. 15). Smellie also included rocks in the Walton Mountains within the fore-arc, but these are now believed to be of deep-water origin (p. 14).

This tectonic setting for the Trinity Peninsula Group is supported by Hyden and Tanner (1981) who suggested that the Gibbs Island dunite/serpentine complex may constitute part of an ophiolite floor to the basin. They also demonstrated on compositional grounds that the detrital garnets within the Trinity Peninsula Group are unlikely to be derived from the metamorphic rocks of the subduction complex. There are, however, two main objections to the above model:

i. The Trinity Peninsula Group, in contrast to fore-arc basins identified elsewhere, contains little volcaniclastic detritus, although Fig. 57 suggests that the lithic content of most Trinity Peninsula Group sandstones is rather richer in volcanic material than sandstones from the Miers Bluff Formation, possibly part of the coeval trench fill.

ii. The Trinity Peninsula Group has undergone polyphase deformation with local development of broken formation, and has in parts attained greenschist facies metamorphism. Fore-arc basin sediments are typically less deformed and metamorphosed than their related subduction complexes.

d. *Magmatic arc*. Poorly known quartz-keratophyres and tuffs in the Mobiloil Inlet area (Fraser and Grimley, 1972) together with deformed and metamorphosed basalts, andesites, quartz-keratophyres and tuffs in north-eastern Palmer Land (Davies, 1976) were taken as evidence for a late Palaeozoic–early Mesozoic volcanic arc by Smellie (1981), inferring that the axis of the arc lies on the wide continental shelf east of the Antarctic Peninsula. However, a single-sample whole-rock Rb-Sr provisional model age of 140 Ma obtained from the Engel Peaks granite (personal communication from R. J. Pankhurst) which is unconformably overlain by the metasedimentary and metavolcanic succession of northern Palmer Land implies that the latter rocks may be correlatives of the middle–late Jurassic Latady Formation of Black, Lassiter and Orville coasts.

Plutonic activity related to the arc is also difficult to demonstrate, although probably the best indicators are the late Triassic–early Jurassic dates obtained from gneisses and plutonic rocks in Marguerite Bay (Gledhill and others, 1982). Gneisses near Jason Peninsula, which have yielded 237–243 [242–248] Ma dates (Rex, 1976), may represent roots of a late Palaeozoic arc although these dates can also be interpreted as evidence for early Palaeozoic or earlier continental basement (see below).

e. *Pre-late Palaeozoic sialic basement*. Evidence for sialic basement of this age in the Antarctic Peninsula is meagre. The close juxtaposition of the geneisses near Jason Peninsula, which have yielded Permian dates, with low grade rocks of the Trinity Peninsula Group suggests that the two may be separated by a major unconformity, the gneisses forming part of the floor to the Trinity Peninsula Group. The dates from the gneisses would then reflect partial resetting of isotopic systems by more recent thermal events. It is possible that some of the high-grade banded gneisses, amphibolites and migmatites which crop out extensively in western Palmer Land may represent older sialic crust.

3. *Jurassic–Cretaceous volcanic arc-trench system in the Antarctic Peninsula*

Although identification of elements of a (?) late Palaeozoic–early Mesozoic volcanic arc is rather speculative, the corresponding components of a late Jurassic–Cretaceous arc in the Antarctic Peninsula can be recognized more confidently (Suárez, 1976; Thomson, 1982). The calc-alkaline lavas and pyroclastic rocks of the Antarctic Peninsula Volcanic Group, which rest uncomformably on the Trinity Peninsula Group, constitute considerable evidence for an ensialic volcanic arc that was active from at least middle Jurassic to early Cretaceous times. The shallow marine and deltaic sediments of the Fossil Bluff Formation are considered to represent a late Jurassic–early Cretaceous fore-arc basin, whereas a back-arc environment has been proposed for the mainly late Jurassic Latady Formation of eastern Palmer Land and Orville Coast. Early Cretaceous sediments of Crabeater Point near Mobiloil Inlet may represent the continuation of back-arc sedimentation into the Cretaceous. The identification of a subduction complex related to this Jurassic–Cretaceous arc has remained problematical, although evidence of an easterly source for parts of the Fossil Bluff Formation led Thomson (1982) to speculate that the rocks of the LeMay Group may have been uplifted to form a non-volcanic outer arc which supplied detritus to the fore-arc basin. Suárez (1976) noted that the deformed rocks of Alexander Island had characteristics of a trench assemblage, but their age, considered to be (?) late Palaeozoic–early Mesozoic, suggested that they were accreted during an early stage of subduction. However, the recent discovery that part of the LeMay Group is probably of mid-Cretaceous age (p. 7) implies that some of it may have accumulated seaward of a Jurassic–Cretaceous volcanic arc.

4. *The Pacific margin of Gondwana*

The deformation of the 'greywacke-shale' sequences and some metamorphic terrains in the Antarctic Peninsula area has been attributed to an early Mesozoic 'Gondwanian' event. This term was originally coined by du Toit (1937) in referring to the folding of this age undergone by sedimentary sequences in South America, South Africa and Australia which were once united in the 'Samfrau' geosyncline before the break-up of Gondwana. It is now widely believed that this deformation was related to subduction of Pacific Ocean crust beneath the western margin of Gondwana (de Wit, 1977; Dalziel and Elliot, 1973; Dalziel, 1982). The identification of components of an arc-trench gap in the Antarctic Peninsula area is outlined above.

