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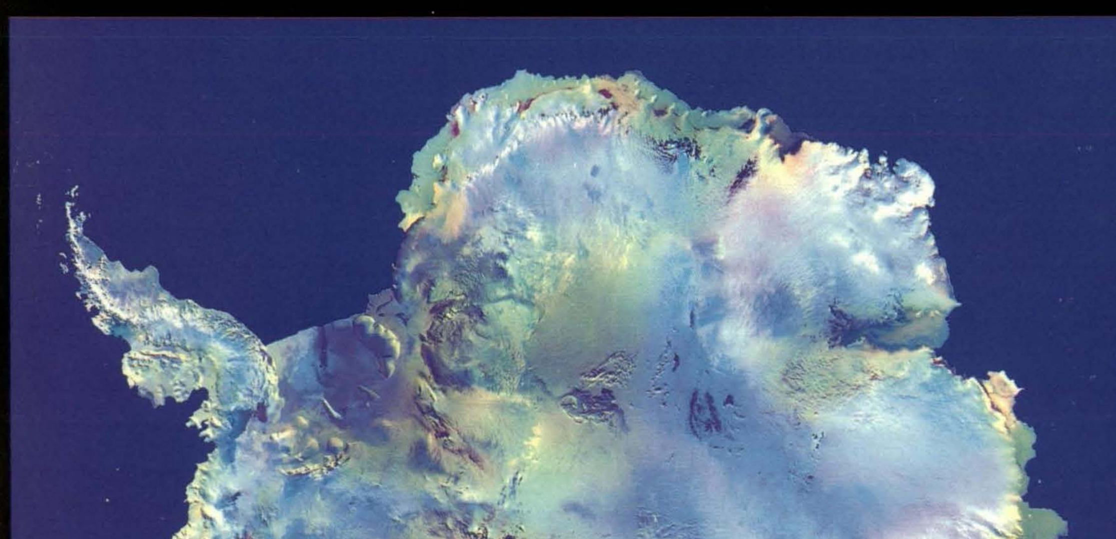
Commentary on schematic geological map of Antarctica Scale 1:10 000 000



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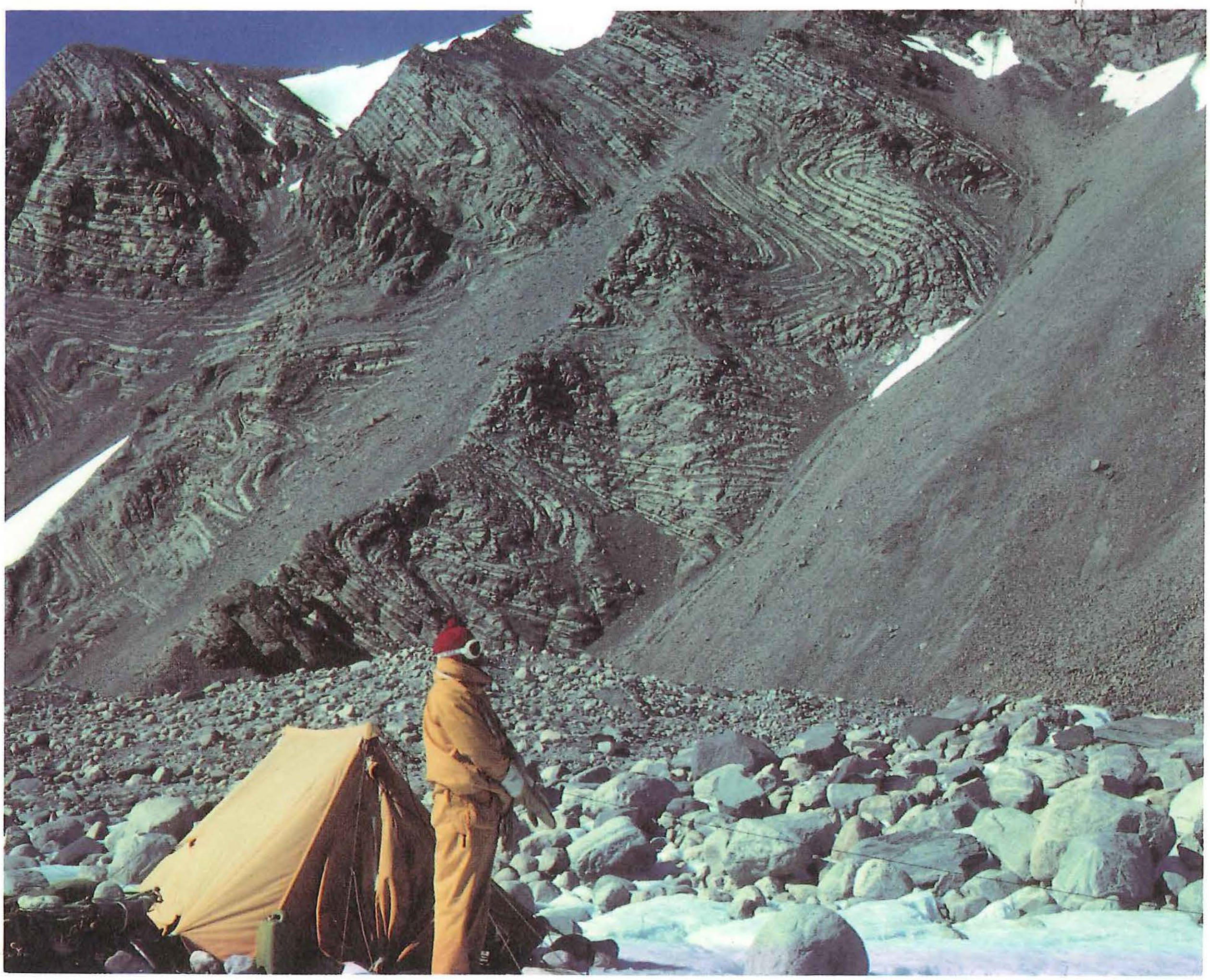

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DEPARTMENT OF PRIMARY INDUSTRIES AND ENERGY
BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

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Commentary on schematic geological map of Antarctica Scale 1:10 000 000

Compiled by
R.J.TINGEY

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Cover: Mosaic of AVHRR (Advanced Very High Resolution Radiometer) imagery over Antarctica. (Reproduced by permission of the United Kingdom National Centre for Remote Sensing; satellite data acquired by the United States National Oceanographic and Atmospheric Administration.) The mosaic is a combination of selected parts of about 30 separate scenes acquired on different dates and with a range of sun elevations and azimuths; its preparation is described by Merson (1989).

Frontispiece: Folded meta-sediments (Ᵽs) on the north face of Mt. Rubin, Southern Prince Charles Mountains.

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INTRODUCTION

Compared to the other continents, Antarctica is geologically distinctive in being almost wholly covered by ice, appearing to be essentially free from earthquake activity, and in apparently having had an almost fixed location for the past 200 million years (Ma) or so. However, it must be emphasized that glaciation of Antarctica is an unusual and geologically quite recent condition, and that the continent has been ice free for most of its geological history. Other distinctive geological features of Antarctica include the ultra high-grade metamorphic rocks of the Napier Complex in Enderby Land, the Wohlthat Massif anorthosite complex in Dronning Maud Land, the immense Dufek intrusion that is partly exposed in the Pensacola Mountains, and the related and very widespread early Mesozoic tholeiitic intrusive rocks, the assemblage of microcontinents that makes up West Antarctica, and local concentrations of meteorites on the ice surface.

The purposes of this Bulletin are to explain and describe the accompanying 1:10 000 000-scale geological map, to discuss briefly the map's units, and to provide readers and users with a guide to the rapidly expanding literature of Antarctic geology, from which they can obtain more detailed information. The map is intended as a replacement for the maps compiled by Craddock (1970, 1972), and as an alternative to the map explained by Grikurov (1979) and based on a map compiled by Soviet Antarctic Expedition geologists led by Professor M.G.Ravich (Ravich & Grikurov, 1976). These earlier maps are now out of date, and either out of print or difficult to obtain. The map described here is drawn on a topographic map published in Australia by the former Division of National Mapping (now the Australian Survey and Land Information Group [AUSLIG]). It depicts the gross form of the continental ice cap by means of approximate contours, and the shape of the continental shelf through bathymetric contours (isobaths).

Like its predecessors, this map is greatly generalized. It is essentially self-explanatory and presents an up-to-date summary of Antarctic geology compiled from the work of earth scientists from most of the countries now active in the southern polar continent. It will serve as a basis for illustrations and slides, and as a teaching aid. Novel features include the use of striping to indicate the close intermingling of different rock units (in the Antarctic Peninsula, for example), and of special symbols to indicate the general location of Proterozoic mafic dyke swarms, Phanerozoic alkaline dykes, and early Mesozoic tholeiitic dolerite intrusives.

The main obstacle to Antarctic geological exploration is, and has been, the fact that only about 2% of the continent's bedrock is not covered by ice, and thus accessible to surface examination. A subsidiary problem is the difficult access to these outcrops, many of which are in large cliff faces (Fig.1) or isolated nunataks adjacent to which the ice surface is commonly crevassed and deeply scoured by wind erosion (see also Figure 12). Antarctic geologists have the challenging task of unravelling from these sparse outcrops the geological record of a continent almost twice the size of Australia. An additional problem is that the research involves scientists from more than twenty nations, which makes it difficult to compile and interpret information across the whole continent. The special problems posed for field work by the severe Antarctic climate are well known.

DuToit (1937) described Antarctica as the 'key-piece' of Gondwana, the former super-continent that split up from about 250 Ma onwards to yield modern Africa, Antarctica, Australia, India, Sri Lanka, Madagascar, and South America. It is almost entirely surrounded by mid-ocean spreading ridges (Bentley, 1991) that define the edge of the Antarctic lithospheric plate. The spreading ridges were created when oceanic crust was

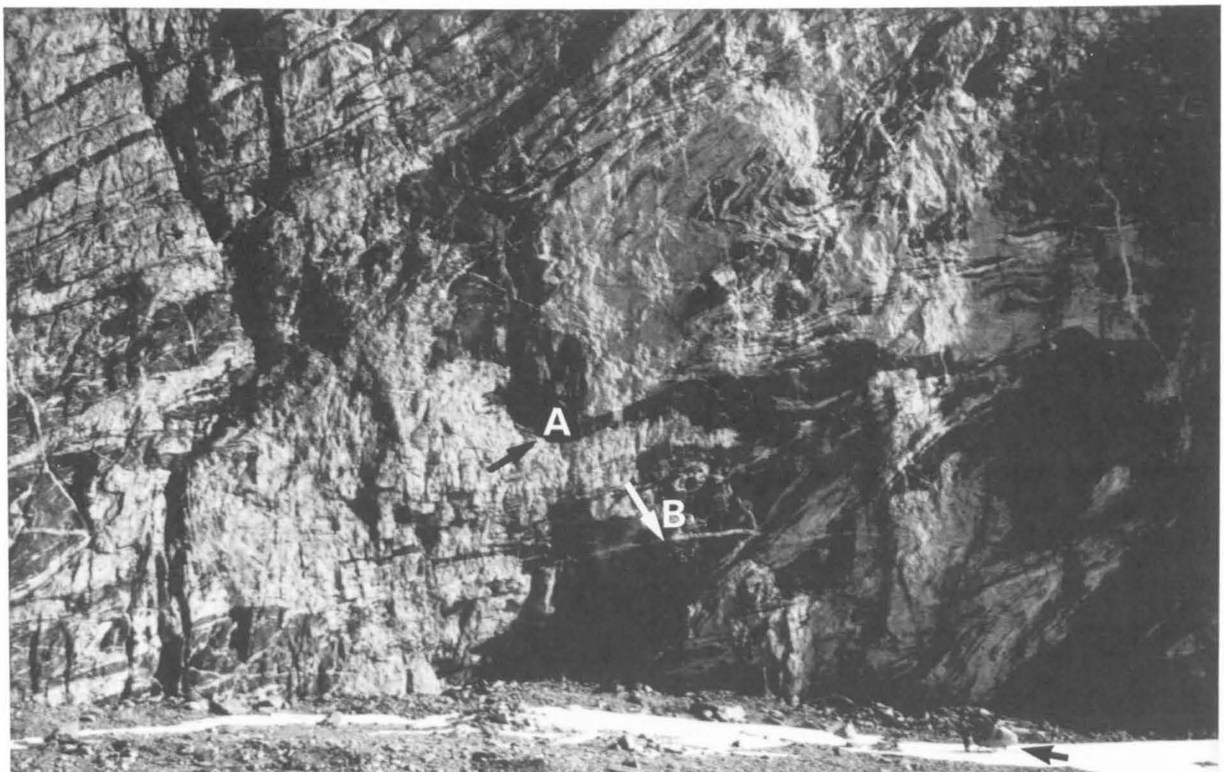

Fig.1. Cliff exposure of Precambrian metamorphic basement rocks at Mount Twigg, southern Prince Charles Mountains, East Antarctica (helicopter for scale). The black unit A is a metamorphosed basic dyke that intruded the layered rocks before they were folded, probably at about 1000 Ma. Unit B intersects and therefore post-dates the fold and was probably emplaced at about 500 Ma.

