

First Carboniferous and ?Permian marine macrofaunas from Antarctica and their tectonic implications

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Abstract: The first Carboniferous and ?Permian marine macrofaunas from the Antarctic continent are described from three sites near Mount King, Alexander Island, Antarctic Peninsula. They include bivalves, brachiopods, bryozoans, crinoids, gastropods, a possible monoplacophoran, nautiloids and a possible serpulid or microconchid. Overall the faunas of two localities are Carboniferous in age and compare well with the *Levipustula levis* Zone of Argentina and eastern Australia, and are of Namurian (Serpukhovian–Bashkirian) age, based mainly on the brachiopod and bryozoan faunas. Less positive brachiopod evidence from a third locality indicates the presence of a linoproductid fauna of possible Carboniferous or Permian (Gzhelian–Artinskian) age, having affinities with the Argentinian *Cancrinella* fauna. The lithological and structural characteristics of the Mount King beds are comparable to the accretionary complex of the LeMay Group (hitherto of only proven Jurassic–Cretaceous age) of Alexander Island, in which they are provisionally placed. However, the beds may also correlate with the Trinity Peninsula Group (Carboniferous–Triassic) of the northern Antarctic Peninsula. The features of the Mount King beds are consistent with the presence of an accretionary complex related to an island arc in the Late Palaeozoic, but are not necessarily conclusive proof of the presence of such a terrane at that time in what is now Alexander Island.

Keywords: Antarctica, Carboniferous, Permian, macrofaunas, tectonics.

The first Carboniferous and ?Permian marine macrofaunas from Antarctica were discovered in the vicinity of Mount King in NE Alexander Island (Figs 1–4) by the British Antarctic Survey (S.R.A.K. & P.A.D.) during the 1992–1993 field-season. They comprise the oldest faunas known from Alexander Island and the Antarctic Peninsula region, and have important palaeogeographical and tectonic implications for the southern high latitude regions. A brief note on this discovery was published by Dickins (1995).

The new faunas occur mainly in calcareous mudstones, informally termed here the Mount King beds. Fossils are locally abundant and include: bivalves, brachiopods, bryozoans, crinoids, gastropods, ?monoplacophoran, orthocone nautiloids, a ?serpulid worm or microconchid, and trace fossils. Their age-range is interpreted as from Early Carboniferous–?Early Permian (Serpukhovian to Artinskian).

The occurrence of Palaeozoic invertebrates in Antarctica

was reviewed by Cooper & Shergold (1991). Records of marine macrofaunas were essentially limited to the Ellsworth Mountains and the Transantarctic Mountains (Fig. 1), where Cambrian faunas are dominated by trilobites (see also Wolfart 1994) and archaeocyathids, and Devonian faunas by bivalves and brachiopods. Although no Carboniferous marine macrofaunas were recorded by Cooper & Shergold (1991), Carboniferous sedimentary rocks were recognized in the largely non-marine Beacon Supergroup (Devonian to Triassic) of the Transantarctic Mountains, the Ellsworth Mountains

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and the Pensacola Mountains (Fig. 1). These occurrences were reviewed by Barrett (1991), and are known to include glacio-sedimentary successions (Woolfe 1994). Glacially influenced sediments with marine faunas comparable to those of the Mount King beds occur in Argentina (González 1990; Buggisch *et al.* 1994) and Australia (Campbell 1962; Dickins 1985, 1996) at times of marked eustatic falls in sea level (Ross & Ross 1987).

The position of the Mount King beds within a higher lithostratigraphic framework is uncertain at present. They may be assigned to the LeMay Group (Burn 1984) of Alexander Island or to the Trinity Peninsula Group (Adie 1957) of the Antarctic Peninsula, or perhaps represent a completely new lithostratigraphical unit. However, there are problems with each of these alternatives. The Mount King beds are much older than the currently accepted age (Early Jurassic–Early Cretaceous) of the LeMay Group (Holdsworth & Nell 1992), and they are geographically distant (*c.* 500 km) from the main outcrop of the Trinity Peninsula Group (although the Carboniferous and Permian ages are consistent). We place the Mount King beds provisionally in the LeMay Group (Fig. 2), for reasons given below.

In this study, responsibility for the stratigraphic synthesis and geological interpretations rests with S.R.A.K. and P.A.D. The palaeontological determinations were made as follows: bivalves (J.M.D., S.R.A.K.) and gastropods (J.M.D.), nautiloids (S.R.A.K.), brachiopods (C.H.C.B.), bryozoans

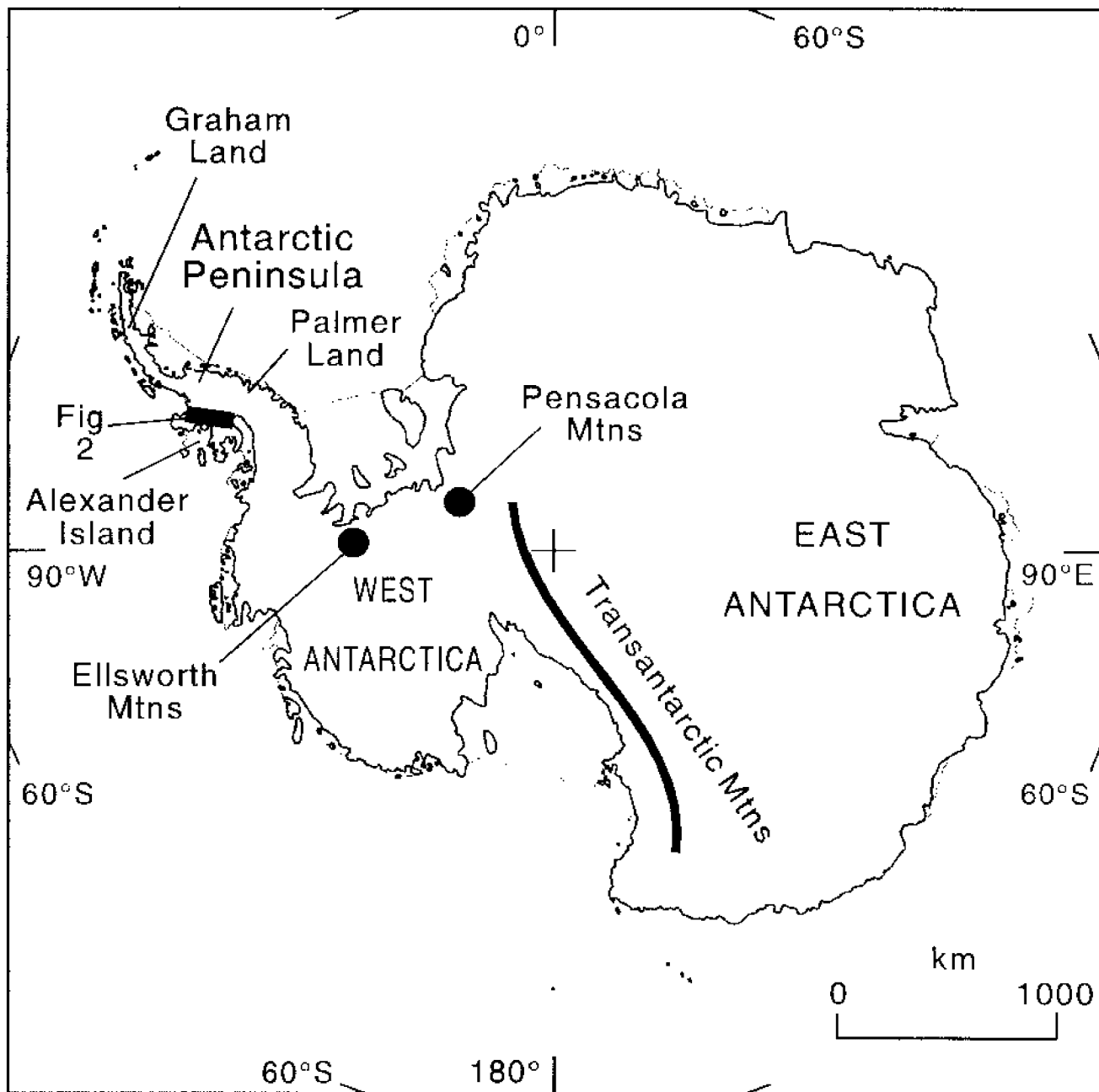


Fig. 1. Antarctica, showing the principal Late Palaeozoic sites mentioned in the text.

(P.D.T.), crinoids (G.D.S.). All the specimens collected in this study are housed at the British Antarctic Survey palaeontological collections in Cambridge.