Attention has been drawn to the similarities between the greywacke-shale sequences of the Antarctic Peninsula and the Madre de Dios basin of southern South America (Dalziel and Elliot, 1973) and Dalziel (1982) has identified fore-arc assemblages in that region. The New Zealand geosyncline represents rocks that accumulated at an active subduction zone on the south-west margin of Gondwana between Permian and early Jurassic times (Carter and others, 1978). In present Gondwana reconstructions (e.g. Molnar and others, 1975) New Zealand is placed adjacent to Lesser Antarctica, near Marie Byrd Land, and Hyden and Tanner (1981) have pointed out a number of features that the Torlesse terrain of New Zealand (Coombs and others, 1976) has in common with the Trinity Peninsula Group:

i. It consists of greywackes and argillites of deep-water origin with uncommon occurrences of chert and red and green argillite.
ii. It is derived from a similar mixed provenance of plutonic sedimentary and volcanic rocks.
iii. Pillow lavas occur within the sediments.
iv. Deformation is complex and multiphase; locally mélange zones and broken formation are developed (Bradshaw, 1973).
v. It has undergone similar low-grade metamorphism largely of zeolite and prehnite-pumpellyite facies.

Hyden and Tanner suggest that both the Torlesse and the Trinity Peninsula Group were deposited in similar fore-arc basin environments. However, it is clear that the LeMay Group (which is considered to be a subduction complex) also has the above features in common with the Torlesse. The fact that the lavas of the Torlesse are not considered to be parts of an ophiolite suite (Coombs and others, 1976), whereas those of the LeMay Group are possibly of oceanic origin may be an important difference and relevant to the interpretation of the tectonic settings of both sequences, but there is insufficient evidence from Alexander Island to resolve this at present. Despite the fact that the identification of components of the fore-arc assemblage remains speculative, there is a growing body of evidence that a continuous late Palaeozoic–early Mesozoic subduction zone existed along the Pacific margin of Gondwana from South America, along the Antarctic Peninsula to New Zealand.

VIII. ACKNOWLEDGEMENTS

I wish to thank Drs M. R. A. Thomson, J. L. Smellie and P. W. G. Tanner for helpful discussion during the preparation of this report. Thanks are also due to I. E. Henderson and R. Atkinson for their assistance in the field and Dr G. Hyden for carrying out electron microprobe analyses.

IX. REFERENCES

Adie, R. J. 1954. The petrology of Graham Land: 1. The Basement Complex; early Palaeozoic plutonic and volcanic rocks. *Falkland Islands Dependencies Survey Scientific Reports*, No. 11, 22 pp.

Adie, R. J. 1957. The petrology of Graham Land: III. Metamorphic rocks of the Trinity Peninsula Series. *Falkland Islands Dependencies Survey Scientific Reports*, No. 20, 26 pp.

Aitkenhead, N. 1975. The geology of the Duse Bay–Larsen Inlet area, north-east Graham Land (with particular reference to the Trinity Peninsula Series). *British Antarctic Survey Scientific Reports*, No. 51, 62 pp.

Allen, J. R. L. 1970. The sequence of sedimentary structures in turbidites with special reference to dunes. *Scottish Journal of Geology,* **6**, 146–61.

Anckorn, J. F. 1977. *The geology of part of north-eastern Palmer Land, Antarctica.* M.Sc. thesis, University of Birmingham, 77 pp. [Unpublished.]

Bailey, E. H., Irwin, W. P. *and* Jones, D. L. 1964. Franciscan and related rocks and their significance in the geology of western California. *Bulletin California Division of Mines and Geology*, **183**, 1–176.

Ballance, P. F. 1964. Streaked-out mud ripples below Miocene turbidites, Puriri Formation, New Zealand. *Journal of Sedimentary Petrology*, **34**, 91–101.

Bell, C. M. 1973*a*. The geology of Beethoven Peninsula, south-western Alexander Island. *British Antarctic Survey Bulletin*, No. 32, 75–83.

Bell, C. M. 1973*b*. The geology of southern Alexander Island. *British Antarctic Survey Bulletin*, Nos. 33 and 34, 1–16.

Bell, C. M. 1974. Geological observations in northern Alexander Island. *British Antarctic Survey Bulletin*, No. 39, 35–44.

Bell, C. M. 1975. Structural geology of parts of Alexander Island. *British Antarctic Survey Bulletin*, Nos. 41 and 42, 43–58.

Bishop, D. G. 1972. Progressive metamorphism from prehnite-pumpellyite to greenschist facies in the Dansey Pass area, Otago, New Zealand. *Geological Society of America Bulletin*, **83**, 3177–97.

Black, P. M. 1974. Mineralogy of New Caledonian metamorphic rocks. *Contributions to Mineralogy and Petrology,* **45**, 281–8.

Boles, R. J. *and* Coombs, D. S. 1977. Zeolite facies alteration of sandstones in the Southland syncline, New Zealand. *American Journal of Science,* **277**, 982–1012.

Bouma, A. H. 1962. *Sedimentology of some flysch deposits.* Amsterdam, Elsevier, 168 pp.

Bradshaw, J. D. 1973. Allochthonous Mesozoic fossil localities in mélange within the Torlesse rocks of North Canterbury. *Journal of the Royal Society of New Zealand*, **3**, 161–7.

Burn, R. W. 1981. Early Tertiary calc-alkaline volcanism on Alexander Island. *British Antarctic Survey Bulletin*, No. 53, 175–93.