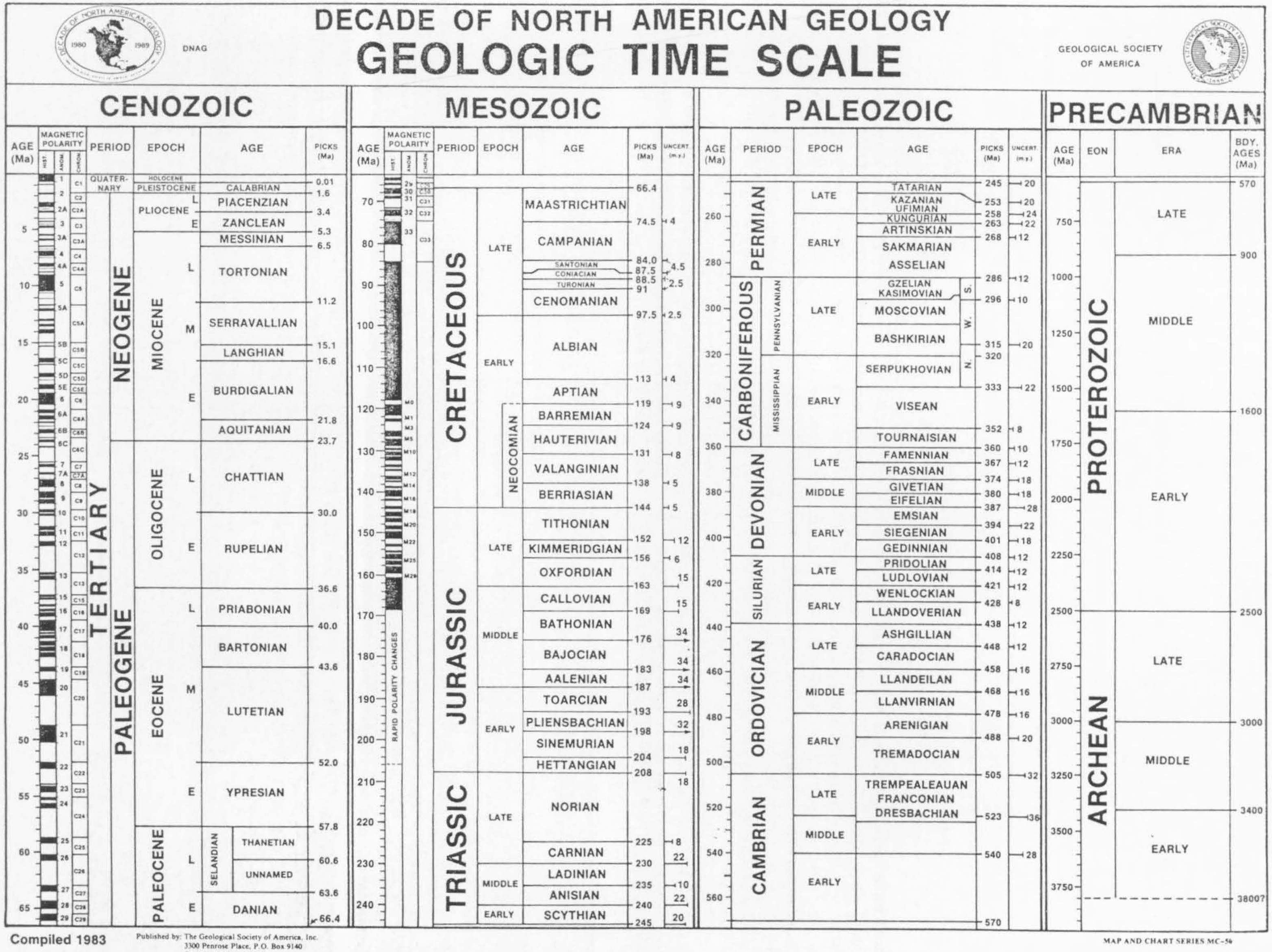

Fig.2. Decade of North American Geology Time Scale. (Reproduced with permission of the Geological Society of America.)

generated beneath rift valleys on Gondwana and caused them — and the formerly adjacent land masses — to migrate away from the Antarctic continent. The margins from where the Gondwana fragments split off are classed as passive (Anderson, 1991), and Antarctica's only convergent (or active) continental margin is in the Antarctic Peninsula region (Barker & others, 1991).

The map focusses on bedrock geology, and units ranging in age from Archaean to Cainozoic (see geological time scale, (Fig. 2) are depicted. Although glacial deposits and the modern ice cap — arguably Antarctica's most distinctive modern geological features — are only depicted in a very general way, some of the more important late Cainozoic rock units, such as the glacial deposits in the Victoria Land Dry Valleys, and the 'Marine Plain' deposits in the Vestfold Hills, Princess Elizabeth Land, are shown. However, the Sirius Formation (or drift — see Webb & others, 1984 and Denton & others, 1991), a Cainozoic glacial deposit that mantles the Transantarctic Mountains, and Quaternary glacial drift deposits (Fig.3), are omitted. These units are important for studies of Antarctica's Cainozoic glacial and palaeo-environmental history (see Webb & others, 1984; Denton & others, 1991), as are offshore sequences drilled by the Deep Sea Drilling Project (DSDP; Hayes, Frakes & others, 1975), the Ocean Drilling Program (ODP : Barker, Kennett & others, 1988; Barron, Larsen & others, 1988); inshore sequences sampled by the McMurdo Sound Sediment and Tectonics Studies (MSSTS) (Barrett, 1986) and CIROS (Cenozoic Investigations of the western Ross Sea) drilling (Barrett, 1989), and onshore sequences cored in the Dry Valleys Drilling Project (DVDP; McGinnis, 1981). The DSDP and ODP results, and those of the MSSTS, CIROS, and DVDP drilling (see discussion by McKelvey, 1991) indicate that Antarctica's current glaciation started in Eocene/Oligocene (early to middle Cainozoic) times.

For geological discussion it is convenient to divide Antarctica into West Antarctica (which includes the Antarctic Peninsula); the Transantarctic Mountains (here defined as extending from the Pensacola Mountains to northern Victoria Land); and East Antarctica (i.e. that part of the continent between longitudes 40°W and 155°E).

SOURCES OF INFORMATION

The need for a revised geological map of Antarctica became apparent during compilation of the monograph *Geology of Antarctica* (Tingey, 1991a). The chapters therein (which are authoritative reviews of nineteen aspects of Antarctic earth science) have proved to be important sources of information for the map and this Bulletin.

Previously published geological maps of Antarctica (Craddock, 1970; 1972; Ravich & Grikurov, 1976; Grikurov, 1979; Craddock & others, 1989), and the proceedings volumes of the five international symposia on Antarctic earth science held since 1963 (Adie, 1964, 1972; Craddock, 1982; Oliver & others, 1983; Thomson & others, 1991) also yielded important information, as did regional geological syntheses published at the national level (for example Crohn, 1959; Gunn & Warren, 1962; Ravich & others, 1968; Ravich & Soloviev, 1969; Wolmarans & Kent, 1982; Stump, 1986; Sheraton & others, 1987b). In addition, reference has been made to papers in national and international earth science journals, and the proceedings volumes of the international Gondwana symposia (for example, Campbell, 1973; Cresswell & Vella, 1981; McKenzie, 1987), and other meetings (for example Glover & Groves, 1981). Finally, it should be noted that unrefereed publications, such as the *Antarctic Journal of the United States* and the *New Zealand* and *Japanese Antarctic Records*, contain much relevant information.

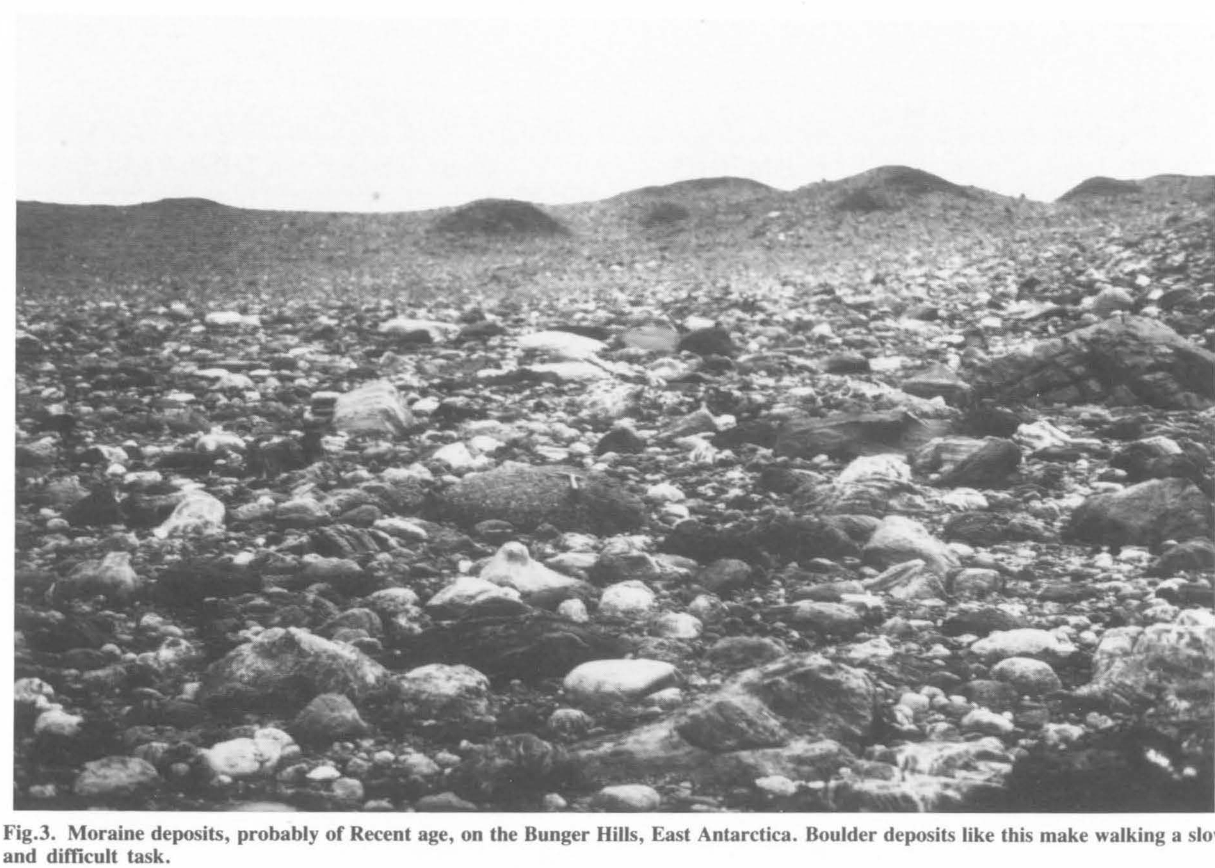

Fig.3. Moraine deposits, probably of Recent age, on the Bunger Hills, East Antarctica. Boulder deposits like this make walking a slow and difficult task.