Geological setting

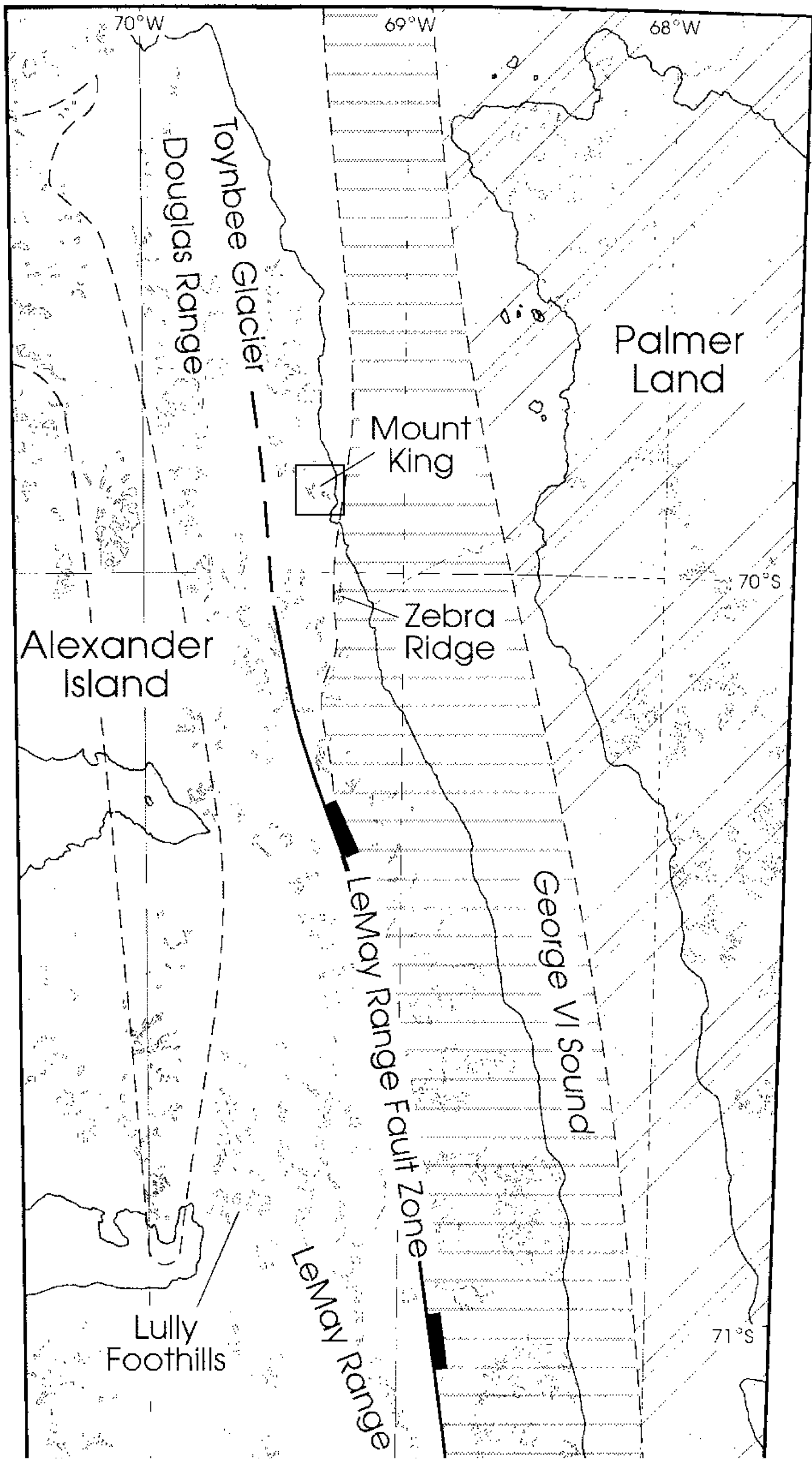
Antarctic Peninsula

The Antarctic Peninsula comprises part of a long-lived arc–trench system that existed from Cambrian to Tertiary times at the proto-Pacific margin of Gondwana. Although it is composed of mainly Mesozoic rocks, the oldest known rocks are orthogneisses and paragneisses that are thought to represent calc-alkaline (subduction-related) phases of magmatism during the Cambro-Ordovician in northwest Palmer Land (Harrison & Loske 1988) and the Silurian in Graham Land (Milne & Millar 1989). While the polarity of subduction during these earlier phases is unknown, during the Mesozoic there are distinct and well-preserved fore-arc (west of the Antarctic Peninsula), arc and back-arc components (east of the Antarctic Peninsula) (Storey & Garrett 1985). Subduction to the west of the Antarctic Peninsula ceased in the Tertiary due to a series of ridge crest–trench collisions (Barker 1982).

Alexander Island

The fore-arc rocks exposed on Alexander Island are represented by an accretionary complex, the LeMay Group (Burn 1984), and trench-slope break to fore-arc basin, the Fossil Bluff Group (Butterworth *et al.* 1988).

The LeMay Group was originally defined as the LeMay Formation by Edwards (1982) and subsequently given group status by Burn (1984). The rocks typically comprise a monotonous sequence of greywackes, reddish-weathering arkosic sandstones, shales and subordinate conglomerates (Bell 1975; Burn 1984; Nell 1990; Tranter 1991; Doubleday *et al.* 1993). All these authors have also noted that the



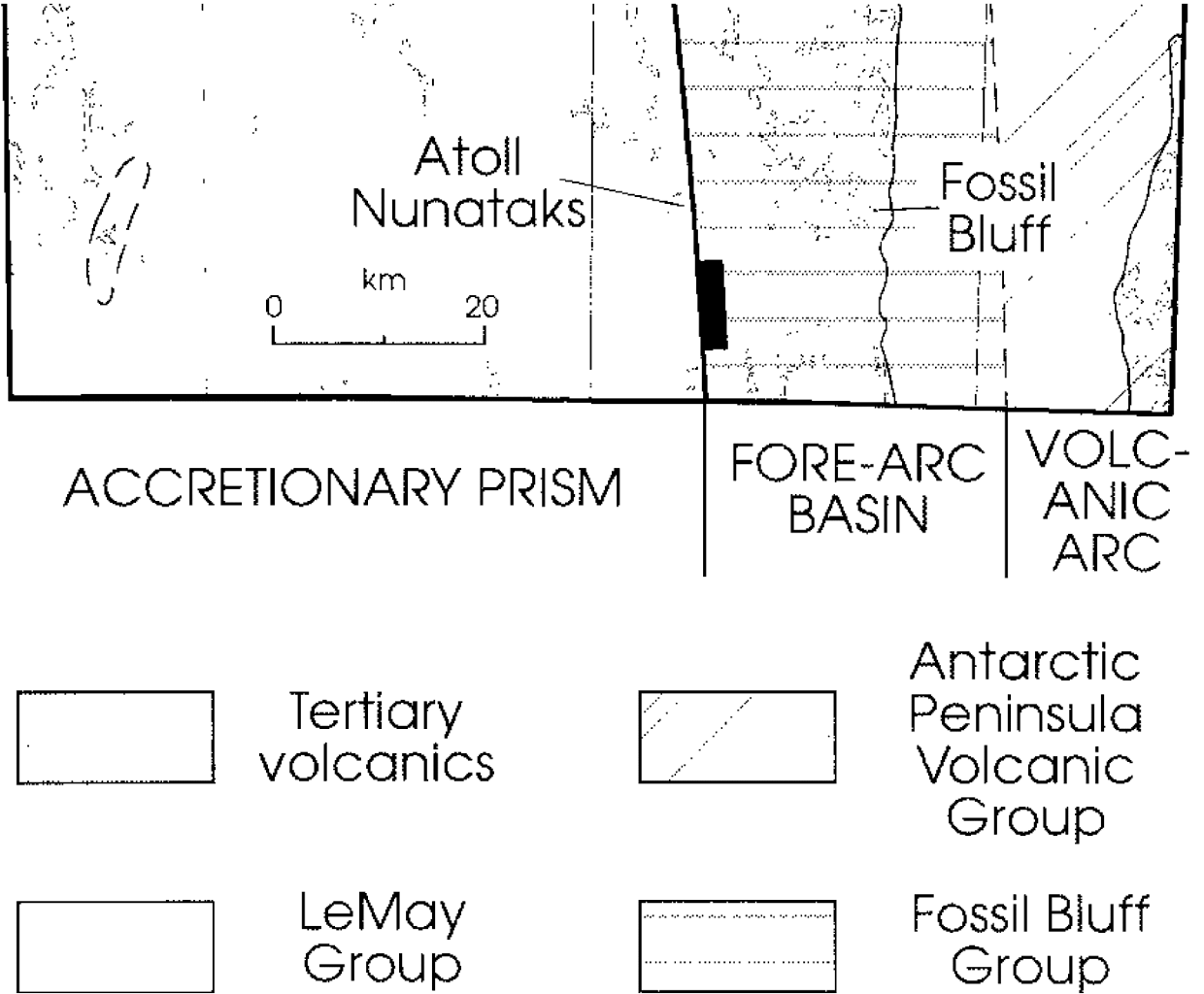


Fig. 2. Geological sketch map of eastern Alexander Island showing the position of Mount King. Most of the land areas are ice and snow covered apart from the nunataks which are shown in outline only. For general location see Fig. 1; inset shows the position of Fig. 3.