Burn, R. W. *and* Thomson, M. R. A. 1981. Late Cenozoic tillites associated with intraglacial volcanic rocks, Lesser Antarctica. (*In* Hambrey, M. J. *and* Harland, W. B. *eds. Pre-Pleistocene tillites: a record of Earth's glacial history*. Project 38 of the International Geological Correlation Programme. Cambridge, Cambridge University Press.)

Care, B. W. 1980. The geology of Rothschild Island, north-west Alexander Island. *British Antarctic Survey Bulletin*, No. 50, 87–112.

Care, B. W. In press. The petrology of the Rouen Mountains, northern Alexander Island. *British Antarctic Survey Bulletin*, No. 52.

Carter, R. M., Hicks, M. D., Morris, R. J. *and* Turnbull, I. M. 1978. Sedimentation patterns in an ancient arc–trench–ocean-basin complex: Carboniferous to Jurassic Rangitata orogen, New Zealand. (*In* Stanley, D. J. *and* Kelling, G. *eds. Sedimentation in submarine canyons, fans and trenches*. Stroudsberg, Pennsylvania, Dowden Hutchinson and Ross, 340–61.)

Connelly, W. 1978. Uyak complex, Kodiac Islands, Alaska: a Cretaceous subduction complex. *Geological Society of America Bulletin,* **89**, 755–69.

Coombs, D. S. 1960. Lower grade mineral facies in New Zealand. *Report. International Geological Congress, 21st session, Norden, 1960*, **13**, 339–51.

Coombs, D. S. 1971. Present status of the zeolite facies. *Molecular sieve zeolites – I, Advances in Chemistry Series*, No. 101, American Chemical Society, 317–27.

Coombs, D. S., Ellis, A. J., Fyfe, W. S. *and* Taylor, A. M. 1959. The zeolite facies, with comments on the interpretation of hydrothermal synthesis. *Geochimica et Cosmochimica Acta*, **17**, 53–107.

Coombs, D. S., Horodyski, R. J. *and* Naylor, R. S. 1970. Occurrence of prehnite-pumpellyite facies metamorphism in northern Maine. *American Journal of Science*, **268**, 142–56.

Coombs, D. S., Landis, C. A., Norris, R. J., Sinton, J. M., Borns, D. J. *and* Craw, D. C. 1976. The Dun Mountain ophiolite belt, New Zealand, its tectonic setting, constitution and origin, with special reference to the southern portions. *American Journal of Science*, **276**, 561–603.

Cowan, D. S. *and* Boss, R. F. 1978. Tectonic framework of the south-west Kenai Peninsula, Alaska. *Geological Society of America Bulletin*, **89**, 155–82.

Dalziel, I. W. D. 1971. Structural studies in the Scotia Arc: the South Orkney Islands (R/V Hero Cruise 71–1). *Antarctic Journal of the United States*, **6**, No. 4, 124–6.

Dalziel, I. W. D. 1972. Large scale folding in the Scotia Arc. (*In* Adie, R. J., *ed. Antarctic geology and geophysics*. Oslo, Universitetsforlaget, 47–55.)

Dalziel, I. W. D. 1976. Structural studies in the Scotia Arc: "basement" rocks of the south Shetland Islands (R/V Hero Cruise 76–1). *Antarctic Journal of the United States*, **11**, No. 2, 75–6.

Dalziel, I. W. D. 1982. The pre-Jurassic history of the Scotia Arc: a review and progress report. (*In* Craddock, C. *ed. Antarctic geoscience*. Madison, University of Wisconsin Press.)

Dalziel, I. W. D. *and* Elliot, D. H. 1973. The Scotia arc and Antarctic margin. (*In* Stehli, F. G. *and* Nairn, A. E. M. *eds. The ocean basins and margins,* Vol. 1. New York, Plenum Publishing Corporation, 171–246.)

Dalziel, I. W. D., Elliot, D. H., Jones, D. L., Thomson, J. W., Thomson, M. R. A., Wells, N. A. *and* Zinsmeister, W. J. 1981. The geological significance of some Triassic microfossils from the South Orkney Islands, Scotia Ridge. *Geological Magazine*, **118**, No. 1, 15–25.

Davies, T. G. 1976. *The geology of part of northern Palmer Land, Antarctica*. Ph.D. thesis, University of Birmingham, 152 pp. [Unpublished.]

de Wit, M. J. 1977. The evolution of the Scotia arc as a key to the reconstruction of Gondwanaland. *Tectonophysics*, **37**, 53–81.

du Toit, A. L. 1937. *Our wandering continents*. Edinburgh, Oliver and Boyd.

Dzulynski, S. *and* Walton, E. K. 1965. Sedimentary features of flysch and greywackes. *Developments in Sedimentology, 7*. Amsterdam, Elsevier.

Dzulynski, S., Ksiazkiewicz, M. *and* Keunen, P. H. 1959. Turbidites of the flysch of the Polish Carpathian Mountains. *Geological Society of America Bulletin*, **70**, 1089–118.

Edwards, C. W. 1980*a*. New evidence of major faulting on Alexander Island. *British Antarctic Survey Bulletin*, No. 49, 15–20.

Edwards, C. W. 1980*b*. Early Mesozoic marine fossils from central Alexander Island. *British Antarctic Survey Bulletin*, No. 49, 33–58.