A COMPARISON WITH OTHER MAPS

This map differs from those of Craddock (1970; 1972) in several ways:

— First, the Antarctic Peninsula is interpreted as a Mesozoic/Cainozoic magmatic arc complex, instead of a volcanic and sedimentary pile of that age overlying a Palaeozoic or Precambrian metamorphic basement. Isotopic dating of the metamorphic 'basement' in the Antarctic Peninsula has yielded (Milne & Millar, 1989) a Rb-Sr isochron age of 426 ± 12 Ma (Silurian) for the emplacement of a gneissic granite, and Sm-Nd ages of 331 ± 8 Ma and 311 ± 8 Ma (Carboniferous) for the subsequent metamorphism; no Precambrian ages have been obtained.

— Second, since 1970, a considerable research effort has been devoted to the acquisition of an improved understanding of the East Antarctic metamorphic basement shield. This is reflected on the map by the age and lithological subdivision of the shield rocks; they were mapped by Craddock (1970) on the basis of lithology and metamorphic grade. Grikurov (1979) assigned ages to the metamorphic shield rocks by correlation with metamorphic grade: the highest-grade rocks (those formed at the highest temperatures and greatest pressures) being regarded as the oldest, and lower-grade ones younger. On the accompanying map, ages are assigned to rock units on the basis of isotope geochronology and field observations. Although the highest-grade metamorphic rocks in Antarctica (the Napier Complex in Enderby Land) yield the oldest isotopic ages (see Sheraton & others, 1987b), it does not follow that a rock's age can be inferred from its metamorphic grade. In Australia and southern Africa, for example, many Archaean greenstone (metamorphosed mafic volcanic rocks) sequences are of low grade.

— Third, the concept of suspect, exotic, or allochthonous terranes that have been moved into their present positions by strike-slip faulting or other tectonic processes is applied in northern Victoria Land (Bradshaw & others, 1985; Ganovex Team, 1987) and possibly also farther south in the Transantarctic Mountains (Rowell & Rees, 1989). Schopf (1969) probably anticipated these ideas with his suggestion that the Ellsworth Mountains had originally been aligned with the Transantarctic Mountains.

In northern Victoria Land, the Robertson Bay and Bowers Terranes consist of contrasting suites of slightly metamorphosed Early Palaeozoic rocks (**Pze**) separated by a major tectonic dislocation, intruded by Devonian granitoids (**Pzg**$_{D}$), and overlain by Devonian and Cainozoic volcanics (**Pzv, Czv**). They are separated by a major fault from the Wilson Terrane, which lies to the west (and is inadvertently not indicated on the map). The Wilson Terrane consists of metamorphic rocks, probably of late Precambrian age (**Ᵽm, Ᵽs**), intruded by Palaeozoic granitoids (**Pzg, Pzg**$_{D}$) and Mesozoic tholeiites (black dot), and overlain by Devonian lavas (**Pzv**), sedimentary rocks of continental origin (**B**), and Mesozoic and Cainozoic volcanics (**Mvt, Czv**). It is not clear when the terranes were juxtaposed: the inference (Ganovex Team, 1987) that Devonian granites are present in all three terranes suggests that they were adjacent at that time, whereas the absence of Jurassic tholeiitic rocks from the Robertson Bay Terrane may indicate that it was moved next to the rest of northern Victoria Land later in the Mesozoic.

Similar concepts are involved in determining the relative motions of the crustal blocks of which West Antarctica is composed (see Dalziel & Elliot, 1982; Lawver & others, 1985; and Barker & others, 1991).

— Fourth, it is now possible to map the subglacial extent of the Dufek intrusion by interpretation of airborne and ground geophysical surveys (Behrendt & others, 1981). A small portion of this layered mafic intrusion (Ford, 1983; Ford & Himmelberg, 1991) is exposed in the Dufek Massif and Forrestal Ranges of the Pensacola Mountains (see Fig.16).

Craddock & others (1989) incorporated most of these advances in their map, and depicted the geology of the continental shelf in broad outline. Diagrammatic logs of holes drilled in the Antarctic region by the DSDP and ODP ships are also shown. However, Craddock & others treated Antarctica from a Circum-Pacific perspective, whereas the map described here focusses on the Antarctic continent. Furthermore, this Bulletin provides a more comprehensive account of Antarctic geology than the notes provided by Craddock & others (1989). The present map is described first by map units in order of decreasing age, and second by geographical region moving eastwards from the Antarctic Peninsula. As outcrops in East Antarctica are mainly distributed around the edge of this almost circular landmass, they are mostly referred to in terms of their longitude.

FUTURE MAPS

On the accompanying map several features of Antarctic geology are insufficiently treated, one example being the above-mentioned Cainozoic glacial deposits. Future maps should attempt to rectify these deficiencies and also show details (surface and bedrock contours, ice streams and ice thickness data; see Drewry, 1983) of the modern ice cap, Antarctica's most distinctive modern geological feature. Ice surface contours on the present map convey an impression of the overall shape of the ice cap, but are only approximate. Information from the new generation of polar-orbiting satellites can be expected to yield a more accurate picture in the next five or ten years.

The Antarctic ice cap has expanded onto, and contracted back from, the continental shelf several times during the Cainozoic. Anderson (1991) argues that these events have had a profound influence on the shelf's morphological and geological development. The topography of the Antarctic continental shelf, its great water depth relative to other continental shelves, and its slope towards the continent are illustrated by the bathymetric contours on the map, but no details of submarine geology are shown. Future maps will build on the compilation of Craddock & others (1989) and illustrate the geology of the continental margins, currently the target of marine and airborne geophysical surveys (Behrendt, 1983; 1991) as well as marine geological studies (Anderson, 1991) and scientific drilling. Geological knowledge of the Antarctic margins is improving rapidly, and, as has been found elsewhere (Dunning, 1985), the offshore geology is in vivid contrast to that exposed onshore. For example, Ocean Drilling Program Leg 119 in Prydz Bay (Barron, Larsen & others, 1988) sampled Cretaceous rocks that have no known onshore equivalents.

The present map was compiled by 'traditional' techniques, but it is likely that future maps will utilise computer-aided-drafting methods and a digital base derived from satellite imagery. The map could be stored in a Geographical Information System and be progressively updated as new information becomes available.

ANTARCTIC ONSHORE GEOLOGY

Precambrian

The Precambrian units shown on the map are based on age (Archaean or Proterozoic), rock type (granitoid, volcanic, metamorphic), and grade of metamorphism or metamorphic facies (amphibolite, granulite). In this section, general reference is made to a review of Antarctic Precambrian geology by Tingey (1991c).

Research results have provided no direct evidence that Precambrian rocks are present in the Antarctic Peninsula, although certain interpretations of isotopic data point to the involvement of a Precambrian component in the genesis of at least some rocks (see Moyes & Hamer, 1983; and Pankhurst, 1983). The oldest known isotopic dates (Milne & Millar, 1989) indicate that in one area at least intrusive precursors of gneissic granite gneiss were emplaced between 426 ± 12 Ma and 410 ± 15 Ma, that no significantly older crustal material was present, and that ages of 331 ± 8 Ma, 311 ± 8 Ma, and 297 ± 3 Ma refer to a later amphibolite facies metamorphism. However, Grikurov (1979) argued that the lack of isotopic ages older than middle Palaeozoic in the Antarctic Peninsula was attributable to resetting of isotope systems in rocks, which, by virtue of their metamorphic grade, must be of Precambrian age. In more recent accounts, the Antarctic Peninsula's metamorphic rocks are regarded as products of a Mesozoic/Cainozoic magmatic arc complex at the Pacific margin of Antarctica (Thomson & others, 1983; Barker & others, 1991). In the Antarctic region, a modern volcanic arc is exposed in the South Sandwich Islands north of the Weddell Sea and just outside the map area (Barker & others, 1991).

Precambrian metamorphic rocks are, however, exposed in West Antarctica at the remote Haag Nunataks north of the Ellsworth Mountains. These small outcrops consist of granitic gneiss (orthogneiss: map symbol **Pm**) intruded by veins of pegmatite and granite. Isotopic dating indicates that the rocks were formed about 1000 Ma ago and did not have a significant prior crustal history. In the south Atlantic Ocean region, rocks of comparable age are exposed on the Falkland/Malvinas Islands (Cingolani & Varela, 1976; Dalziel, 1982).

Most bedrock exposures in East Antarctica consist of Precambrian metamorphic and igneous rocks that can only be dated by isotopic methods. In the Transantarctic Mountains, metamorphic rocks of Precambrian age are exposed in Victoria Land, and near the Nimrod Glacier; in addition, sedimentary rock sequences of low metamorphic grade are tentatively inferred to be of late Proterozoic age.

Archaean units

The letter symbol **Ag** represents Archaean granulite facies metamorphic rocks. The most extensive and best-studied exposures of such rocks constitute the Napier Complex in Enderby Land (Fig.4; longitude 50°E) (Sheraton & others, 1987b). As a result of field investigations by the Australian National Antarctic Expeditions (ANARE) between 1975 and

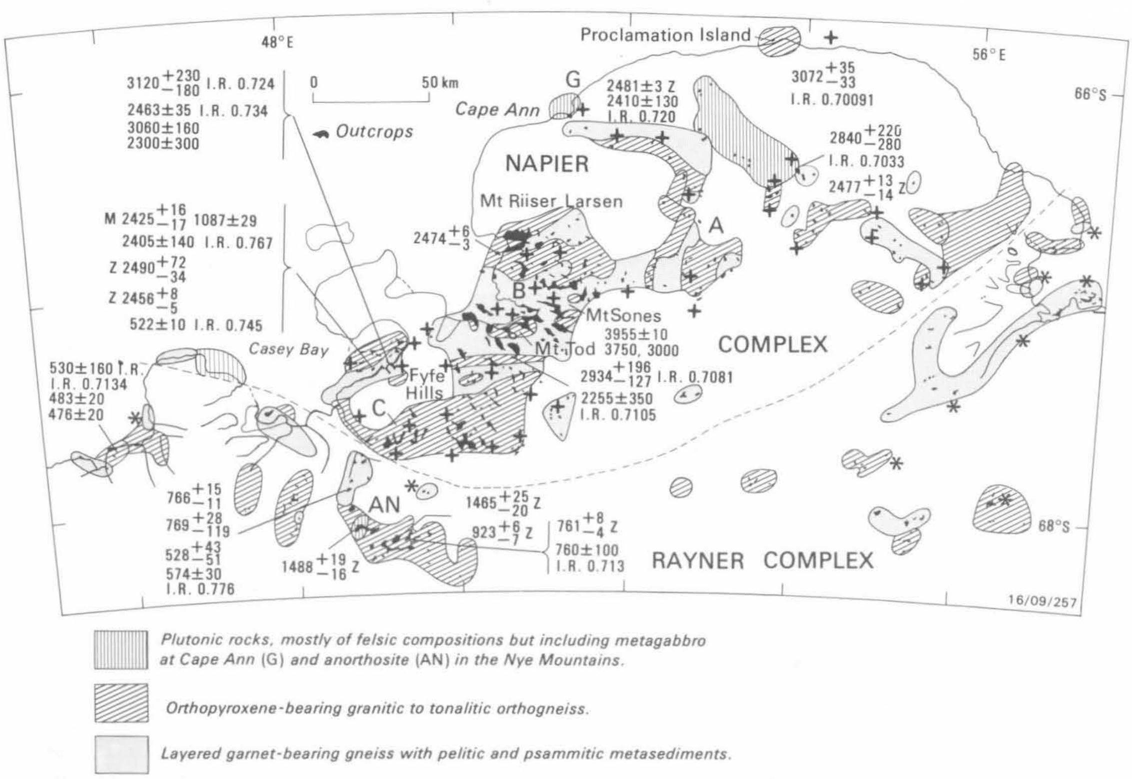

Fig.4. Geological sketch map of Enderby Land, East Antarctica, the site of Antarctica's highest-grade metamorphic rocks, as well as of its most ancient rocks.