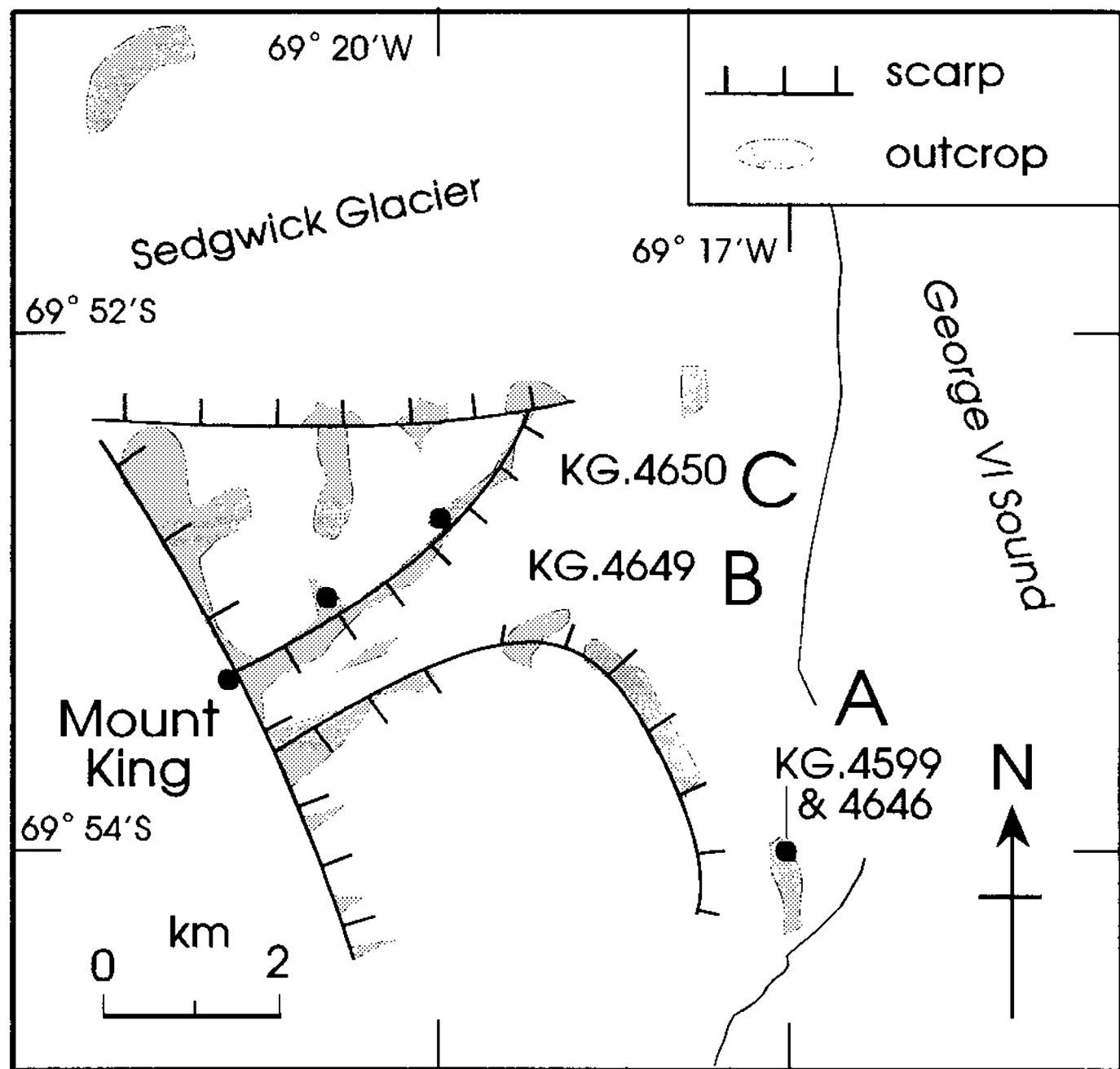


Fig. 3. Sketch locality map of the Mount King area.

sequences are commonly steeply dipping and disrupted to varying extents, both on a regional scale by large faults, and in outcrop to hand-specimen scale by small faults, boudinage and other stratal disruption. Tranter (1987, 1992), Doubleday *et al.* (1993) and Doubleday (1994) have all described and illustrated examples of deformation of unlithified sediments within the LeMay Group. The accretionary complex was formed by the eastward subduction of proto-Pacific oceanic crust on the west side of the Antarctic Peninsula, comparable to the present circum-Pacific. It consists predominantly of trench-fill sedimentary rocks, but significant quantities of ocean-floor and ocean-island rocks also occur (Tranter 1992; Doubleday *et al.* 1994). Lithologically the complex has been compared with the Trinity Peninsula Group (Hyden & Tanner 1981; Pankhurst 1983) in the northern part of the Antarctic Peninsula.

The LeMay Group sedimentary rocks were initially dated as Late Palaeozoic in age by A. F. Dibner (*in* Grikurov 1971), who identified Carboniferous to Permian spores from the LeMay Range (Fig. 2). Mesozoic macrofossils, from an atypical succession of volcanic tuffs at Lully Foothills (Fig. 2; Tranter 1987), included a fauna of bivalves, brachiopods and echinoids which was first dated as Triassic (Edwards 1980). Further material, including additional echinoderms and the ammonite *Epophioceras?*, showed this assemblage to be Early

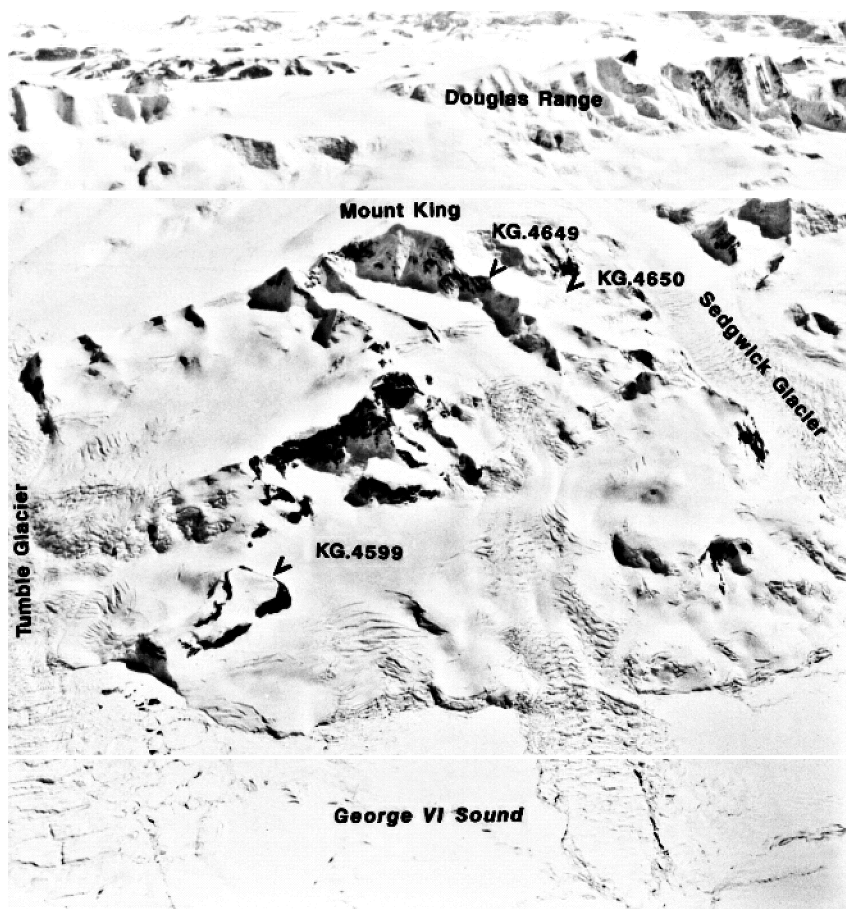


Fig. 4. Oblique air-photograph of Mount King from the east, showing position of Late Palaeozoic sites of the Mount King beds. Photograph courtesy of US Geological Survey EROS Data Centre.

Jurassic, probably Sinemurian, in age (Thomson & Tranter 1986). Absence of support for the spore identifications of Dibner (Truswell 1991) was followed by Holdsworth & Nell's (1992) discovery of Late Jurassic and Early Cretaceous radiolaria in cherts which originally comprised ocean-floor pelagic sedimentary rocks. These authors believed that the earlier concept of the LeMay Group as 'pre-Jurassic basement' was untenable. However, LeMay Group rocks do underlie Early Jurassic parts of the Selene Formation of the Fossil Bluff Group (Doubleday *et al.* 1993; Macdonald *et al.* 1999; Kelly *et al.* 1993).

The Fossil Bluff Group crops out along the east coast of Alexander Island (Fig. 2) to the east of the LeMay Group outcrops (Butterworth *et al.* 1988). The predominantly sedimentary succession is about 7 km in thickness and is interpreted as trench-slope break to fore-arc basin deposits (Doubleday 1994; Doubleday *et al.* 1993). The oldest rocks of the Fossil Bluff Group are of Early Jurassic age (Kelly *et al.* 1993; Kelly 1995), and the youngest are Early Cretaceous (Albian: Kelly & Moncrieff 1992; Moncrieff & Kelly 1993). It is now apparent that the Jurassic to Cretaceous accreted elements of the LeMay Group are coeval with the deposition of the Fossil Bluff Group in the adjacent fore-arc basin (Holdsworth & Nell 1992).

Mount King beds

The Mount King outcrops are situated near the eastern margin of the LeMay Group, adjacent to George VI Sound (Fig. 2) (and as shown on the 1:500 000 geological map; J. W. Thomson 1981). They occur 10 km to the north of the northernmost Fossil Bluff Group exposure which is at Zebra Ridge. The contacts of the Mount King beds with both the rest of the LeMay Group and the Fossil Bluff Group are obscured by glacier ice. The Mount King beds are also in proximity to the LeMay Range Fault zone, which may run to the west of the outcrops. This fault zone forms much of the contact separating the LeMay Group from the Fossil Bluff Group (Fig. 2). The Mount King beds are to the east of most other exposures of the LeMay Group, and their position is consistent with being an early accreted prism of the complex.

Three exposures of the Mount King beds were examined at localities A–C (Figs 3, 4), but the field stratigraphic relationships between the sites are unclear, apart from Locality B being probably at a higher stratigraphic level than Locality C. The total stratigraphic thickness is estimated provisionally at in excess of 1 km, but this figure must be treated with caution until more accurate observations can be obtained.