Edwards, C. W. 1980*c*. *The geology of eastern and central Alexander Island*. Ph.D. thesis, University of Birmingham, 228 pp. [Unpublished.]

Edwards, C. W. 1982. Further palaeontological evidence of Triassic sedimentation in western Antarctica. (*In* Craddock, C. *ed. Antarctic geoscience*. Madison, University of Wisconsin Press.)

Elliot, D. H. 1965. Geology of north-west Trinity Peninsula, Graham Land. *British Antarctic Survey Bulletin*, No. 7, 1–24.

Elliot, D. H. 1966. Geology of the Nordenskjöld Coast and a comparison with north-west Trinity Peninsula, Graham Land. *British Antarctic Survey Bulletin*, No. 10, 1–43.

Elliot, D. H. 1967. The geology of Joinville Island. *British Antarctic Survey Bulletin*, No. 12, 23–40.

Elliot, D. H. 1975. Tectonics of Antarctica: a review. *American Journal of Science*, **275 A**, 45–106.

Elliott, M. H. 1974. Stratigraphy and sedimentary petrology of the Ablation Point area, Alexander Island. *British Antarctic Survey Bulletin*, No. 39, 87–113.

Ernst, W. G. 1975. *Subduction zone metamorphism*. Stroudsberg, Pennsylvania, Dowden Hutchinson and Ross.

Ernst, W. G., Seyi, Y., Onuki, H. *and* Gilbert, M. C. 1970. Comparative study of low-grade metamorphism in the California coast ranges and the outer metamorphic belt of Japan. *Memoirs. Geological Society of America*, **124**, 276 pp.

Essene, E. G. *and* Fyfe, W. S. 1967. Omphacite in Californian metamorphic rocks. *Contributions to Mineralogy and Petrology*, **15**, 1–23.

Fleet, M. 1965. Metamorphosed limestone in the Trinity Peninsula series of Graham Land. *British Antarctic Survey Bulletin*, No. 7, 73–6.

Fleet, M. 1968. The geology of Oscar II Coast, Graham Land. *British Antarctic Survey Scientific Reports*, No. 59, 46 pp.

Floyd, P. A. *and* Winchester, J. A. 1975. Magma type and tectonic setting using immobile elements. *Earth and Planetary Science Letters*, **27**, 211–18.

Floyd, P. A. *and* Winchester, J. A. 1978. Identification and discrimination of altered and metamorphosed volcanic rocks using immobile elements. *Chemical Geology*, **21**, 291–306.

Fraser, A. G. *and* Grimley, P. H. 1972. The geology of parts of the Bowman and Wilkins Coast, Antarctic Peninsula. *British Antarctic Survey Scientific Reports*, No. 67, 59 pp.

Gledhill, A., Rex, D. C. *and* Tanner, P. W. G. 1982. K-Ar and Rb-Sr geochronology of igneous and metamorphic rocks suites from the Antarctic Peninsula. (*In* Craddock, C. *ed. Antarctic geoscience*. Madison, University of Wisconsin Press.)

Grikurov, G. E. 1971. Geologischeskoe stroenie tsentral'noy chasti Zemli Aleksandra I [The geological structure of the central part of Alexander I Land]. (*In Antarktika, Mezhduvedomstvennaya komissiya po izucheniyu Antarktiki* [Antarctica. Interdepartmental commission for the study of the Antarctic]. Moskva, Izdatel'stvo Nauka, 13–42.)

Grikurov, G. E. 1972. *Geology of the Antarctic Peninsula* (translated from Russian). New Delhi, Amerind Publishing Company.

Grikurov, G. E. *and* Dibner, A. F. 1968. Novye dannye o serii Triniti (C_{1-3}) v zapadnoy Antarktide. *Doklady Academii Nauk SSSR*, Geology, 179, No. 2, 410–12. [English translation: More information on the Trinity Series (C_{1-3}) of western Antarctica. *Doklady (Proceedings) of the Academy of Sciences of the USSR*, Geological Sciences Section, **179**, 39–41.]

Grikurov, G. E., Krylov, A. Ya. *and* Silin, Yu. I. 1967. Absolyutnvy vozrast netkotorykh porod dugi Skotiya i Zemli Aleksandra I (Zapadnaya Antarktika). *Doklady Academii Nauk SSSR*, Geology, **172**, 168–171. [English translation: Absolute age of some rocks from the Scotia arc and Alexander I Land (Western Antarctica). *Doklady (Proceedings) of the Academy of Sciences of the USSR*, Geological Sciences Section, **172**, 19–22.]

Halpern, M. 1964. Cretaceous sedimentaton in the 'General Bernardo O'Higgins' area of north-west Antarctic Peninsula. (*In* Adie, R. J. *ed. Antarctic geology*. Amsterdam, North-Holland Publishing Company, 334–47.)

Halpern, M. 1972. Rb-Sr total-rock and mineral ages from the Marguerite Bay area, Kohler Range and Fosdick Mountains. (*In* Adie, R. J. *ed. Antarctic geology and geophysics*. Oslo, Universitetsforlaget, 197–204.)

Hashimoto, M. 1966. On the prehnite-pumpellyite metagreywacke facies. *Journal of the Geological Society of Japan*, **72**, 253–65.

Higgins, M. W. 1971. Cataclastic rocks. *Professional Paper. United States Geological Survey*, No. 687, 97 pp.

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

Horne, R. R. 1967. Structural geology of part of south-eastern Alexander Island. *British Antarctic Survey Bulletin*, No. 11, 1–22.