1980, the Napier Complex has, despite its remote location, achieved prominence in the international literature of metamorphic and Precambrian geology (see Harley, 1989).

The Napier Complex is notable in several respects. For example, it includes rocks that have yielded some of the world's oldest isotopic ages (about 3900 Ma) in U-Pb studies of individual zircon grains, using the **S**uper **H**igh Mass **R**esolution **I**on **M**icro**p**robe (**SHRIMP**) at the Australian National University (Black & others, 1986b). In addition, unusual metamorphic mineral assemblages (coexisting sapphirine and quartz; Dallwitz, 1968; Fig.5: regional occurrence of osumilite and mesoperthitic feldspar) testify to very high metamorphic temperatures (950 to 1000°C) and low water pressures (Ellis, 1980; Harley, 1985, 1987a; Sheraton & others, 1987b). Also, lower-pressure mineral assemblages in surface rocks in the north and higher-pressure assemblages (such as sillimanite + orthopyroxene) towards the southern boundary are interpreted as evidence that different levels of the Archaean crust are exposed across the complex. Petrological studies of reaction textures (see Fig.6, and review in Sheraton & others, 1987b, pp.31–36) indicate that peak metamorphic conditions were followed by long-continued (600 Ma or possibly 2000 Ma) cooling at more or less constant pressure (isobaric cooling) as first proposed by Ellis (1980) and supported by Harley (1985, 1987a). Shear zones within and along the southern margins of the Napier Complex have yielded evidence of decompression during the main metamorphism of the adjacent Rayner Complex at about 1000 Ma (Sandiford, 1985; Harley & others, 1990). A decompression reaction from the Rayner Complex is shown in Figure 6B (see discussion in Sheraton & others, 1987b).

Structural geology studies, combined with multi-method isotope geochronology, have revealed the tectonic history of the Napier Complex. Intense ductile deformation and granulite facies ultrametamorphism at about 3100 Ma obliterated all earlier fabrics, and were followed by a less-pervasive ductile deformation at about 2900 Ma with broadly similar high-grade metamorphic conditions. After a third ductile deformation at about 2450 Ma imposed a dome-and-basin structural pattern, the now-consolidated (or cratonised) complex responded to stress by brittle fracturing, which provided pathways for the intrusion of mafic dykes. A first episode of mafic dyke emplacement occurred shortly after the 2450 Ma metamorphism, and at least two more took place before about 1200 Ma. The dykes are signified by an asterisk symbol (*) which indicates their presence in nearby outcrops, and they serve as a stratigraphic marker (James & Tingey, 1983) that distinguishes the Napier Complex from the adjacent Rayner Complex (map symbol **Pm**; Black & others, 1987), which is composed of much younger high-grade metamorphic rocks.

Archaean metamorphic rocks of slightly lower grade than those in the Napier Complex are exposed in the Vestfold Hills (78°E), and are intruded by swarms of mafic dykes that are this area's main geological interest (Sheraton & others, 1987a; Kuehner, 1987). Once again the mafic dykes are not seen in nearby outcrops of Proterozoic metamorphics, although metamorphosed relics which have been modified during the main Proterozoic metamorphism at about 1000 Ma are present in a transition zone. An isolated outcrop of high-grade metamorphic rocks, south of the Prince Charles Mountains at longitude 64°E, is also included in unit **Ag**.

Map unit **Ai** signifies rocks of generally granitic composition that intrude the Napier Complex (Black & others, 1986a), and are in turn intruded by mafic dykes; they have yielded isotopic dates of about 2500 Ma.

Amphibolite-facies granitic orthogneisses and metasediments of Archaean age are extensively exposed in the southern Prince Charles Mountains (Fig.7; longitude 60 to 70°E; Tingey 1982a,b), and are commonly intersected by metamorphosed mafic dykes. They have been mapped as unit **Aa** as have isolated outcrops of granitic orthogneiss in western Dronning Maud Land (longitude 5°W; Krynauw & others,

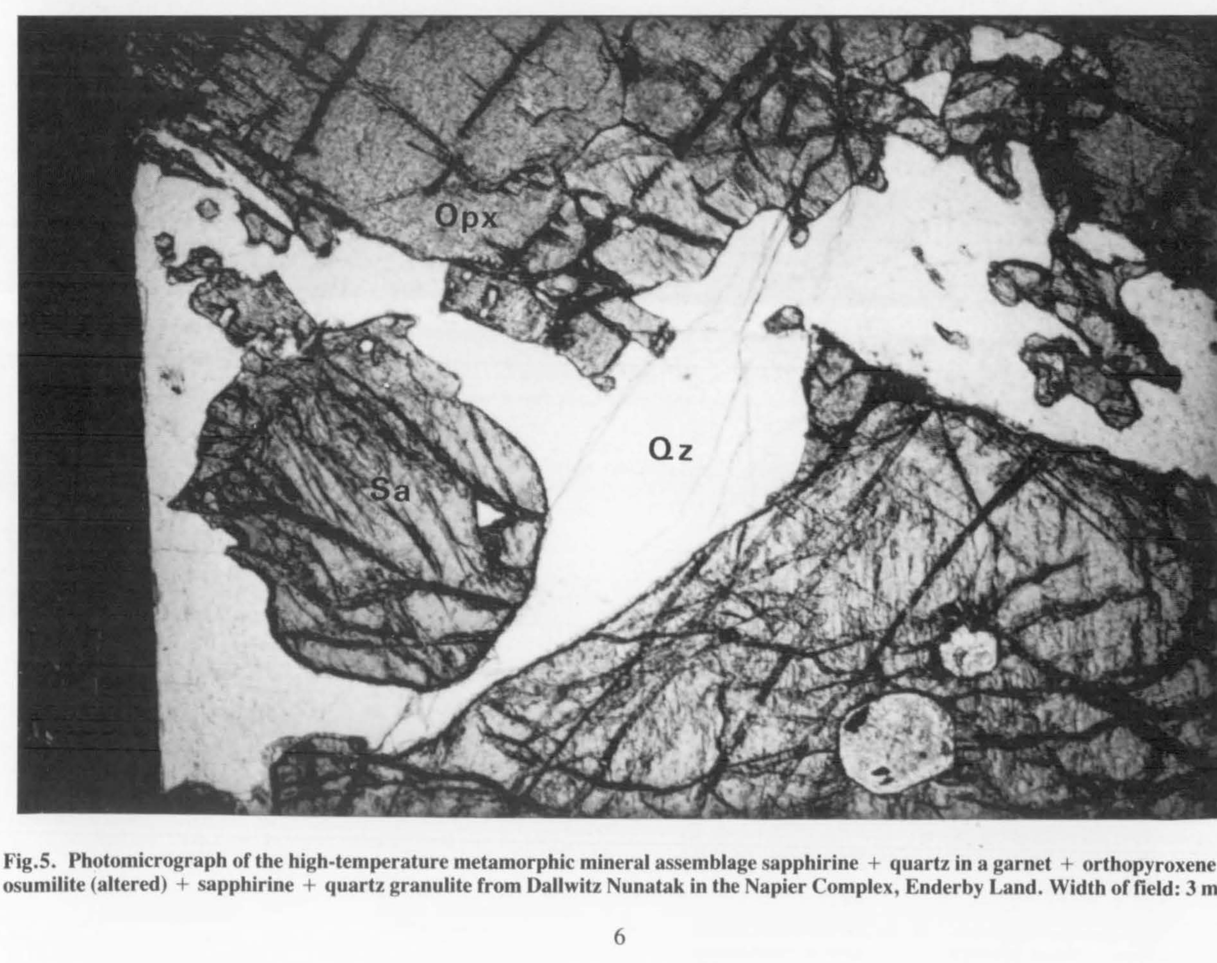

Fig.5. Photomicrograph of the high-temperature metamorphic mineral assemblage sapphirine + quartz in a garnet + orthopyroxene + osumilite (altered) + sapphirine + quartz granulite from Dallwitz Nunatak in the Napier Complex, Enderby Land. Width of field: 3 mm.

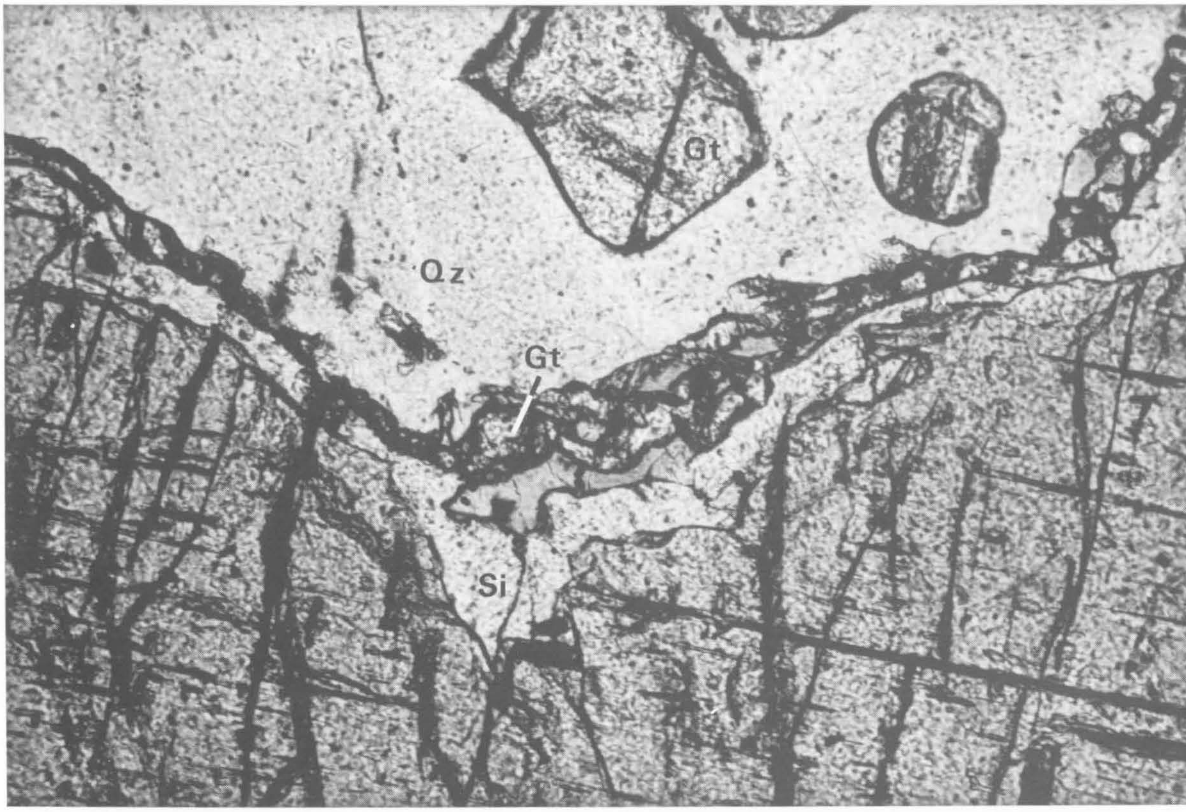

Fig.6A. Rim of sillimanite + garnet formed as a result of isobaric cooling between sapphirine and quartz in a sapphirine + orthopyroxene + biotite + K-feldspar + sillimanite + garnet + quartz granulite from the Napier Complex, Enderby Land. Width of field 0.8 mm.