Locality A. Summit, altitude *c.* 300 m, between Mount King and George VI Sound, 6 km ESE of Mount King (KG.4599, KG.4646; 69°17'W 69°54'S). The lower part of the section exposed on the summit is mainly mudstone, overlain by medium-grained sandstones and conglomerates (KG.4599.3), which are locally brecciated (KG.4599.4). Large cobble-sized clasts of sandstone, up to 250 mm diameter, in the conglomerates contain fractures with void infilling by matrix, indicating cataclastic deformation before lithification. Rare calcite veins are microfaulted in an extensional sense, and larger extensional faults also occur. There are no clearly defined penetrative structural fabrics. The mudstones are dark and contain calcareous concretions, the latter brecciated



Fig. 5. Typical Mount King beds lithologies at Locality B. Alternating mudstones and muddy sandstones; scale bar *c.* 0.4 m.

and with calcareous veins. Bedding is locally visible in the mudstones, but is generally obscured by the uniformity of the lithology and by trace fossil homogenization. Macrofossils occur in a single bed, traceable laterally for about 20 m.

Locality B. Summit of ridge, altitude 1380 m, 1.5 km NNE of Mount King (KG.4649; 69°26'W 69°53'S). About 10 m of sedimentary rocks, mainly mudstones, are exposed, dipping 20° due north. The upper part is more sandy, containing clean, arkosic, sharp-based sandstones up to 50 cm thick with locally matrix-supported conglomeratic bases. The lower part contains sandy mudstones, some of which are massive, whereas others show graded units up to 40 cm in thickness; higher levels are composed of alternating muddy sandstone and mudstone (Fig. 5). Load structures are present and there is much synsedimentary slumping. Near the base of the section there is a single 3 cm brachiopod shell bed containing lino-productids. Bioturbation is present as *Planolites* (KG.4649.10) and *Zoophycos*-type burrows (KG.4649.6) in the coarser sediments.

Locality C. Low ridge, altitude *c.* 1200 m, 3 km NNE Mount King (KG.4650; 69°25'W 69°52'S). The sedimentary rocks there are composed almost entirely of fossiliferous mudstones, and the dip is approximately similar to Locality B.

Faunas

The faunas collected from the three Mount King localities are listed in Table 1, and the principal taxa are illustrated in Figs 6 & 7. Each assemblage should be treated individually, although it is probable that if localities B and C are in stratigraphic continuity, then C is the lower of the two. The preservation of the faunas varies from the articulated valves of nuculoid bivalves and largely complete gastropods, to fragmentary orthocone nautiloids, broken portions of bryozoan colonies and disarticulated crinoid ossicles. Apart from

Bivalves

Anthraconeilo sp.
 cf. *Cardiomorpha?* sp.*
Cypricardinia? sp.
Limipecten sp.
Phestia? sp.†
Streblopteria sp.

Gastropods

Mourlonia sp.
Ptychomphalina cf. *kuttungensis* (Campbell)
 Undetermined pleurotomariid

Monoplacophoran

Metoptoma? sp.

Nautiloid

Orthocone, smooth
Sueroceras sp.

Brachiopods

cf. *Canocrinella* sp.
 cf. *Crurithyris* sp.
 Lingulid
 Reticulariacean?
 Spiriferid
 cf. *Streptorhynchus* sp.
 Neospiriferin

Bryozoans

Australofenestella cincta (Crockford)
Australofenestella cf. *stroudensis* (Campbell) *stroudensis* Engel
Australopolypora neerkolensis (Crockford)
 Fenestellid
 cf. *Glyptopora* sp.
Leioclema? sp.
 'Polypora' sp.
Rectifenestella cf. *loganensis* Wass
Retepora sp.
 Rhabdomesine? cryptosome
 Stenoporid trepostome

Crinoids

Cladid

cf. *Cyclocaudex* sp.

cf. *Pentaridica rothi* Moore & Jeffords.

Platycrinitid

Undetermined

Annelid/microconchid

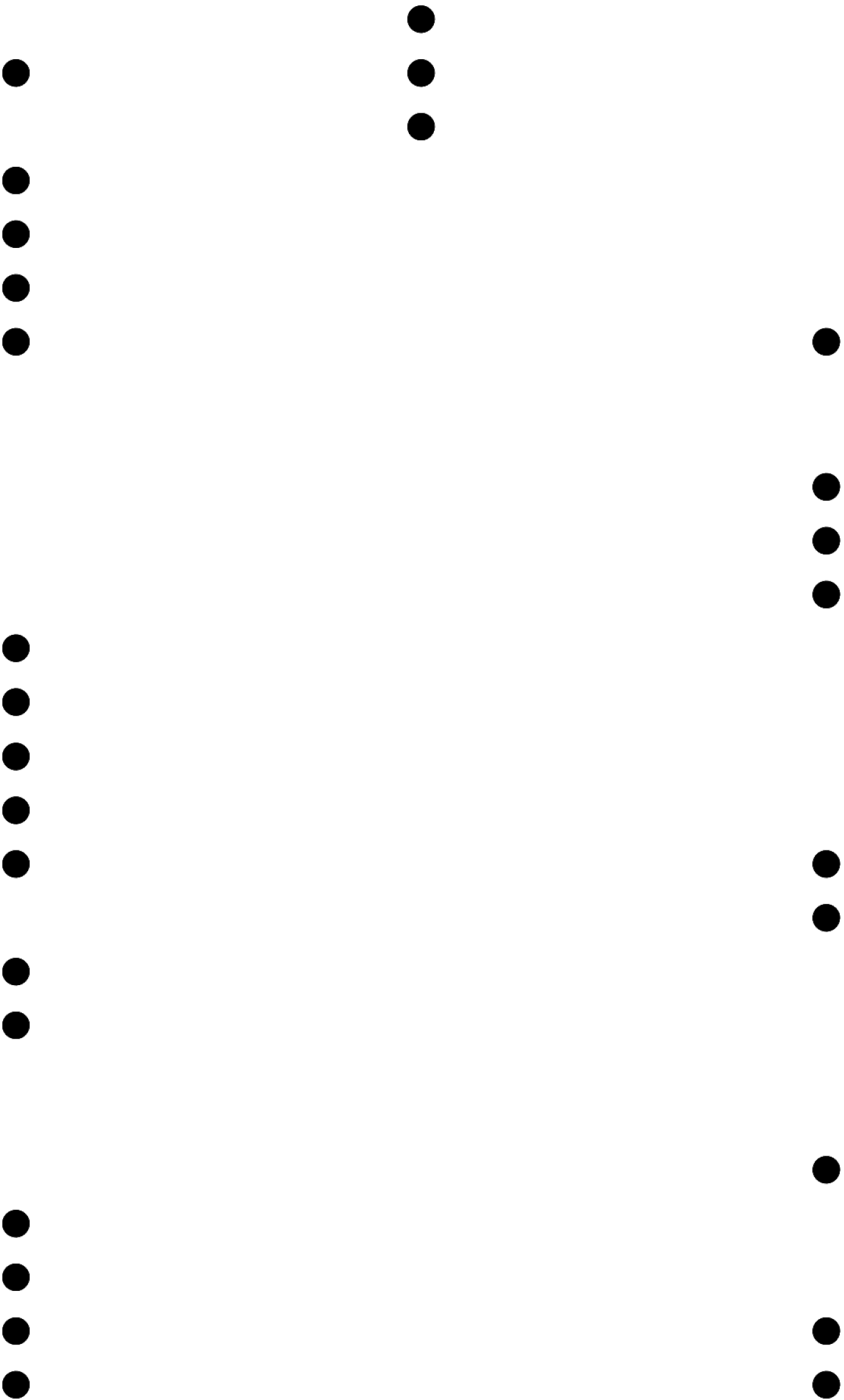
Undetermined

Trace fossils

Planolites? ichnosp.

Zoophycos ichnosp.





*Possibly *Astartella* or *Astartila*.

†Possibly a parallelodontid.

the trace fossils, most of the specimens show some degree of reworking or fragmentation. The formerly aragonitic specimens are preserved as moulds and the calcitic faunal elements are usually partly decalcified. There is weak tectonic strain distortion.

Locality A (KG.4599). The fauna (Table 1) is characterized by abundant fragmentary bryozoans, common pleurotomarioid

gastropods, bivalves, including *Anthraconeilo* sp. (Fig. 7a, b) and the pectinid, *Limipecten* sp., and fragmentary orthocone nautiloids. The bryozoans are mostly dendroid trepostomes and ?rhabdomesine cryptostomes and are difficult to identify even to family level because key internal features are missing as a result of decalcification. Spiriferides dominate the brachiopod fauna and include cf. *Crurithyris* sp. (Fig. 6 h) and an indeterminate neospiriferin, while a small orthotetacean