Horne, R. R. 1968. Petrology and provenance of the Cretaceous sediments of south-eastern Alexander Island. *British Antarctic Survey Bulletin*, No. 17, 73–82.

Horne, R. R. 1969. Sedimentology and palaeogeography of the Lower Cretaceous depositional trough of south-eastern Alexander Island. *British Antarctic Survey Bulletin*, No. 22, 61–76.

Hsü, K. J. 1974. Mélanges and their distinction from olistostromes. (*In* Dott, R. H. *and* Shaver, R. H. *eds. Modern and ancient geosynclinal sedimentation.* Tulsa, Society of Economic Palaeontologists and Mineralogists Special Publication, No. 19, 321–33.)

Hubert, J. F. 1966. Sedimentary history of upper Ordovician geosynclinal rocks, Girvan, Scotland. *Journal of Sedimentary Petrology*, **36**, 677–99.

Hutton, C. O. *and* Turner, F. J. 1936. Metamorphic zones in north-west Otago. *Transactions of the Royal Society of New Zealand*, **65**, 405–6.

Hyden, G. *and* Tanner, P. W. G. 1981. Late Palaeozoic–early Mesozoic fore-arc basin sedimentary rocks and the Pacific Margin in western Antarctica. *Geologische Rundschau*, **70**, 529–41.

Iltchenko, L. N. 1972. Late Precambrian acritarchs of Antarctica. (*In* Adie, R. J. *ed. Antarctic geology and geophysics*. Oslo, Universitetsforlaget, 599–602.)

Irvine, T. N. *and* Barager, W. R. A. 1971. A guide to the chemical classification of the common volcaniclastic rocks. *Canadian Journal of Earth Sciences*, **8,** 523–48.

Karig, D. E. *and* Sharman, G. F. 1975. Subduction and accretion in trenches. *Geological Society of America Bulletin*, **86,** 377–89.

Kellog, K. S. 1979. Structural geology of Orville Coast and eastern Ellsworth Land. *Antarctic Journal of the United States*, **14,** No. 5, 19–21.

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

Landis, C. A. *and* Bishop, D. G. 1972. Plate tectonics and regional stratigraphic–metamorphic relations in the southern part of the New Zealand geosyncline. *Geological Society of America Bulletin*, **83,** 2267–84.

Laudon, T. S. 1972. Stratigraphy of eastern Ellsworth Land. (*In* Adie, R. J. *ed. Antarctic geology and geophysics*. Oslo Universitetsforlaget, 215–23.)

Leitch, E. C. 1975. Zonation of low grade regional metamorphic rocks, Nambucca slate belt, northeastern New South Wales. *Journal of the Geological Society of Australia*, **22,** 413–22.

Liou, J. G. 1971. Synthesis and stability relations of prehnite. *American Mineralogist*, **56,** 507–31.

Macdonald, G. A. *and* Katsura, T. 1964. Chemical composition of Hawaiian lavas. *Journal of Petrology*, **5,** 82–133.

Marsh, A. F. 1968. *Geology of parts of Oscar II and Foyn coasts, Graham Land*. Ph.D. thesis, University of Birmingham, 291 pp. [Unpublished.]

Miller, J. A. 1960. Potassium-argon ages of some rocks from the South Atlantic. *Nature, London*, **187,** No. 4742, 1019–20.

Miyashiro, A. 1972. Metamorphism and related magmatism in plate tectonics. *American Journal of Science*, **272,** 629–56.

Miyashiro, A. 1973*a*. *Metamorphism and metamorphic belts*. Old Woking, Surrey, Unwin Brothers Ltd, 491 pp.

Miyashiro, A. 1973*b*. The Troodos ophiolite complex was probably formed in an island arc. *Earth and Planetary Science Letters*, **19,** 218–24.

Molnar, P., Atwater, T., Mammericky, J. *and* Smith, S. M. 1975. Magnetic anomalies, bathymetry and the tectonic evolution of the South Pacific since the late Cretaceous. *Geophysical Journal of the Royal Astronomical Society*, **40,** 383–420.

Mutti, E. *and* Ricci-Lucchi, F. 1975. Turbidite facies and facies environments. (*In: IX International Sedimentological Congress, Nice*. Field trip A11, 21–36.)

Nisbet, E. G. *and* Pearce, J. A. 1977. Clinopyroxene composition in mafic lavas from different tectonic settings. *Contributions to Mineralogy and Petrology*, **63,** 149–60.

Pearce, J. A. 1976. Statistical analysis of major element patterns in basalts. *Journal of Petrology*, **17,** 15–43.

Pearce, J. A. *and* Cann, J. R. 1973. Tectonic setting of basic volcanic rocks determined using trace element analysis, *Earth and Planetary Science Letters*, **19,** 290–300.

Pearce, T. H., Gorman, B. E. *and* Birkett, T. C. 1975. The TiO_2–K_2O–P_2O_5 diagram: a method of discriminating between oceanic and non-oceanic basalts. *Earth and Planetary Science Letters*, **24,** 419–26.

Pettijohn, F. J., Potter, P. E. *and* Siever, R. 1972. *Sand and sandstones*. New York, Springer-Verlag.

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

Rex, D. C. 1976. Geochronology in relation to the stratigraphy of the Antarctic Peninsula. *British Antarctic Survey Bulletin*, No. 43, 49–58.