Fig.6B. Reaction rims of calcic plagioclase + orthopyroxene surrounding garnet in an orthopyroxene + garnet + plagioclase + clinopyroxene granulite from the Rayner Complex, Enderby Land. They resulted from the decompression reaction:
garnet + clinopyroxene + quartz ⟶ anorthite + orthopyroxene.
Width of field 10 mm.

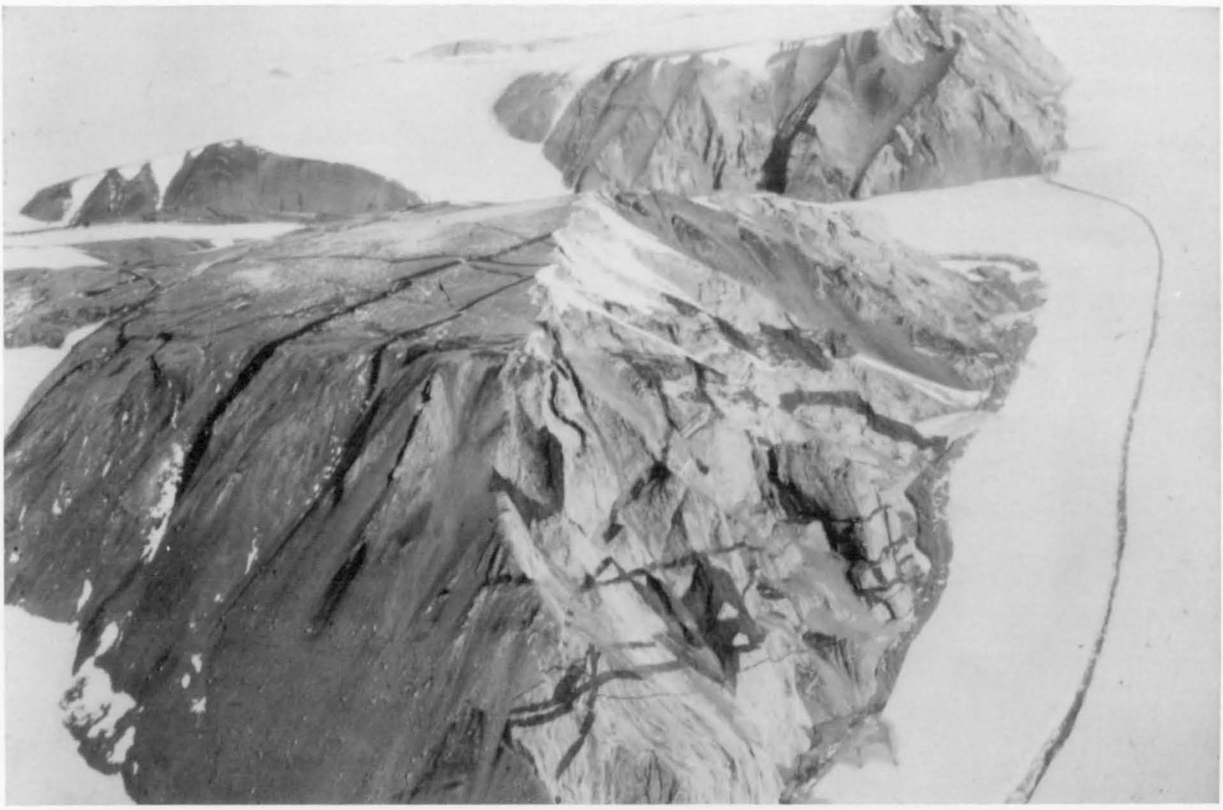

Fig.7 Outcrop of Archaean granitic basement gneiss intersected by metamorphosed mafic dykes; southern Mawson Escarpment, Prince Charles Mountains, East Antarctica. Note the flat erosion surface on the top of the escarpment; it has been glaciated but is not the result of glacial erosion. Accurate dating of this surface will be an important task for future geological investigations. The cliffs are about 800 m high.

1984; Barton & others, 1987). Geochronological studies have yielded reconnaissance Rb-Sr whole-rock isochron ages between 2600 and 3000 Ma (Tingey, 1982a,b; Barton & others, 1987) for these rocks, although the amphibolite and/or greenschist facies mineral assemblages in the southern Prince Charles Mountains are attributed to overprinting by later metamorphic events at 1000 and 500 Ma (Tingey, 1982a,b). The precursors of the Prince Charles Mountains metasedimentary rocks are thought to have originally been deposited unconformably on the granites, although contacts between the two are now obscured either by shearing or poor exposure. The metasediments include a prominent unit of white or green fuchsite (chromium mica)-bearing quartzite (Fig.8), and, on one mountain, lenticular bodies of banded iron formation. Airborne magnetic surveys by the Soviet Antarctic Expedition (SAE) indicate that the iron-rich rocks may extend under the ice for more than 100 km from the outcrops (Ravich & others, 1982). These banded iron formations have been the subject of speculation in considerations of the resource potential of Antarctica (see page 24 below and Splettstoesser & Dresschoff, 1990).

Soviet Antarctic Expedition geologists infer (Grikurov, 1979) that the amphibolite facies metamorphics in the southern part of the Prince Charles Mountains are younger than granulites in the northern part. The converse age assignment on the accompanying map is based on Rb-Sr geochronological data (Tingey 1982a,b); the complex metamorphic history of the southern Prince Charles Mountains is illustrated in Figure 9 which shows how successive metamorphic events have overprinted one another. The structural history is undoubtedly just as complicated, but it has not been adequately investigated.

Fig.8. Fuchsite-bearing Archaean quartzite from the southern Prince Charles Mountains, East Antarctica. The unit from which this sample came is widespread and prominent in this region; similar rocks appear to be common in Archaean metasedimentary terranes across the world.

Proterozoic units

It is not possible to arrange Proterozoic units in strict chronological order in the map legend, as some of them include rocks that range in age across much of Proterozoic time. For example, unit **Ps** (Proterozoic metasediments) encompasses rocks in western Dronning Maud Land (longitude 2°W; Wolmarans & Kent, 1982; Ferreira, 1986) that are at least 1700 Ma old, as well as others in the southern Prince Charles Mountains no older than about 1000 Ma (Tingey, 1982a,b), and metamorphosed turbidites in the Transantarctic Mountains of probable Late Proterozoic age. Thick sheets of dolerite and gabbro (**Pi**) that range in age up to about 1700 Ma (Wolmarans & Kent, 1982) intrude the Dronning Maud Land metasediments, whereas the Prince Charles Mountains examples are intersected, not by Proterozoic mafic dykes — like those seen on adjacent mountains — but by Cambrian granites (**Pzg**). Note that the map legend for this unit should be labelled **Pi** instead of **Pi(A)**, a symbol that is intended to indicate (and is confined on the map to) one of Antarctica's more interesting geological features, the Wolthat Massif anorthosite complex (12°E; Ravich & Soloviev, 1969). This spectacularly exposed rock mass stands up to 1500 m above the nearby ice cap, and is strongly layered, extensively cataclasised, and intersected by a few dykes of gabbro/dolerite and lamprophyre. Its central and marginal facies are described by Ravich & Soloviev (1969),

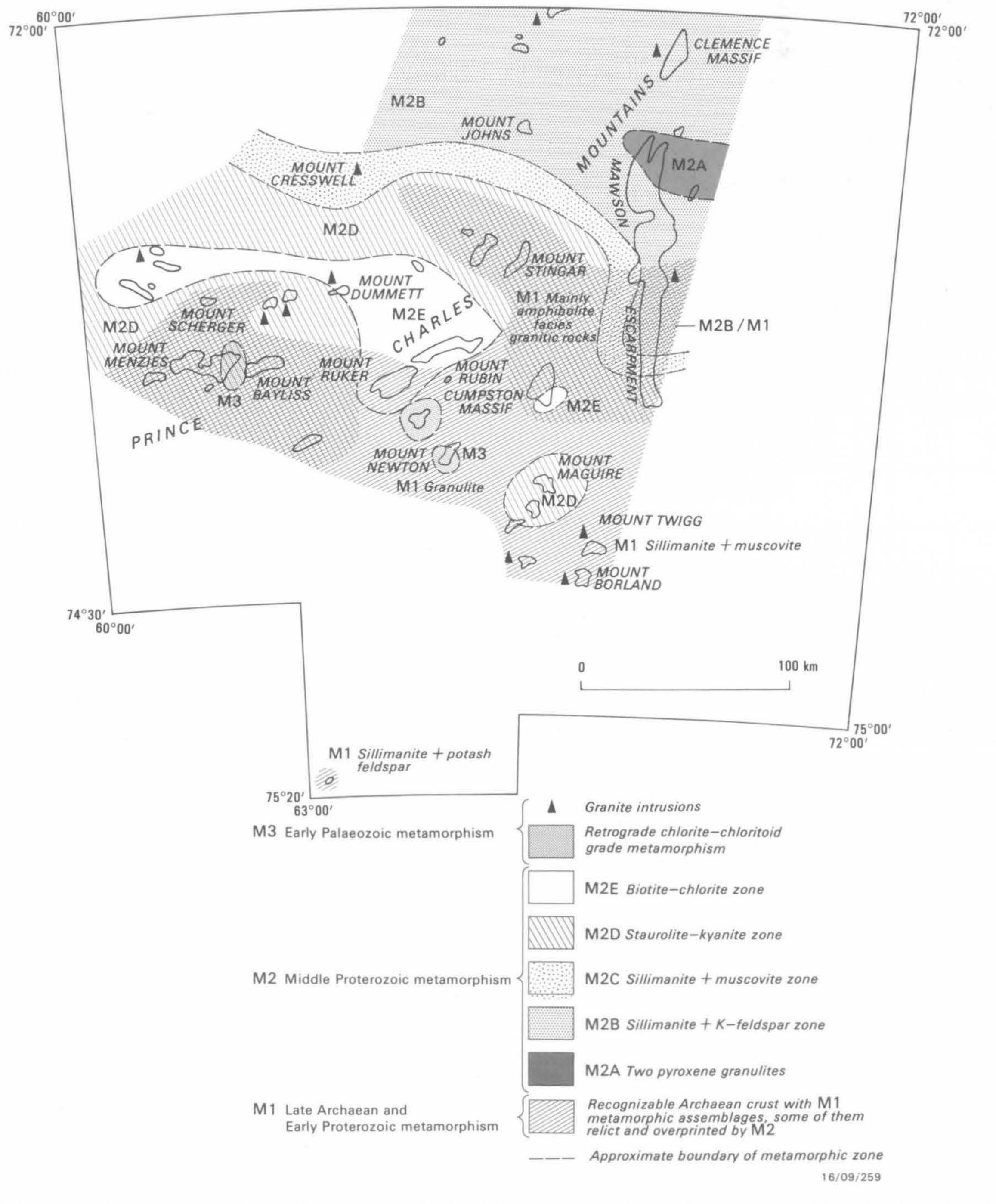

Fig.9. Metamorphic geology of the southern Prince Charles Mountains, East Antarctica. The map illustrates how successive metamorphic events have overprinted one another.

but further investigation is clearly overdue. Very little is known about the mafic rock mass on the northern fringe of the Sor Rondane (25°E); the metamorphosed gabbro in the Prince Charles Mountains is intersected by metamorphosed mafic dykes as are metabasalt and granite on a nearby mountain. Substantial intrusions of gabbro to monzogabbro crop out in the Bunger Hills (102°E), and some appear to have gradational contacts with charnockite intrusions.