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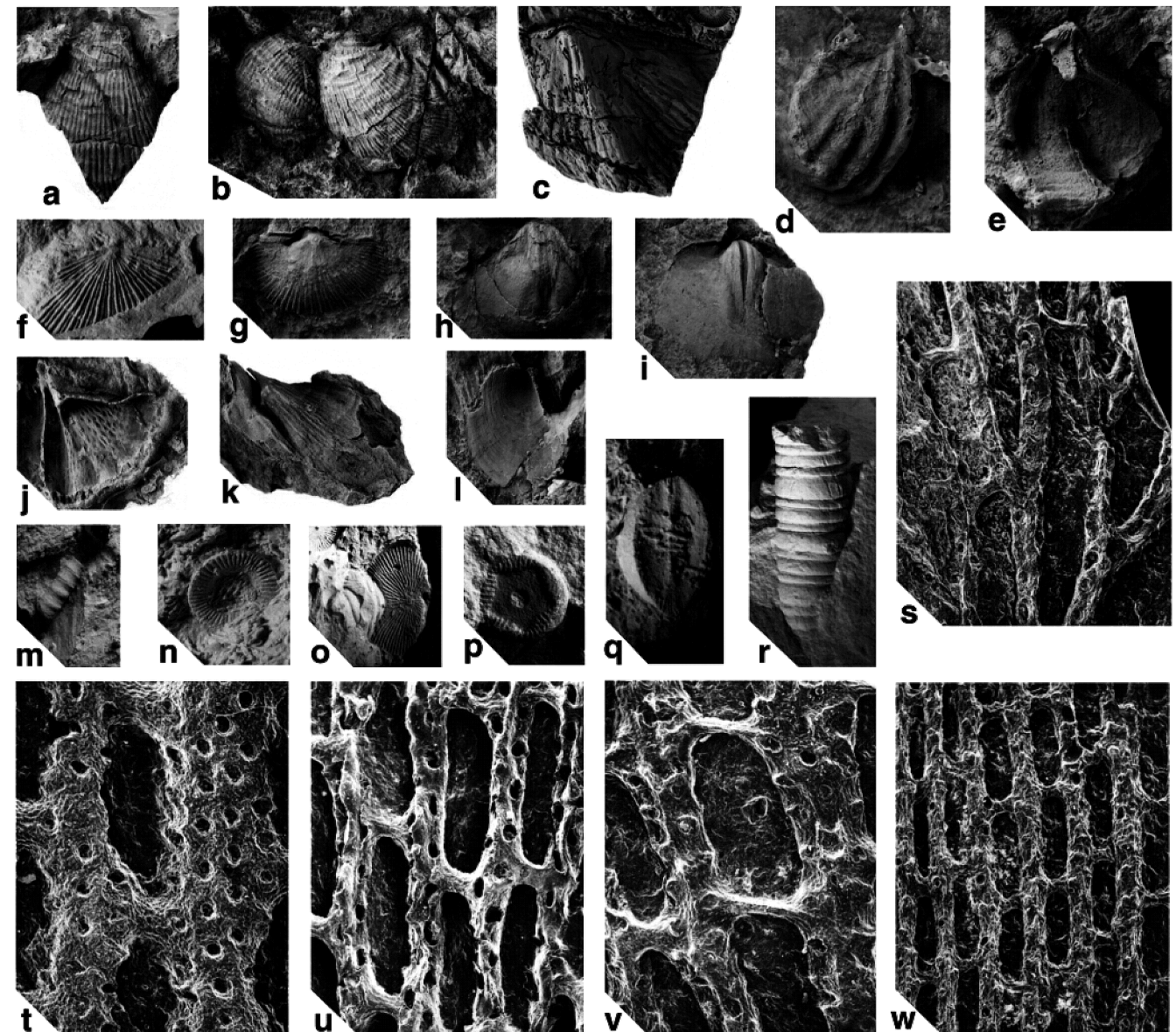


Fig. 6. Brachiopods (a–l), crinoids (m–r) and bryozoans (s–w) from the Mount King beds. (a, b) cf. *Cancrinella* sp.: (a) KG.4649.9d, ventral valve, $\times 1.5$; (b) KG.4649.9 g, ventral valves, $\times 2$. (c) undetermined neospiriferin, KG.4650.50, dorsal valve, $\times 1$. (d, e, j, k) undetermined spiriferids: (d) KG.4599.19d, ventral valve, silicone rubber cast of exterior, $\times 2$; (e) KG.4599.17b, ventral valve, silicone rubber cast of interior, $\times 4$; (j) KG.4599.13b, ventral valve, latex cast of interior, $\times 2$; (k) KG.4599.17k, ventral valve, internal mould, $\times 2$. (f, g) cf. *Streptorhynchus* sp.: (f) KG.4599.20c, dorsal valve, silicone rubber cast of exterior, $\times 1.5$; (g) KG.4599.10e, dorsal valve, internal mould, $\times 3$. (h, i) cf. *Crurithyris* sp.: (h) KG.4599.9 g, ventral valve, partly exfoliated, $\times 3$; (i) KG.4599.22n, dorsal valve, internal mould, $\times 3$. (l) probable lingulid sp., KG.4649.9i, silicone rubber cast, $\times 2.5$. (m, n) *Platycrinites* sp.: (m) KG.4599.24c, columnal, lateral aspect, silicone rubber cast, $\times 2$; (n) KG.4650.50, columnal, articular surface, silicone rubber cast, $\times 2$; (o) undetermined, KG.4650.39, elliptical pluricolumnal, silicone rubber cast, $\times 2$. (p, r) cf. *Pentariidica rothi* Moore & Jeffords: (p) KG.4599.13c, articular face of isolated columnal, silicone rubber cast, $\times 3$. (r) KG.4599.14a, pluricolumnal showing cirrus scar, silicone rubber cast, $\times 2$. (q) platycrinid, KG.4650.54, columnal showing articular surface, silicone rubber cast, $\times 1.5$. (s) *Australofenestella cineta* (Crockford), KG.4650.24c, latex cast, $\times 11$. (t) *Australopolyora* cf. *neerkolensis* (Crockford), KG.4650.6b, latex cast, $\times 17$. (u) *Australofenestella* cf. *maclayensis* (Campbell), KG.4650.8a, latex cast, $\times 17$. (v) *Australofenestella* cf. *stroudensis* *stroudensis* Engel, KG.4650.20, latex cast, $\times 17$. (w) *Rectifenestella* cf. *loganensis* (Wass), KG.4650.24, latex cast, $\times 17$. Specimens a–r are coated with ammonium chloride prior to photography; figs s–w are scanning electron micrographs of gold coated specimens. British Antarctic Survey collections, Cambridge.

resembles either a small schuchertellid or *Streptorhynchus*-like genus (Fig. 6f, g). The cf. *Crurithyris* also bears a resemblance to *Attematella*.

The bivalve *Limipecten* sp. is usually fragmentary but characterized by external ornament showing commarginal lamellae

between the spiny processes on the costae. The nuculoid, *Phestia?* sp. (Fig. 7f), superficially resembles *P. tepuelensis* González 1969 (see also González 1977), but bears distinctive fine subvertical ornament; the hinge is not seen. The specimen provisionally identified as the edmondiid, *Cardiomorpha?* sp.