Rivano, S. *and* Cortes, R. 1976. Note on the presence of the lawsonite sodic amphibole association on Smith Island, South Shetland Islands, Antarctica. *Earth and Planetary Science Letters*, **29,** 34–36.

Rowe, P. J. 1973. The geology of the area between Riley and Bertram Glaciers, Palmer Land. *British Antarctic Survey Bulletin*, No. 35, 51–72.

Rupke, N. A. 1978. Deep clastic seas. (*In* Reading, H. G. *ed. Sedimentary environments*. Oxford, Blackwell Scientific Publications, 372–415.)

Saunders, A. D., Tarney, J., Stern, C. R. *and* Dalziel, I. W. D. 1979. Geochemistry of Mesozoic marginal basin floor igneous rocks from southern Chile. *Geological Society of America Bulletin*, **90,** 237–58.

Schopf, J. M. 1973. Plant material from the Miers Bluff Formation of the South Shetland Islands. *Report. Institute of Polar Studies. Ohio State University Research Foundation*, No. 45, 45 pp.

Seely, D. R., Vail, P. R. *and* Walton, G. G. 1974. Trench slope model. (*In* Burke, C. A. *and* Drake, C. L. *eds. The geology of continental margins*. New York, Springer-Verlag, 249–60.)

Seki, Y. 1969. Facies series in low grade metamorphism. *Journal of the Geological Society of Japan*, **75,** 255–66.

Seki, Y., Onuki, H., Oba, T. *and* Mori, R. 1971. Sanbagawa metamorphism in the central Kii Peninsula, Japan. *Japanese Journal of Geology and Geography*, **41,** 65–78.

Singleton, D. G. 1980. The geology of the central Black Coast, Palmer Land. *British Antarctic Survey Scientific Reports*, No. 102, 50 pp.

Skinner, A. C. 1973. Geology of northwestern Palmer Land between Eureka and Meiklejohn Glaciers. *British Antarctic Survey Bulletin*, No. 35, 1–22.

Smellie, J. L. 1979. *Aspects of the geology of the South Shetland Islands*. Ph.D. thesis, University of Birmingham, 198 pp. [Unpublished.]

Smellie, J. L. 1981. A complete arc-trench system recognised in Gondwana sequences of the Antarctic Peninsula region. *Geological Magazine*, **118,** 139–59.

Smellie, J. L. *and* Clarkson, P. D. 1975. Evidence for pre-Jurassic subduction in western Antarctica. *Nature, London*, **258,** No. 5537, 701–2.

Smith, C. G. 1977. *The geology of parts of the west coast of Palmer Land*. Ph.D. thesis, University of Birmingham, 193 pp. [Unpublished.]

Smith, J. V. 1974. *Feldspar minerals*. Berlin, Springer-Verlag.

Stanley, D. J. *and* Unrug, R. 1972. Submarine channel deposits, fluxo-turbidites and other indicators of slope and base of slope environments in modern and ancient marine basins. (*In* Rigby, J. K. *and* Hamblin, W. K. *eds. Recognition of ancient sedimentary environments*. Tulsa, Oklahoma, Society of Economic Palaeontologists and Mineralogists Special Publication No. 16, 287–340.)

Starkey, J. 1959. Chess-board albite from New Brunswick, Canada. *Geological Magazine*, **96,** 141–5.

Stauffer, P. H. 1967. Grain flow deposits and their implication, Santa Ynez Mountains, California. *Journal of Sedimentary Petrology*, **37,** 487–508.

Steiger, R. H. *and* Jäger, E. 1977. Subcommission on geochronology. *Earth and Planetary Science Letters*, **36,** 359–62.

Stout, J. H. 1972. Phase petrology and mineral chemistry of coexisting amphiboles from Telemark, Norway. *Journal of Petrology*, **13,** 99–145.

Stubbs, G. M. 1968. *Geology of parts of Foyn and Bowman coasts, Graham Land*. Ph.D. thesis, University of Birmingham, 244 pp. [Unpublished.]

Suárez, M. 1976. Plate-tectonic model for southern Antarctic Peninsula and its relation to the southern Andes. *Geology*, **4,** 211–14.

Thomson, A. *and* Thomasson, M. R. 1969. Shallow to deep-water facies of the Dimple Limestone (Lower Pennsylvanian) Marthon region, Texas. (*In* Freidman, G. M. *ed. Depositional environments in carbonate rocks*. Tulsa, Oklahoma. Society of Economic Palaeontologists and Mineralogists Special Publication, No. 14, 57–77.)

Thomson, J. W. 1973. The geology of Powell, Christofferson and Michelsen islands, South Orkney Islands. *British Antarctic Survey Bulletin*, Nos. 33 and 34, 137–67.

Thomson, M. R. A. 1975. New palaeontological and lithological observations on the Legoupil Formation, north-west Antarctic Peninsula. *British Antarctic Survey Bulletin*, Nos. 41 and 42, 169–85.

Thomson, M. R. A. 1982. Mesozoic palaeogeography of western Antarctica. (*In* Craddock, C. *ed. Antarctic geoscience*. Madison, University of Wisconsin Press.)

Thomson, M. R. A., Laudon, T. S. *and* Boyles, J. M. 1978. Stratigraphical studies in Orville Coast and eastern Ellsworth Land. *Antarctic Journal of the United States*, **13,** No. 5, 9–10.