The asterisk symbol (*) signifies the general location of mafic dykes of Proterozoic age (Fig.10). These dykes are important stratigraphic markers because they intersect — and locally form dyke swarms in — older metamorphics, but are only found as metamorphosed relics in marginal areas of younger metamorphics. The presence or absence of such dykes has thus proved useful in discriminating between older and younger metamorphic rocks in Antarctica and in many other parts of the world (James & Tingey, 1983). In the Prince Charles Mountains, for example, metamorphosed but undeformed mafic dykes of tholeiitic composition intersect map unit **Aa** in the south (see Fig.7), but have not been mapped in the younger, higher-grade metamorphics (**Pm**) to the north. Such field relationships are well displayed in both Enderby Land (Sheraton & Black, 1981) and the Vestfold Hills (Collerson & Sheraton, 1986), where isotopic dating supports the inferences outlined above. Similar relationships exist in the Bunger Hills, although isotopic ages indicate that the metamorphic country rocks are only slightly older than the dykes.

Proterozoic granulite or upper amphibolite facies metamorphics (**Pm**) constitute a large part of the East Antarctic metamorphic basement shield. Included in this unit are paragneisses, orthogneisses, and rocks of uncertain origin; intrusions of the distinctive hypersthene-bearing granitoid ('charnockite') are widespread and form large batholiths in both the Fimbulheimen (0 to 10°E) and Mac.Robertson Land (60 to 70°E). Most rocks in this unit appear to result from a widespread tectonothermal event at about 1000 Ma, although isotopic data indicate that there were (for example, in the Bunger Hills and Windmill Islands) earlier Proterozoic events. The Rayner Complex in Enderby Land (see Fig.4) is perhaps the best-studied example of these rocks; its formation involved the generation of new crust from the mantle as well as limited reworking of older (Archaean to middle Proterozoic) rocks, including those of the adjacent Archaean Napier Complex (Black & others, 1987). A similar story is emerging in Princess Elizabeth Land (about 78°E), where reworked Archaean rocks form only a small portion of the Proterozoic high-grade gneisses (Sheraton & Collerson, 1983; Harley, 1987b).

In West Antarctica, the plate tectonic history of the microplates that now make up the West Antarctica–Antarctic Peninsula–Scotia Arc region (see Barker & others, 1991) has to take account of the small and isolated outcrops of unit **Pm** at the Haag Nunataks. In East Antarctica, **Pm** metamorphics in the Shackleton Range (20–30°W) were investigated by German geologists in the mid 1980's following reconnaissance studies by geologists of the British Antarctic Survey (BAS) (Clarkson, 1972, 1982; Marsh, 1983, 1984), the Trans-Antarctic Expedition (TAE) (Stephenson, 1966), and the Soviet Antarctic Expedition (SAE). There is apparently no evidence for a major 1000 Ma metamorphic event in the Shackleton Range (Pankhurst & others, 1983), but German geologists have confirmed that the metamorphic basement at Heimefrontfjella (10°W) is about 1000 Ma old (Weber & others, 1987). The metamorphic rocks exposed near Kirwanveggen (near longitude 0°) are being investigated by South African geologists (Wolmarans & Kent, 1982), and in 1987 Norwegian expeditioners revisited the Fimbulheimen, which had not been examined for many years (Ohta & Torudbakken, 1989); in both areas high-grade metamorphism is thought to have occurred about 1000 Ma, followed by intrusion of granitoids at about 500 Ma. In central and eastern Dronning Maud Land, Japanese geologists are progressively re-mapping outcrops of high-grade metamorphic rocks; their results are reported in the Proceedings of the NIPR

Fig.10. A swarm of mafic dykes intruding Archaean orthogneisses in the Vestfold Hills, East Antarctica; a classic locality for such intrusions. Mafic dykes have proved to be useful stratigraphic markers in Precambrian basement terranes.

symposia on Antarctic Geosciences, published by the National Institute of Polar Research in Tokyo. No clear geochronological picture has emerged from these studies.

Outcrops of **Ꝑm** in the northern Prince Charles Mountains in Mac.Robertson Land are now (1991) being studied by Australian geologists following reconnaissance studies in the early 1970's (Tingey, 1982 a,b); SAE geologists have also been recently active in this area. In Queen Mary Land and western Wilkes Land, Australian geologists mapped **Ꝑm** in the Bunger Hills/Denman Glacier region (longitude 100°E) in 1986. The Windmill Islands (110°E) area has recently been studied from an igneous petrology perspective, and a modern structural appraisal is needed to compliment this work. Farther east, Stuwe & Oliver (1989) assessed the structural evolution of the Commonwealth Bay (143°E) region, which was first explored by geologists of Mawson's 1911–1914 Australasian Antarctic Expedition (AAE) (Stillwell, 1918); however, other isolated exposures of high-grade metamorphic rock in Wilkes Land, Terre Adelie, George V Land, and Oates Land have not been examined for many years.

In the Transantarctic Mountains, metamorphic rocks crop out in two areas of Victoria Land (latitudes 70–73°S; 78°S) and in the catchment of the Nimrod Glacier (latitude 83.5°S). Geochronological studies of the Victoria Land metamorphics have yielded a confused picture with little or no evidence for a major metamorphic event at 1000 Ma. Widespread isotopic resetting at about 500–550 Ma probably reflects the intrusion of granites of the early Palaeozoic Granite Harbour Intrusive Complex (Gunn & Warren, 1962). The Nimrod Glacier metamorphics (the Nimrod Group) need to be checked in view of a suggestion that they may be merely a contact-metamorphosed variant of **Ꝑs** (Stump & others, 1987), although a dissenting opinion has been published by Borg & others (1990).

Unit **Ꝑg** comprises igneous intrusive bodies of broadly granitic composition and Proterozoic age, and includes numerous plutons of charnockite, the dark-brown hypersthene-bearing granitoid that is characteristic of granulite facies metamorphic terranes (Sheraton, 1982). The petrogenesis of charnockites at both Mawson (longitude 63°E) and in the Windmill Islands (longitude 110°E) is being investigated and other outcrops have been sampled. The charnockites intrude, and are therefore younger than, the Proterozoic high-grade metamorphics, but are generally regarded as syntectonic. In the Bunger Hills, intrusions which range in composition from gabbro to granite were emplaced during the waning stages of metamorphism between about 1170 and 1150 Ma (L.P.Black, personal communication, 1990).

Proterozoic volcanic rocks (**Ꝑv**) are only exposed in western Dronning Maud Land (near longitude 0°) and at Fisher Massif in the Prince Charles Mountains (longitude 68°E). The former are of basaltic to basaltic/andesitic composition (Watters & others, 1987) and the latter basaltic (Tingey, 1972; Federov & others, 1987).

Proterozoic low-grade metasediments (**Ꝑs**) are widespread in East Antarctica and the Transantarctic Mountains. Those in the Shackleton Range have yielded no evidence of a metamorphism at 1000 Ma (Tingey, 1991c), whereas metasediments in western Dronning Maud Land are intruded by 1700 Ma mafic sills (Wolmarans & Kent, 1982), and are considered on that basis to be about 1800 Ma old. Little is known about the Sor Rondane metasediments, but sandstones, siltstones, and shales in the southern Prince Charles Mountains are older than the 500 Ma granites by which they are intruded, and younger than 800 Ma, the age of a granite clast (Halpern & Grikurov, 1975). A boulder bed in this sequence deserves reexamination to determine if it is a tillite produced by the Late Proterozoic glaciation for which there is evidence from all the Gondwana continents except Antarctica.

Well-bedded and tightly folded turbidites of low metamorphic grade, and presumed late Proterozoic age, crop out along the Transantarctic Mountains from the Pensacola Mountains to northern Victoria Land and the coast of Oates Land and George V Land. They were originally deposited in deep water off the proto-Pacific margin of Gondwana; their age is imprecisely defined by reconnaissance K-Ar and Rb-Sr data, which indicate a peak of tectonothermal activity at about 650 Ma, i.e. the time of the Beardmore Orogeny (Laird, 1991). The Pensacola Mountains' rocks are thought to have been deposited at about 1100 Ma, but it is not clear when those in the Central Transantarctic Mountains were laid down. In northern Victoria Land the Priestley Formation is mapped as **Ꝑs**, whereas other fairly similar low to medium-grade metasediments in the Wilson Terrane are included in unit **Ꝑm**. Turbidites of the Robertson Bay Group were formerly regarded as Precambrian, but early Palaeozoic fossils have been found (Burrett & Findlay, 1984; Wright & others, 1984) in olistoliths within this unit. On the Oates Land–George V Land coast there are outcrops (**Ꝑs**) of the poorly known Berg Group (Ravich & others, 1968), which was formerly correlated with the Robertson Bay Group primarily on the basis of lithological similarity. The fossil discoveries in the Robertson Bay Group highlight the pitfalls of such correlations, and raises doubts about the age of at least some of the rocks assigned to unit **Ꝑs**. A search of these allegedly Precambrian sequences for fossils may well yield interesting results.

Phanerozoic

Palaeozoic units

The late Proterozoic sedimentary rocks (**Ꝑs**) of the Transantarctic Mountains were folded and metamorphosed by the Beardmore Orogeny at about 650 Ma (Laird, 1991) before deposition of sedimentary and volcanic rocks of early Palaeozoic age (**Pze**). In the Shackleton Range and western Dronning Maud Land there is little convincing evidence to support an early Palaeozoic age for the rocks mapped as **Pze**, but in the Ellsworth, Pensacola, and Transantarctic Mountains there are enough fossiliferous horizons to provide a basis for biostratigraphic dating (Laird, 1981; 1991). Archaeocyatha (first discovered by members of the 1907–1909 British Antarctic Expedition led by Ernest Shackleton) and trilobites (Fig.11) have proved the most useful fossils (Cooper & Shergold, 1991). Archaeocyatha-bearing limestone was dredged from the floor of the Weddell Sea in 1904 (see Cooper & Shergold, 1991; Gordon, 1920) and more recently discovered (Wrona, 1989) as clasts in glacial sedimentary rocks on King George Island (longitude 58°W) in the South Shetland Islands north-west of the Antarctic Peninsula; this may be evidence that early Palaeozoic limestone may have had a much wider distribution than is indicated by bedrock exposures, a conclusion that is supported by the widespread occurrence of erratics of fossiliferous early Palaeozoic rocks in the Pensacola Mountains region and on bedrock exposures along the eastern margin of the Filchner Ice shelf (see Cooper & Shergold, 1991).