FIRST CARBONIFEROUS & ?PERMIAN MACROFAUNAS OF ANTARCTICA

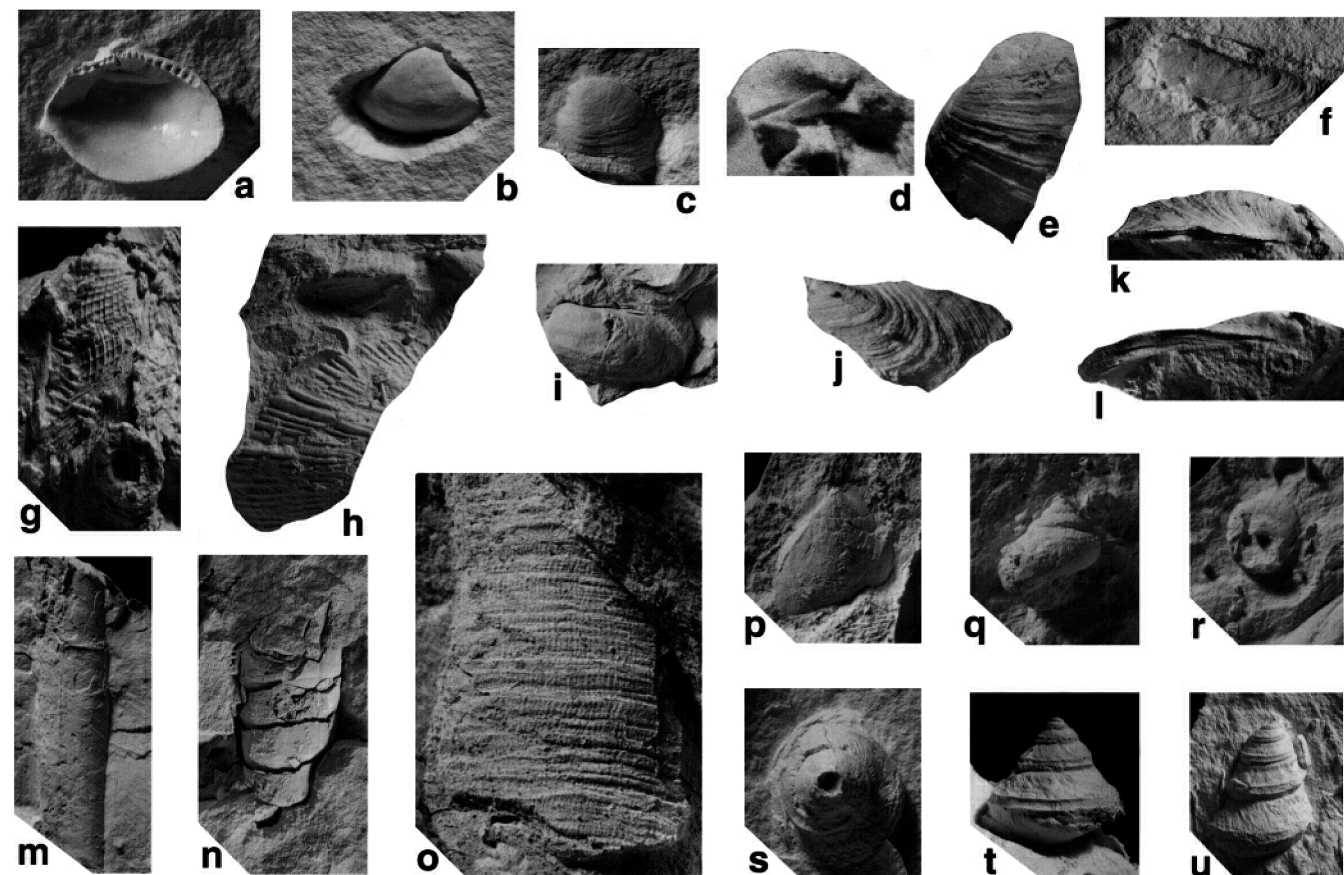


Fig. 7. Molluscs from the Mount King beds. (a, b) *Anthraceoneilo* sp. KG.4599.30, left valve: (a) silicone rubber cast of interior $\times 2$; (b) internal mould $\times 1.5$. (c–e) *Cardiomorpha?* sp.: (c) KG.4599.57, left valve, silicone rubber cast, $\times 1.5$; (d, e) KG.4599.13a, left valve interior and exterior views, silicone rubber cast, $\times 4$. (f) *Phestia?* sp.: KG.4599.24c, right valve, silicone rubber cast, $\times 2$. (g, h) *Limipecten* sp.: (g) KG.4650.50, left valve, anterior auricular region, $\times 3$; (h) KG.4650.51, two valves, interior of hinge and auricle of right valve at top, ventral region exterior at base, silicone rubber cast $\times 1$. (i–l) *Cypricardinia?* sp.: (i) KG.4599.24e, left valve, internal mould, $\times 1$; (j–l) KG.4599.23d, left valve exterior, dorsal and interior aspects, silicone rubber cast, $\times 1.5$. (m, n) undetermined orthocone nautiloid, $\times 1$: (m) KG.4599.7a, silicone rubber cast of exterior; (n) KG.4599.22b, internal mould, $\times 1$. (o) *Sueroceras* sp.: KG.4599.13e, silicone rubber cast of exterior, $\times 1$. (p) *Streblopteria* sp., KG.4650.52, left valve?, silicone rubber cast of exterior. (q, r) *Mournalonia* sp.: (q) KG.4599.13a, lateral aspect, silicone rubber cast, $\times 1.5$; (r) KG.4599.13a, ventral aspect, silicone rubber cast, $\times 1.5$. (s–u) *Ptychomphalina* cf. *kuttungensis* (Campbell): (s) KG.4599.31, dorsal aspect, silicone rubber cast, $\times 1.5$; (t) KG.4599.21a, lateral aspect, silicone rubber cast, $\times 1.5$; (u) KG.4599.19c, lateral aspect, silicone rubber cast, $\times 1.5$. All specimens coated with ammonium chloride prior to photography. British Antarctic Survey collections, Cambridge.

(Fig. 7c–e), is problematical. In the absence of hinge data, it also bears a resemblance to *Astartella* or *Astartila*, but the

specimens show a fine radial ornament on the anterior which is not known in *Cardiomorpha* or *Astartila sensu stricto*, but is present although coarser in the Permian *Astartila* (*Pleurikodonta*) from eastern Australia (Runnegar 1965). Hinge data is required to resolve the determination. One specimen of the cyrtodontid, *Cypricardinia?* sp., shows an elongated (transitional) ligament groove and marked posterior lateral tooth (Fig. 7l). The gastropods include mainly *Ptychomphalina* cf. *kuttungensis* (Campbell 1961) (Fig. 7s–u). Considerable variation is shown in the dimensions of the specimens due to tectonic distortion. The genus is considered to be *Ptychomphalina* because it lacks the distinctive, relatively wide concave band below the slitband which is characteristic of *Peruvispira*, the taxon in which Campbell (1961) originally placed the species. *Mourlonia* sp. (Fig. 7q, r) is less common. The orthocone nautiloids (Fig. 7m–o) include a smooth form (Fig. 7m) and *Sueroceras* sp. (Fig. 7o), the latter with characteristic ornament of reticulate lirae.

The crinoid fauna (Fig. 6m–r) of columnals and plurico-columnals represents at least four different species. Some of these may be compared with taxa described by Moore & Jeffords (1968), which were based almost entirely on stem material and whose relation to taxa based on more complete material is generally not known. Four specimens have a distinctive pentagonal areola (Fig. 6p) and resemble closely ossicles described as *Pentaridica rothi* Moore & Jeffords 1968. These authors made no reference to cirrus scars in *Pentaridica*, but these structures are clearly present in the Antarctic material (Fig. 6r). A single small specimen (KG.4599.44) is a platycrinid, but cannot be identified to generic level. Another single ossicle (KG.4599.23d) may be compared with *Cyclocaudex* Moore & Jeffords. The other taxa are insufficiently well-preserved to be identified.

Locality B (KG.4649). Fossils (Table 1) are generally scarce, but the trace fossil *Zoophycos* (KG.4649.6a) occurs occasionally in muddy sandstones in the upper part of the section. The linoproductid brachiopod-dominated assemblage of finely

ribbed cf. *Cancrinella* sp. (Fig. 6a,b) occurs in a single bed. At the same level other brachiopods occur: cf. *Crurithyris* sp. and a probable lingulid (Fig. 6 l), together with an internal mould of a possible monoplacophoran, *Metoptoma?* sp. (N. J. Morris determination, 1993). At a lower level, scattered *Planolites?* ichnosp. burrows (KG.4649.10) occur in silty mudstones.

Locality C (KG.4650). The fauna (Table 1) is dominated by common fenestrate bryozoans and crinoid ossicles. In contrast to Locality A, the bryozoans are net-like fenestrates (Fig. 6s–w), from which latex casts were prepared showing the exterior form required for determination. One distinctive species, *Australofenestella cincta* (Crockford 1949) (Fig. 6s), shows characteristic coarse meshwork and a large number of apertures per fenestrule. The crinoid fauna of isolated column ossicles, pluricolumnals and brachials represents at least four species which appear distinct from those of Locality A. The most distinctive taxon, represented by a pluricolumnal (KG.4650.39) and the articular face of an isolated columnal (Fig. 6o), has low elliptical ossicles, with long fine crenulae and an apparently excentric minute lumen. Another taxon, represented by several specimens (KG.4650.12, 38, 43), has low columnals with wide pentagonal lumina and short, straight crenulae. A single large platycrinid columnal (Fig. 6q) appears to have fulcral ridges on opposing faces of the ossicle, almost at right angles to each other. In addition to the columnals, there are at least two different types of brachial ossicles that are from cladid crinoids. The brachiopods are represented by an indeterminate neospiriferin (Fig. 6c). The bivalves are characterized by *Anthraconeilo* sp., and pectinoids including *Limipecten* sp. (Fig. 7 g, h) and *Streblopteria* sp. (Fig. 7p).

Faunal correlations

The correlation of the Alexander Island faunas with the brachiopod zonal successions of Argentina and eastern Australia are shown in Fig. 8. Selected lithological units are also shown.

Bryozoans. The fenestrate bryozoan fauna of Locality C shows close similarities to faunas described from the *Levipustula levis* Zone of eastern Australia (Crockford 1949; Campbell 1961, 1962; Wass 1966; Fleming 1972; Engel 1979) and Argentina (Sabattini 1972, 1986; Simanauskas & Sabattini 1997). One species in particular, *Australofenestella cincta* (Crockford 1949), appears to be identical to the Australian specimens, and several others closely resemble Australian forms. According to Engel (1979, p. 164), *A. cincta* is found widely in association with the *Levipustula levis* Zone. The species has also been recorded from the Neerkol Formation in the Stanwell district (Crockford 1949; Fleming 1972), in the Rands Formation of the Yarrol Syncline (Maxwell 1964) of Queensland and in the Booral Formation of New South Wales (Campbell 1961). Simanauskas & Sabattini (1997) recorded several bryozoan species from their *Lanipustula* Zone, equivalent to the base of what they termed the *Levipustula* Zone (Fig. 8). Among them are two Australian species, *Australofenestella stroudensis* (Campbell) and *Australopolypora neerkolensis* (Crockford), both of which are identified from Locality C (the former as 'cf.'). This indicates a correlation of the Antarctic faunas from localities A and C with the *Levipustula* Zone of South America.

Brachiopods. The most diverse assemblage occurs at Locality A, and includes cf. *Streptorhynchus* sp., a genus of Carboniferous–Permian age, a neospiriferin which could be Late Carboniferous–Permian, and cf. *Crurithyris*, a Late Devonian to Permian genus (e.g. Boucot *et al.* 1965). *Streptorhynchus* is a component of the *Lissochonetes jachalensis*–*Streptorhynchus inaequiornatus* Zone of Argentina (Sabattini *et al.* 1990) and of the *Tivertonia*–*Streptorhynchus* Zone (Taboada 1997, 1998) (Fig. 8).

The most common species at Locality B is a linoproductid, but the determination depends upon the depth of the body (or corpus) cavity, which cannot be seen. However, the external ornament (Fig. 6a, b) of elongate swollen spine bases, distributed ventrally on the fine radial ribbing, is indicative of the cosmopolitan genus *Canocrinella*, which ranges from the Gzhelian to the Late Permian (Brunton *et al.* 2000). There is a potentially confusing situation here. Maxwell (1951) described *Levipustula levis* n. gen. et sp. from the Neerkol Series of

Queensland which became the *Levipustula* zone fossil used for certain early Late Carboniferous rocks. Later, Maxwell (1964) described a different genus with the same species name, *Canocrinella levis*, from what he believed was the Early Permian part of the Burnett Formation of Queensland. This second species was subsequently made the type of *Auriculispina* by Waterhouse (1975) and it is clear that the two species belong to widely different taxonomic productid groups. The Antarctic material, termed cf. *Canocrinella* here, is more closely related to *Auriculispina* than to *Levipustula*. *Auriculispina levis* is now interpreted by Roberts *et al.* (1995) to be Westphalian/Stephanian.