Thomson, M. R. A., Pankhurst, R. J. *and* Clarkson, P. D. 1983. The Antarctic Peninsula – A late Mesozoic–Cenozoic arc (Review). (*In* Oliver, R. L., James, P. R. *and* Jago, J. B. *eds. Antarctic Earth Science: Fourth International Symposium*. Cambridge, Cambridge University Press and Canberra, Australian Academy of Sciences, 289–94.)

Turner, F. J. 1935. Metamorphism of the Te Anua Series in the region north-west of Lake Wakatipu. *Transactions of the Royal Society of New Zealand*, **65,** 329–49.

Walker, R. G. 1976. Turbidites and associated coarse clastic deposits. *Geoscience Canada*, **3,** No. 1, 25–36.

Walker, R. G. *and* Mutti, E. 1973. Turbidite facies and facies associations. (*In* Middleton, G. V. *and* Bouma, A. H. *eds. Turbidites and deep-water sedimentation*. Anaheim, Society of Economic Palaeontologists and Mineralogists, Short course lecture notes, 119–57.)

Watanabe, T. 1974. Metamorphic zoning in the Sanbagawa and Chichibu belts in the Koshibu-gawa River area, Oshika district, central Japan, with special reference to pumpellyite-actinolite facies mineral assemblages. *Journal of the Geological Society of Japan*, **80**, 525–38.

WEST, S. M. 1974. The geology of the Danco Coast, Graham Land. *British Antarctic Survey Scientific Reports*, No. 84, 58 pp.

WILLIAMS, P. L. *and* ROWLEY, P. D. 1972. The composition of Jurassic sandstones, Lassiter Coast. *Antarctic Journal of the United States*, **7**, No. 5, 145–6.

WILLIAMS, P. L., SCHMIDT, D. L., PLUMMER, C. C. *and* BROWN, L. W. 1972. The geology of the Lassiter Coast area, Antarctic Peninsula: preliminary report. (*In* ADIE, R. J. *ed. Antarctic geology and geophysics*. Oslo, Universitetsforlaget, 143–8.)

WINKLER, H. G. F. 1965. *Petrogenesis of metamorphic rocks*, 1st edition. New York, Springer-Verlag.

WYETH, R. B. 1977. The physiography and significance of the transition between Graham Land and Palmer Land. *British Antarctic Survey Bulletin*, No. 46, 39–58.

APPENDIX
ELECTRON MICROPROBE ANALYSES

Electron microprobe analyses of minerals in two blueschist facies metabasic rocks from central Alexander Island were carried out by G. Hyden and are presented in Tables X to XII. Specimen KG.2476.1 is a weakly foliated greenstone from the southern Colbert Mountains, and consists of subhedral grains of primary augite in a groundmass of alteration products; chiefly chlorite, white mica, pumpellyite and sphene. Riebeckitic blue amphibole occurs as fringes around the augite grains which also show alteration to a grass-green sodic pyroxene ranging in composition from aegerine-augite to sodic augite. Analyses of the augite and sodic pyroxene are shown in Table X and those of blue amphibole are shown in Table XI. Specimen KG.2477.3 is a strongly foliated greenstone from the same area and consists of a dense mass of high relief minerals which includes pumpellyite, sphene and sodic pyroxene (aegerine-augite) with chlorite and white mica. Lawsonite prisms occur in a quartz vein. Analyses of the lawsonite and sodic pyroxene are given in Tables XII and X respectively.

TABLE X

Representative microprobe analyses of pyroxenes from blueschist facies metabasic rocks from the LeMay Group of central Alexander Island

	Primary pyroxene					*Sodic pyroxene*									
BAS specimen number	*KG.2476.1*														*KG.2477.3*
Analysis number	*5A*	*9*	*16*	*Mean*	*Std. Dev.*	*1A*	*2*	*3*	*4*	*8*	*10*	*12*	*Mean*	*Std. Dev.*	*4*
Weight %															
SiO_2	51.3	50.8	50.4	50.8	0.45	50.9	52.2	52.2	51.7	51.8	51.5	51.7	51.71	0.45	49.1
Al_2O_3	1.98	1.91	2.17	2.02	0.13	2.65	2.76	3.43	2.99	0.99	1.78	1.83	2.35	0.84	8.46
TiO_2	0.68	0.74	0.71	0.71	0.03	0.53	0.51	0.15	0.39	0.21	0.32	0.46	0.37	0.15	0.46
FeO*	16.3	11.3	13.2	13.6	2.52	17.0	19.3	19.8	20.5	16.8	14.7	18.5	18.10	2.03	17.6
MnO	0.23	0.28	0.22	0.24	0.032	0.24	0.26	0.15	0.15	0.20	0.37	0.25	0.23	0.076	0.13
MgO	11.4	15.4	13.43	13.41	2.00	8.71	5.01	3.99	4.49	7.61	9.21	5.52	6.36	2.12	3.63
CaO	14.6	17.6	16.8	16.33	1.55	13.9	12.1	9.74	10.1	16.2	16.8	12.9	13.11	2.75	9.53
Na_2O	2.50	0.47	0.72	1.23	1.11	4.23	6.63	8.24	6.76	4.18	3.37	6.14	5.65	1.76	8.10
Total	99.0	98.5	97.6	98.36	0.71	98.2	98.8	97.7	97.1	98.0	98.0	97.3			97.0
Atomic proportions on the basis of 6 oxygens and all iron as Fe^{2+}.															
Si	1.97	1.93	1.94	1.95	0.02	1.99	2.04	2.06	2.06	2.03	2.00	2.05	2.03	0.028	1.93
Al	0.089	0.085	0.099	0.091	0.007	0.12	0.13	0.16	0.14	0.046	0.082	0.086	0.11	0.039	0.39
Ti	0.020	0.021	0.021	0.021	0.0006	0.016	0.015	0.004	0.012	0.006	0.009	0.014	0.011	0.005	0.014
Fe^{2+}	0.52	0.36	0.42	0.43	0.081	0.56	0.63	0.65	0.68	0.55	0.48	0.62	0.60	0.069	0.58
Mn	0.008	0.009	0.007	0.008	0.001	0.008	0.009	0.005	0.005	0.007	0.012	0.008	0.008	0.002	0.004
Mg	0.65	0.87	0.77	0.76	0.11	0.51	0.29	0.24	0.27	0.44	0.53	0.33	0.37	0.19	0.21
Ca	0.60	0.72	0.70	0.67	0.064	0.58	0.51	0.41	0.43	0.68	0.70	0.55	0.55	0.11	0.40
Na	0.19	0.035	0.054	0.093	0.085	0.32	0.50	0.63	0.52	0.32	0.25	0.47	0.43	0.14	0.62
Total	4.05	4.03	4.01	4.03	0.02	4.10	4.12	4.16	4.12	4.08	4.06	4.13	4.11	0.033	4.15