The early Palaeozoic sedimentary rocks in the Ellsworth (Webers & Sporli, 1983; Webers & others, in press), Pensacola (Schmidt & Ford, 1969), and Transantarctic Mountains (Laird, 1991) are mainly shallow-marine quartzites, limestones, and mudstones, whereas contact-metamorphosed felsic volcanic and volcaniclastic rocks are exposed in the Horlick–Queen Maud Mountains region (latitude 85°S; longitude 130–160°W). Folded and metamorphosed clastic rocks crop out between the Ellsworth and Thiel Mountains (Webers & others, 1983) and in the Whitmore Mountains (Webers & others, 1982). Turbidite-like strata in Marie Byrd Land between longitudes 135 and 155°W appear to be unfossiliferous (Bradshaw & others, 1983), but are designated **Pze** on account of their similarity to the predominant lithological unit in the

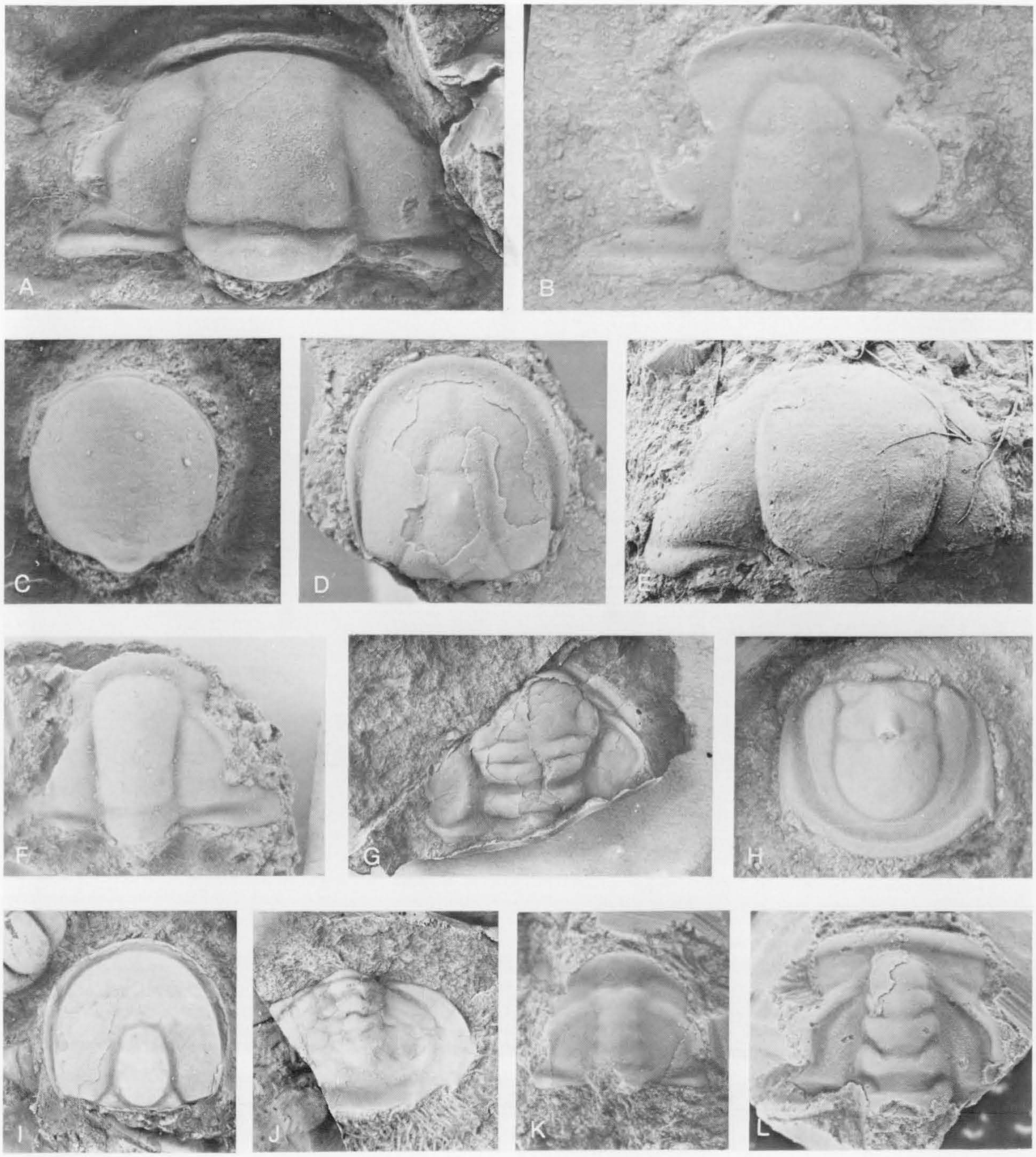

Fig.11. A selection of Antarctic Cambrian trilobites (see Cooper & Shergold, 1991, for discussion). From northern Victoria Land: A. *Prochuangia* aff.*granulosa* Lu, cranidium, x8, ; B.*Proceratopyge* cf. *lata* Whitehouse, cranidium, x12; C.*Leiopyge armata* (Linarsson), cranidium (tilted to rear), x15; D.*Pseudagnostus (Pseudagnostus)* ex gr.*communis* (Hall and Whitfield), cranidium, x10; E.*Catillicephalus* sp., cranidium, x25; F.*Fuchouia* cf.*labda*, Opik, cranidium, x10; G. *Centropleura* sp., cranidium, x10; H.*Homagnostus* cf.*ultraobesus* Lermontova, pygidium, x16; I.*Hypagnostus clipeus*, Opik, cranidium, x3.5; J.*Centropleura* sp., pygidium, x10: Nimrod Glacier area, K. Yunnanocephalus sp., cranidium, x3.5; L.*Wutingaspis* sp., cranidium, x3.5. (Photograph provided by Dr. R. Cooper, New Zealand Geological Survey.)

Robertson Bay terrane in northern Victoria Land, from which early Palaeozoic fossils have been recovered (Burrett & Findlay, 1984; Wright & others, 1984). The early Palaeozoic rocks in both areas are intruded and contact-metamorphosed by Devonian granites (**Pzg$_D$**); and in Marie Byrd Land there are also plutons of Cretaceous granite (**Mg**)(Wade & others, 1977a,b; Adams, 1987; Weaver & others, 1991). Attention is drawn to contact and greenschist facies regional metamorphism of **Pze** rocks by underlining of the letter symbol on the map.

Red sandstones and shales exposed (Fig.12) at longitude 101°E in the upper reaches of the Denman Glacier near the boundary between Queen Mary Land and Wilkes Land in East Antarctica are considered, on doubtful evidence, to be of early Palaeozoic age (Voronov & others, 1959; Ravich & others, 1968). Clasts of similar rocks in coastal moraines as far east as longitude 142°E (Mawson, 1940) may indicate that the unit is very widespread beneath the Wilkes Land ice cap. In western Dronning Maud Land (longitude 5°W), unfossiliferous deformed quartzite and conglomerate (Aucamp & others, 1972; Wolmarans & Kent, 1982) are mapped as **Pze**; they unconformably overlie Precambrian gneisses (**Pm**) and are in turn overlain by terrestrial sediments of probable Permian age (map unit **B**). Unit **Pze** also includes deformed, but only slightly metamorphosed, strata of the Turnpike Bluff and Blaiklock Glacier Groups in the Shackleton Range (longitude 30°W), although the former may be of Precambrian age (Tessensohn–person. communic., 1990). No diagnostic fossils have been collected *in situ*, but brachiopod and trilobite-bearing erratics in the northwest of the range are inferred to provide age control (Laird, 1991; Cooper & Shergold, 1991).

In the Transantarctic Mountains the Ross Orogeny resulted in uplift, folding, and metamorphism of early Palaeozoic strata and older rocks. It was accompanied and followed by widespread intrusion of granitoid plutons, including the Granite Harbour Intrusive Complex (Borg, 1983; Borg & DePaolo, 1987; Borg & others, 1986, 1987; Gunn & Warren, 1962; Laird, 1991; Vetter & others, 1983, 1984) (map unit **Pzg**), for which isotopic dates cluster in the 450–520 Ma range (see Adams & others, 1982; Black & Sheraton, 1990). However, the early to middle Palaeozoic sequence in the Ellsworth Mountains has yielded no evidence for interrupted sedimentation, and no sign that the Ross Orogeny had any effect. If, as Schopf (1969) suggested, the Ellsworth Mountains are an allochthonous block that was originally aligned with the Transantarctic Mountains, the above geological characteristics demand that the Ellsworths moved away from the Transantarctics before about 500 Ma.

In East Antarctica, at about 500 Ma, syenitic to granitic magmas were intruded in the Denman Glacier region (101°E); granites, pegmatite veins, and aplites were emplaced in the Prince Charles Mountains (Fig.13; Tingey, 1982a,b), on the Prydz Bay coast (Sheraton & Collerson, 1983), in Enderby Land (Black & others, 1987), Dronning Maud Land, and the Shackleton Range (see Tingey, 1991c); and dykes of generally alkaline composition (for example, lamproites in Enderby Land and the southern Prince Charles Mountains–Sheraton & England, 1980) were intruded (general location indicated on the map with a diamond-shaped symbol). In addition, there was widespread resetting of Rb-Sr isotopic systems in minerals (Tingey, 1982a; James & Tingey, 1983). The apparent absence of these phenomena from the Heimefrontfjella and the **Ps/Pi/Pv** outcrops north of the Kirwanveggen in western Dronning Maud Land has prompted speculation that a major geological boundary — possibly a microplate boundary or suture – passes to the west of the Fimbulheimen and north of Kirwanveggen and is now marked by a major outlet glacier (Barton & others, in press).

The Ross Orogeny and emplacement of the Granite Harbour Intrusive Complex occurred on what was probably the Pacific margin of Gondwana, whereas the igneous activity in East

Fig.12. Mount Sandow, an isolated peak (nunatak) in the upper reaches of the Denman Glacier in Queen Mary Land. Note the heavily crevassed ice and deep windscour adjacent to the outcrop. Mount Sandow is composed of a basal greenstone overlain by red sandstones and shales believed to be of Cambrian age (Ravich & others, 1968).

Antarctica may have been intracratonic. Although it is difficult to identify links between the two, both may be related to the Pan African event — a term that refers to Gondwana-wide early Palaeozoic crustal heating and igneous activity. This may have been caused by preliminary fracturing of Gondwana in anticipation of break-up several hundred million years later.

Granitoid plutonism later in the Palaeozoic is indicated by Devonian granites (**Pzg_D**) in northern Victoria Land and Marie Byrd Land as far east as longitude 140°W. In northern Victoria Land, at least, these granites (Wyborn, 1981; Borg & others, 1986) appear to be exclusively 'I type' — that is, derived from igneous precursors — and confined to the Robertson Bay and Bowers terranes. Volcanic rocks, regarded as the extrusive equivalents of the Devonian granites (**Pzg_D**) in northern Victoria Land and Marie Byrd Land, are mapped as **Pzv** (Laird & Bradshaw, 1983; Findlay & Jordan, 1984). In both areas, they are accompanied by sedimentary rocks with Devonian plant remains (Grindley & Mildenhall, 1981; Laird, 1991; Truswell, 1991).

Granodioritic orthogneisses and migmatites of Carboniferous age (**Pzg_C**) (Storey & others, 1991) crop out on Thurston Island (100°W) and similar rocks are reported from the eastern Antarctic Peninsula by Milne & Millar (1989). The Trinity Peninsula Group (**Pz**) (Hyden & Tanner, 1981; Barker & others, 1991) is confined to the Antarctic Peninsula, and consists largely of multiply deformed, turbidite facies, marine arkosic sandstone and mudstone of low metamorphic grade. Its age is poorly defined, but probably ranges from late middle Palaeozoic (Carboniferous) to early Mesozoic (Triassic). It is exposed in the centre of the Peninsula and is closely intermingled with various Mesozoic rock units, as depicted by the stripes on the map.

Palaeozoic to Mesozoic units

In the Devonian to Triassic time interval, non-marine sedimentation, in what is now East Antarctica and the Ellsworth and Transantarctic Mountains, resulted in rocks that are collectively assigned to map unit **B** (Barrett, 1991). As Antarctica (and much of Gondwana) was largely glaciated in the Carboniferous period (360–286 Ma), deposition was not continuous, either geographically or temporally.