In La Rioja, Argentina, Lech & Aceñolaza (1987) and Lech *et al.* (1990) identified *Canocrinella* sp. in the latest Carboniferous. At a higher level, *Canocrinella* aff. *farleyensis* (Etheridge & Dun) (Fig. 8) characterized the low diversity *Canocrinella* fauna, which was regarded as late Sakmarian to early Artinskian, while further *Canocrinella* and *Crurithyris* occurred higher in the *Neochonetes* Zone of possible late Artinskian to early Kungurian age (Simanauskas & Sabbattini 1997). Pujana (1986) recognized *Crurithyris* in what was believed to be an equivalent of the *Canocrinella* fauna in Chubut, although ascribing a latest Carboniferous age.

Bivalves. *Cypricardinia?* sp. is similar to *Cypricardinia* sp. illustrated by Campbell (1961, pl. 61, fig. 7) from the Booral Formation, *Levipustula levis* assemblage of New South Wales, as well as to material from Patagonia figured by González (1972) as *Cypricardinia?* sp. and *Cypricardinia?* aff. *elegantula* Dickins 1963. *Limipecten* sp. ranges through the Early and Late Carboniferous, and the Antarctic specimens are comparable with forms figured by Campbell (1961) from the Booral Formation. *Streblopteria* sp. is less useful stratigraphically, ranging from Carboniferous–Permian (Newell *et al.* 1969). A number of species of *Phestia* have been recorded from the Carboniferous of Argentina, including Patagonia (González 1972, 1992).

Gastropods. The species *Ptychomphalina* cf. *kuttungensis* (Campbell 1961) is typical of the *Levipustula levis* assemblage of the Booral Formation of New South Wales. It is very similar to ‘*Montospira*’ *montoensis* Maxwell (1964) of the Burnett Formation, Yarrol Basin, Queensland and to *Barrealispira mesigoi* Taboada & Sabbattini (1987) from Argentina, both of similar age. *P.* cf. *kuttungensis* is not recognized in any Chubut faunas (J.M.D. observations). *Mourlonia* sp. is

INTERNATIONAL SCHEME			ARGENTINA		AUSTRALIA				ANTARCTICA
			BRACHIOPOD ZONES	RIO BIANCO	CALLINGASTA- USPALLATA	BRACHIOPOD ZONES	QUEENSLAND	NEW SOUTH WALES	ALEXANDER ISLAND
PERMIAN			? Neochonetes			<i>Echinalosia preoavallis</i> <i>Echinalosia warwicki</i> <i>Echinalosia curiosa</i> <i>Tomioipsis strzeleckii</i> <i>Bandoproductus</i> n. sp.	Owl Gully volcanics Yarrol Fm	Braxton Sbgp Grete Coal Measures	
			(? ‘ <i>Eurydesma</i> ’) <i>Costatumulus amosi</i> (formerly <i>Cancinella aff. farleyensis</i>)	Cerro Agua Negra Fm		<i>Strophalosia subcircularis</i> <i>Strophalosia concentrica</i> <i>Eurydesma/Triganoiretra</i>	Allandale Fm Lochinvar Fm		*? Locality B KG-4649
CARBONIFEROUS			Tivertonia- Streptorhynchus	Cortaderas Fm		hiatus	Burnett Fm		*? Locality A,C KG-4599 KG-4650
			Balakhonia-Geniculifera		Molón de Hierro Fm	<i>Auriculispina levis</i>	Rands Fm		
			Levipustula Lampustula		unfossil- iferous	<i>Levipustula levis</i>		Seatham Fm	
			Rugosochonetes- Bulahdelia	Mallman Gp	Pampa de Tepuel Fm	<i>Marginiturgus barringtonensis</i> <i>Rhipidomella forlimuscula</i> <i>Linoprofontia tenuirugosa</i> <i>Inflatia elegans</i>	* * * * * * * * * * * * * * * * *	*Youdale Fm *Kullaline Fm *Booral Fm	
							* * * * * * * * * * * * * * *	Paterson Fm Mt Johnstone Gillmore Volcs Wairaringa Fm *Flagstaff Fm	

* zonal faunas present in unit
Taboada 1997, 1999 at left
Simanaukas & Sabbattini 1997 at right
Roberts et al. 1995
Taboada 1999
Gonzalez 1981
Taboada 1997
Maxwell 1964
Roberts et al. 1995
Kelly et al. herein

Fig. 8. A simplified correlation table of the Late Palaeozoic faunas from Alexander Island, Antarctica with the brachiopod zones of Argentina and eastern Australia. Some principal lithostratigraphic units are shown.

common in austral Carboniferous and Permian strata (J.M.D. observations as well as Dickins 1963; Pujana 1986; Taboada & Sabattini 1987; Sabattini *et al.* 1990). All the gastropods occur at Locality A.

Nautiloids. Riccardi & Sabattini (1975) described *Sueroceras*, an orthoconic form with reticulate ornament, from the Late Carboniferous of Patagonia. Revised stratigraphy of the Chubut Basin in Argentina suggests that the genus ranges from the Sakmarian to Artinskian and possibly into the Kungurian of the Permian (Simanauskas & Sabattini 1997). The genus was also recorded from the Carboniferous of Uruguay, Alaska, Oklahoma (USA), Ireland, south Urals (Russia), and ?Permian of Australia (Riccardi & Sabattini 1975). All specimens occur at Locality A.

Crinoids. Because few late Palaeozoic faunas of disarticulated crinoid ossicles have been described, particularly from the southern hemisphere, the crinoid faunas of localities A and C give little indication of the exact age of the rocks. The presence of platycrininitids indicates a Carboniferous or Permian age. *Pentaridica rothi* Moore & Jeffords (1968), to which several ossicles from Locality A are compared, was originally described from the Virgilian (Gzhelian) of the USA. Other species of *Pentaridica* have been recorded from the Tournaisian of Kazakhstan (Polozhichina 1980), the Late Visean and Namurian A (Late Visean–Serpukhovian) of Poland (Gluchowski 1981), the Moscovian of Russia (Dubolatova 1976) and from the Desmoinesian–Virgilian (Moscovian–Gzhelian) of the USA (Moore & Jeffords 1968). *Cyclocaudex* has a long stratigraphic range (Moore & Jeffords 1968).

Discussion

Faunal dating

Originally Campbell & McKellar (1969) believed that the *Levipustula levis* Zone in eastern Australia ranged through much of the Westphalian. Roberts *et al.* (1976) also dated the zone as Namurian–Westphalian, although it has been taken to be Westphalian or Stephanian, based on the occurrence of the ammonoid *Cravenoceras* and radiometric data. However, evidence for the Westphalian age now appears to be lacking. Roberts *et al.* (1993) concluded that the base of the *Levipustula levis* Zone was Namurian, although the upper limit there has not yet been established. The Early Permian date based on U–Pb zircon analysis from supposed rhyolites can now be discounted as these belong to sills (Roberts *et al.* 1993). The presence of *Australofenestella cincta*, which ranges towards the top of the Rands Formation in Queensland (Maxwell 1964), is accompanied by *Liriplica alta*, a species which first appears in the *L. levis* Zone. *A. cincta* could, therefore, indicate an age slightly younger than that of the *L. levis* Zone. But whether this age should extend the *L. levis* Zone into the Westphalian is uncertain (J. Roberts pers comm. 1999). In New South Wales, the age of the top of the *Levipustula levis* Zone cannot be determined precisely because of a transition to non-marine deposition and poor faunas combined with an absence of volcanic rocks, which could provide isotopic ages (J. Roberts pers comm. 1999). In New South Wales the *L. levis* Zone is present in the Booral Formation, Yagon Siltstone and Kullatine and Youdale formations. SHRIMP U–Pb ages from volcanic rocks both above and within the *L. levis* Zone constrain the age of the top of the zone to about 322 Ma, which is Early Namurian (Roberts *et al.* 1995). Thus, in Australia, there is no direct evidence for the *L. levis* zone extending into the Westphalian. This interpretation is reflected in Fig. 8.

In Argentina, González (1981) regarded the *L. levis* Zone as comparable to the Namurian–Westphalian of the European succession and to the Serpukhovian–Moscovian of Russia. In South America, according to Sabattini *et al.* (1990), the *L. levis* Zone is underlain by the *Rugosochonetes–Bulahdelia* Zone of latest Visean to earliest Namurian age, and is overlain by the *Lissochonetes jacalensis–Streptorhynchus inaequiornatus* Zone (the former Intermediate Zone), which contains the *Buxtonia–Heteralosia* fauna of Late Westphalian to

Stephanian age (i.e. Moscovian–Gzhelian). Taboada (1997) placed the upper boundary of the *Levipustula* Zone, with the *Balakhonia–Geniculifera* Zone imprecisely in the Westphalian. In contrast to other authors, Simanauskas & Sabattini (1997) divide the *Levipustula* Zone of the Pampa de Tepuel Formation of Chubut into (from the base up): the *Lanipustula* Zone (Namurian–Stephanian; i.e. Serpukhovian–Gzhelian), *Pyramus faunule* (Asselian) and *Tuberculatella* Zone (lower part of Sakmarian) (Fig. 8). But again, as in Australia, there is no direct evidence that the *L. levis* zone should be extended into the Westphalian (Fig. 8).