* Total iron as FeO.

K_2O was not detected.

TABLE XI

Electron microprobe analyses of blue amphibole from blueschist facies metabasic rocks from the LeMay Group of central Alexander Island

Mineral	*Blue amphibole*				
BAS specimen number	*KG.2476.1*				
Analysis number	*6*	*7*	*13*	*Mean*	*Std. Dev.*
Weight%					
SiO_2	53.9	54.1	52.9	53.6	0.64
Al_2O_3	2.72	3.02	4.01	3.25	0.68
FeO*	25.9	25.3	25.1	25.4	0.42
MnO	–	–	0.14	0.05	0.081
MgO	5.44	5.86	6.01	5.77	0.30
CaO	1.18	1.35	1.44	1.32	0.13
Na_2O	6.28	6.16	6.16	6.20	0.069
Total	95.4	95.8	95.8	95.6	0.23
Atomic proportions on the basis of 23 oxygens and all iron as Fe^{2+}					
Si	8.28	8.25	8.09	8.21	0.102
Al	0.49	0.54	0.72	0.58	0.121
Fe^{2+}	3.32	3.22	3.20	3.25	0.064
Mn	–	–	0.019	0.006	0.011
Mg	1.24	1.33	1.37	1.31	0.067
Ca	0.20	0.22	0.24	0.22	0.020
Na	1.87	1.82	1.83	1.84	0.026
Total	15.40	15.38	15.47	15.42	0.047
Atomic proportions on the basis of 23 oxygens recalculated after Stout (1972) for maximum Fe^{3+}.					
Si	8.07	8.04	7.84	7.98	0.125
Al	0.48	0.53	0.70	0.57	0.115
Fe^{3+}	1.18	1.20	1.38	1.25	0.110
Fe^{2+}	2.06	1.94	1.73	1.91	1.167
Mn	–	–	0.018	0.006	0.010
Mg	1.21	1.30	1.33	1.28	0.062
Ca	0.19	0.21	0.23	0.21	0.020
Na	1.82	1.77	1.77	1.79	0.029
NAM_4§	1.81	1.77	1.77	1.79	0.023
Fe_2O_3†	10.5	10.7	12.4	11.2	1.04
FeO‡	16.4	15.6	13.9	15.3	1.28

– Not detected.

*Total iron as Fe^{2+}.

† Fe_2O_3 wt % from calculated Fe^{3+}.

‡ FeO wt % from calculated Fe^{2+}.

§ Sodium in M_4 sites (8-fold co-ordination).

TiO_2 and K_2O were not detected.

TABLE XII

Electron microprobe analyses of lawsonite from blueschist facies metabasic rocks from the LeMay Group of central Alexander Island

Mineral	*Lawsonite*				
BAS specimen number	*KG.2477.3*				
Analysis number	*7*	*8*	*9*	*Mean*	*Std. Dev.*
Weight%					
SiO_2	37.4	37.4	37.2	37.33	0.12
Al_2O_3	30.0	29.4	30.4	29.93	0.50
TiO_2	0.33	0.65	0.18	0.39	0.24
FeO*	2.02	2.63	2.00	2.22	0.36
MnO	–	–	–	–	–
MgO	–	–	–	–	–
CaO	18.4	18.1	18.2	18.23	0.15
Na_2O	–	–	–	–	–
K_2O	–	–	–	–	–
Total	88.2	88.2	88.0	88.13	0.12
Atomic proportions on the basis of 8 oxygens and all iron as Fe^{2+}.					
Si	2.00	2.00	1.99	2.00	0.006
Al	1.89	1.86	1.90	1.88	0.021
Ti	0.013	0.026	0.007	0.015	0.009
Fe	0.09	0.12	0.089	0.10	0.018
Mn	–	–	–	–	–
Mg	–	–	–	–	–
Ca	1.05	1.04	1.04	1.04	0.006
Na	–	–	–	–	–
K	–	–	–	–	–
Total	5.04	5.05	5.04	5.04	0.006

– Not detected. *Total iron as Fe^{2+}.