With regard to the *Canocrinella* fauna, Simanauskas & Sabattini (1997) believed it was of late Sakmarian to early Artinskian age. There follows the *Neochonetes* Zone, also containing *Canocrinella*, which ranges up to the Kungurian (Fig. 8). In contrast Taboada (1997, 1999) replaced the *Canocrinella* aff. *farleyensis* Zone with that of *Costatumulus amosi*, which ranges through the Asselian into the early Sakmarian.

The faunas from Localities A and C clearly belong to the *Levipustula* fauna. At present it would be inappropriate to use the term zone. This fauna appears suddenly in both eastern Australia and southern South America with little transition with underlying faunas. In eastern Australia there is a widespread major hiatus between beds which may not be younger Namurian and beds which are not older than Asselian, and in many cases younger. No forms have been recognized or described which could be fitted into this hiatus. There are good indications of unconformity, disconformity and structural change. In Patagonia there is a clear break between the *Levipustula* fauna and younger forms from which identifications seem to include Permian taxa, although identifications and descriptions are rather unsatisfactory. In western Argentina there is a fauna between the *Levipustula* and well described *Canocrinella* faunas which is clearly Late Carboniferous (González 1993). The *Lanipustula*, *Pyramus* and *Tuberculata* faunas of Simanauskas & Sabattini (1997) contain Carboniferous species and genera which are quite distinct from any Permian fauna known to J.M.D., in Australia or anywhere else. The three contain elements of the *Levipustula* fauna and their differences could be palaeo-

ecological or provincial (see also González 1999). Although *Eurydesma* is reported from the Early Sakmarian (Tastubian) and possibly the Late Sakmarian (Sterlitamakian) of eastern Argentina, the relationship to the *Costatumulus amosi* fauna remains unclear (Taboada 1999). Further collections seen (by J.M.D.) from Patagonia indicate that the '*Eurydesma*' is not true *Eurydesma*.

Based on the molluscan and bryozoan faunas, it is concluded that the Mount King beds at localities A and C are best

correlated with the *Levipustula levis* Zone of eastern Australia, and the *Levipustula* fauna of Argentina, and are therefore ascribed to the Namurian (i.e. Serpukhovian–Bashkirian). Positive evidence for the fauna extending into the Westphalian remains lacking or uncertain. Locality B yields a brachiopod assemblage of probable younger aspect, most likely comparable to the *Canocrinella* fauna. This has been interpreted as of late Sakmarian–early Artinskian age, but may belong in the Asselian/Sakmarian *Costatumulus amosi* Zone. A less likely comparison is with faunas of the *Neochonetes* Zone, late Artinskian to early Kungurian age, of Chubut, Argentina. However, as the normal range of *Canocrinella* is from the latest Carboniferous (Gzhelian), it is most likely that the Locality B fauna may range from Gzhelian to Artinskian age.

Lithostratigraphic relationship of the Mount King beds

The outcrops of the Mount King beds are located adjacent to LeMay Group strata. An exposure of the LeMay Group at the southeastern end of the Toynbee Glacier (Fig. 2), which was visited by B. W. Care (BAS) in 1975–1977, is situated only 6 km to the NW of our localities B and C; it also lies to the east of the supposed position of the LeMay Range Fault (Fig. 2). A modal analysis for an arkosic arenite from the Toynbee Glacier locality was presented by Burn (1984, fig. 21), and on a QFL plot lies in a similar position to the LeMay Group sandstones of the Douglas range. On that basis, Burn (1984) placed the Toynbee Glacier locality and surrounding areas (including Mount King) within the LeMay Group. This is further evidence that the LeMay Group outcrops extend to the

east coast of northern Alexander Island.

Although the sedimentary rocks of the LeMay Group are generally regarded as having been accreted, this has only been demonstrated at a few localities. Accretion cannot be proved in the Mount King beds, although the lithologies and textures are consistent with their formation under such tectonic conditions. In addition, accretionary complexes include autochthonous trench-slope as well as allochthonous units, such that even if the Mount King beds were not formed by such a process, this would not necessarily preclude their inclusion within the LeMay Group.

It is possible that the Mount King beds could represent a basement to the Fossil Bluff Group, the nearest outcrop of which is 10 km to the south at Zebra Ridge (Fig. 2). The intervening area is snow and ice filled and no contact between the Mount King Beds and other parts of the LeMay Group is recognized. At Zebra Ridge, and south to Atoll Nunataks, the basal Selene Nunataks Formation of the Fossil Bluff Group rests unconformably on undated rocks of the LeMay Group (Doubleday *et al.* 1993; Macdonald *et al.* 1999).

The Trinity Peninsula Group crops out in the northern Antarctic Peninsula. It comprises turbiditic clastic rocks with cherts, pillow lavas and greenstones. Although it is currently interpreted as an accretionary prism complex (Storey & Garrett 1985), the exact depositional setting remains unclear (Smellie 1991). Dating of the Trinity Peninsula Group ranges from Carboniferous to Triassic, based on Triassic biostratigraphy (M. R. A. Thomson 1975*a, b*) and radiometric methods (Pankhurst 1983; Hervé *et al.* 1991). Burn (1984) compared the LeMay Group with the Trinity Peninsula Group, and it is clear that there are also similarities between the Mount King beds and the latter.

On balance the Mount King beds are provisionally placed within the LeMay Group rather than the Trinity Peninsula Group, but there are features in common with both groups. Only future fieldwork will resolve their lithostratigraphic position more precisely. If the Mount King beds are to be separated from the LeMay Group they will need to have a mappable boundary between them and this boundary is not at present recognized.

Tectonic implications

The presence of Carboniferous fossils within the LeMay Group raises important questions concerning the tectonic evolution of the region at that time. Firstly, do the beds containing the faunas indicate that subduction was taking place beneath the Antarctic Peninsula margin during the Late Palaeozoic, and was the polarity the same as in the Mesozoic and Cenozoic? Secondly, was this subduction occurring at the Pacific margin of Gondwana?

Bedding disruption, sediment mobilization features, cataclasis, brecciation and a general lack of penetrative fabrics have been described by Tranter (1987, 1992) and Doubleday *et al.* (1993) from the LeMay Group. These authors interpreted such structures as indicators of deformation of unlithified sediments and of rapid burial during subduction near the toe of an accretionary complex. In accretionary prism models, the fact that the sediments are unlithified during deformation and burial indicates that accretion occurred soon after deposition. The structures from the Mount King beds are comparable to those of the LeMay Group and are certainly consistent with deformation within an accretionary complex, but on their own they are not conclusive. Therefore, in view of the regional geology and the lack of contradictory evidence, we feel that it is probable that the Mount King Beds originally formed part of such a Late Palaeozoic complex.

The polarity of the postulated Carboniferous subduction at Alexander Island is unknown. No structures are present in the Mount King Beds that show vergence. Mesozoic tectonic transport directions elsewhere in the LeMay Group are mostly towards the west or NW (Tranter 1987, 1992; Nell 1990; Doubleday & Tranter 1994), which suggests east or SE-directed subduction at that time, consistent with the presence of a coeval subduction-related magmatic arc to the east. Studies of Antarctic Peninsula basement rocks (Harrison & Loske 1988; Milne & Millar 1989) indicated that the arc was probably also active in the Palaeozoic; Milne & Millar (1989), for example, provided evidence from Graham Land of Silurian arc-related granites that were metamorphosed in the Late Carboniferous. Assuming the metamorphism was also subduction related, then east or SE directed subduction is also

possible, but still unproven, for the Late Carboniferous.

The Late Palaeozoic history of the southern Pacific margin of Gondwana is not particularly well-understood or agreed upon. It is well known that subduction was occurring along the margin in Chile (Bahlburg 1993) and also in Australia, but the exact history of some of the accreted terranes involved in both these regions is uncertain (Dickins *et al.* 1992; Bahlburg 1993). Most interesting for the purposes of this paper is the evolution of Patagonia, which was along strike from the Antarctic Peninsula within the Andean chain (or Antarctandes) during the Mesozoic. The data presented here reinforces some links between the two regions by showing chronological and faunal relationships between them in the Late Carboniferous. It has been suggested by Ramos (1984) that, prior to the Late Palaeozoic, Patagonia was not part of Gondwana, but was

accreted to it sometime during Permo-Triassic time. The same author also suggested that this may have applied to the Antarctic Peninsula and other minor plate fragments.

Conclusions

The fossils of the Mount King beds provide the first records of marine Carboniferous and possible Permian macrofaunas from the Antarctic continent. They represent the oldest faunas collected from the Antarctic Peninsula. Two sites contain molluscs and bryozoans which correlate largely with the Carboniferous *Levipustula levis* Zone faunas of eastern Australia and Argentina. They are of probable Serpukhovian or possibly earliest Bashkirian age. A third site contains brachiopods of less well defined age which may correlate with the Permian *Canocrinella* fauna of Argentina, but which may be of Late Carboniferous–Permian (Gzhelian–Artinskian) age. The palaeobiogeographic evidence demonstrates affinities of the faunas of Alexander Island with those of Argentina and eastern Australia in Carboniferous and Early Permian times.

The Mount King beds are provisionally placed in the LeMay Group of Alexander Island on lithological grounds, although they may also correlate with the Trinity Peninsula Group of the northern Antarctic Peninsula. More confident

allocation to either of these groups or to a new unit must await more detailed fieldwork in the region, including mapping of lithostratigraphic boundaries. The sedimentary and structural features of the Mount King beds are consistent with accretionary prism processes as previously recognized in the LeMay and Trinity Peninsula groups, but do not prove accretion in Alexander Island in the Late Palaeozoic. The nature of the deformation in these beds suggests only shallow burial as the sediments appear to have been unconsolidated on deformation.

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