The Beacon Supergroup, the formal name of these rocks in the Transantarctic Mountains, comprises a basal succession (Taylor Group) of Devonian non-marine sandstones, quartzites, and siltstones, disconformably overlain by late Carboniferous to early Permian glacigene sediments which are in turn overlain by the classic, Permian to Triassic, 'Gondwana' sequence (Victoria Group) of terrestrial sandstones, siltstones, shales, and coal measures. The rocks are sparsely fossiliferous, and in any case fossil preservation has been adversely affected by contact metamorphism by early Mesozoic dolerite intrusions (see Fig. 17). However, fragments, as well as more complete remains, of fossil fish have been found in the Devonian rocks (Young, 1991), and a Lower Triassic formation has yielded many fossils of the tetrapod *Lystrosaurus*, also known from South Africa and other former Gondwana landmasses (Colbert, 1982; 1991), as well as remains of other vertebrates, possibly including dinosaurs (McKelvey, *person. communic.* 1991). The discovery of fossils of the Permian plant *Glossopteris* in Beacon Supergroup rocks (then called the Beacon Sandstone) by members of R.F.Scott's 1910–1913 British Antarctic (Terra Nova) Expedition (Seward, 1914; Tingey, 1983; Truswell, 1989; 1991) was important in establishing geological links between Antarctica and other Gondwana fragments. Links between peninsular India and the southern continents were postulated late in the 19th century (Suess, 1904–09), when it was realised that similar rocks and fossils of about the same age occurred in these now-separated land masses. They were initially explained on the basis of ancient land bridges that had since sunk into the ocean basins, but modern explanations invoke continental drift brought about by plate tectonic processes.

The Beacon Supergroup formations contain a significant component of epiclastic felsic volcanic debris believed to have been derived from what is now Marie Byrd Land, although no related volcanic rocks are exposed in this source region. However, an early to middle Mesozoic change from felsic to mafic volcanism is recorded in the central Transantarctic Mountains (about latitude 85°S, longitude 180°), by the Prebble Formation (Barrett & Elliot, 1972). The Beacon Supergroup is typically not deformed, but correlatives in the Weddell Sea region (the Ellsworth and Pensacola Mountains, for example) were folded and tilted no later than the early–middle Jurassic in the Weddell Orogeny (Ford, 1972). Folding of much the same age in South Africa, South America, and the Falkland/Malvinas Islands is attributed to the Gondwanide Orogeny (DuToit, 1937).

Also included in map unit **B** are Triassic strata at Horn Bluff in George V Land (longitude 150°E; Ravich & others, 1968), and Permian to Triassic sandstones, siltstones, shales and coal measures at Beaver Lake in the Prince Charles Mountains (Fig.14; longitude 69°E). Fossil plant remains at Horn Bluff are poorly preserved because of contact metamorphism by a thick dolerite sill which caps the exposure, but preservation at Beaver Lake, where there are no early Mesozoic dolerite intrusions, is much better. Continental strata at Kirwanveggen and Vestfjella in western Dronning Maud Land (longitude 5 to 15°W), and in Coats Land (30°W) are also mapped as unit **B**.

Igneous intrusive rocks

The diamond symbol in the map legend indicates the general location of dykes of alkaline (generally potassium-rich) character (Fig.15). These rocks span wide compositional and age ranges, and their tectonic significance is poorly understood. Some are of Ordovician age and may have been intruded as a consequence of the early Palaeozoic Ross Orogeny, or as is the case in the Prince Charles Mountains and Enderby Land, the Pan African event. Additionally, in the Prince Charles Mountains the Permo-Triassic strata (unit **B**) are intruded by Cretaceous alnoite sills and Cainozoic alkaline ultramafic breccias. As these intrusives have broad affinities to the kimberlitic suite with which diamond deposits are associated elsewhere in the world, they have some relevance to considerations of Antarctica's resource potential.

The general distribution of relatively small, early Mesozoic (Jurassic, about 180 Ma) tholeiitic dolerite intrusives is indicated by black dots which signify that sills or dykes are present in nearby bedrock outcrops. Larger bodies of tholeiite, notably the huge Dufek intrusion (Ford & Himmelberg, 1991) as well some outcrops in the Victoria Land sector of the Transantarctic Mountains, are signified by red diagonal striping and letter symbol **Ji**. (Note that the map legend mistakenly implies that the red stripes and letter symbol **Ji** are confined to the Dufek intrusion). A small fraction of the Dufek intrusion is spectacularly exposed in the Pensacola Mountains (Fig.16) (longitude 50–60°W; latitude 80–85°S), and geophysical surveys have revealed its subglacial extent, as shown on the map. The sills and (the less common) dykes occur along the Transantarctic Mountains, where they intrude Beacon Supergroup strata (Fig.17) and older formations. The sills are of quite uniform composition and have strong affinities with the Tasmanian dolerites in terms of major and minor element

Fig.13. Cambrian granite intruding layered gneisses at Mount Borland, southern Prince Charles Mountains, East Antarctica. Granites were emplaced in many parts of Antarctica at about this time (i.e. about 500 Ma).

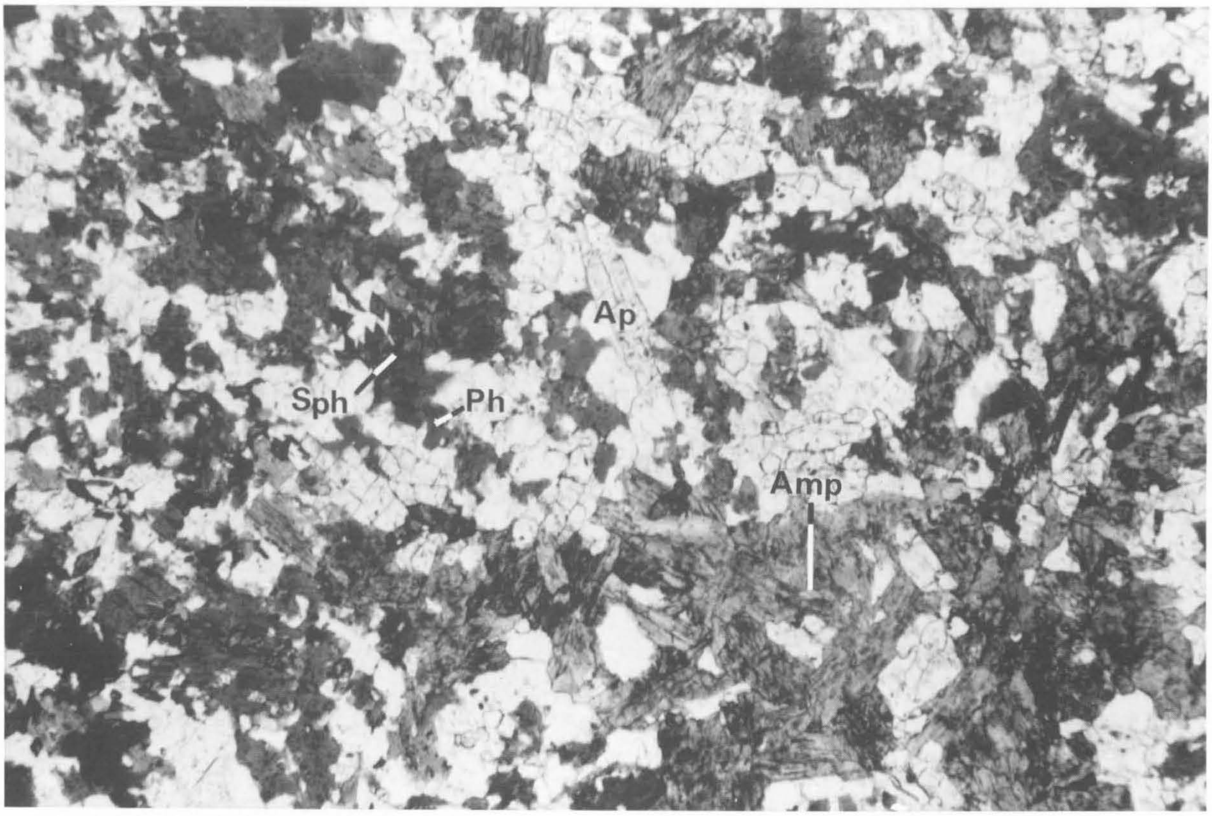

Fig.15. Photomicrograph of an alkali melasyenite dyke rock from Mount Priestley, in the Archaean Napier Complex, Enderby Land, East Antarctica. The minerals K-arfvedsonite (Amp), phlogopite (Ph), apatite (Ap), sphene (Sph), and microcline are visible in this 4 mm-wide field of view.

contents. In particular, both the Transantarctic Mountains' and the Tasmanian dolerites have anomalously high initial $^{86}Sr/^{87}Sr$ ratios more typical of crustal than of mantle-derived rocks (Compston & others, 1968; Hergt & others, 1989; Tingey, 1991a). The two main hypotheses advanced to explain this isotopic signature (see Hergt & others, 1989, for discussion) are (1) contamination by crustal rocks through which the magmas passed, and (2) derivation of the magmas from a mantle source of unusual (or 'anomalous') composition. This anomalous composition is in turn explained as the result of the assimilation of crustal material via subduction-like processes many hundreds of millions of years before the sills were emplaced. Hergt & others (1989) favour the 'anomalous mantle source' explanation.

Jurassic tholeiite sills and dykes in Coats Land (longitude 20°W) and western Dronning Maud Land (0–20°W) do not have the geochemical attributes of the Transantarctic Mountains' intrusives. They do, however, have geochemical affinities with the Karroo dolerites in southern Africa, which was adjacent to this part of Antarctica in the Gondwana supercontinent. Jurassic tholeiite intrusives (and their volcanic counterparts) in Antarctica can thus be divided on the basis of geochemistry into the Weddell Sea and Transantarctic Mountains provinces.

The Dufek intrusion is much the largest Jurassic mafic intrusive in Antarctica. It is strongly layered as a consequence of crystal fractionation and multiple intrusion (Ford & Himmelberg, 1991) and there has been speculation about its prospectiveness for platinum group metals (see De Wit, 1985). In this regard, the Dufek intrusion has been compared to the Bushveldt and other large layered mafic intrusions, and it has been suggested that any Dufek equivalent of the Bushveldt's platinum-rich Merensky reef would be at a much lower level than the sections exposed in the Pensacola Mountains. This implies that mineral exploration would require deep drilling and any mining would be deep underground. Both activities would be difficult and very expensive, given the remote location and vigorous climatic regime of the Pensacola Mountains, but it is conceivable that they might be attempted for non-economic reasons.

The distribution of the Jurassic tholeiites has a bearing on the geological history of certain parts of Antarctica. For example, Schopf (1969) speculated that the Ellsworth Mountains were moved to their present position from the vicinity of Coats Land. The fact that no Jurassic tholeiite intrusions are known from the Ellsworth Mountains implies that any move from the Coats Land area must have occurred before the Jurassic. Similarly, no Jurassic intrusions are known from the Robertson Bay terrane in northern Victoria Land, although they are abundant in adjacent areas; a possible implication is that the Robertson Bay terrane was moved into its present position after the Jurassic intrusions were emplaced in the terranes that are now adjacent.

The Jurassic phase of tholeiitic intrusive activity was accompanied by widespread volcanism and the resulting rocks (**Mvt**) are found in Coats Land, western Dronning Maud Land, and along the Transantarctic Mountains (Fig.18). Most of these volcanics are thought to be about 180 Ma old (see Tingey, 1991b), but those at Vestfjella (longitude 15°W) may be slightly older, about 200 Ma (Furnes & Mitchell, 1978). The Vestfjella volcanics are altered, and are intersected by unaltered basalt dykes which have yielded an average K-Ar age of 169 ± 3 Ma (Furnes & Mitchell, 1978). The Mesozoic tholeiitic volcanics share the geochemical characteristics of their intrusive counterparts, are generally flat-lying, and have thin

Fig.14. Coal-bearing strata of the Permo-Triassic Amery Group at Beaver Lake, northern Prince Charles Mountains, East Antarctica.

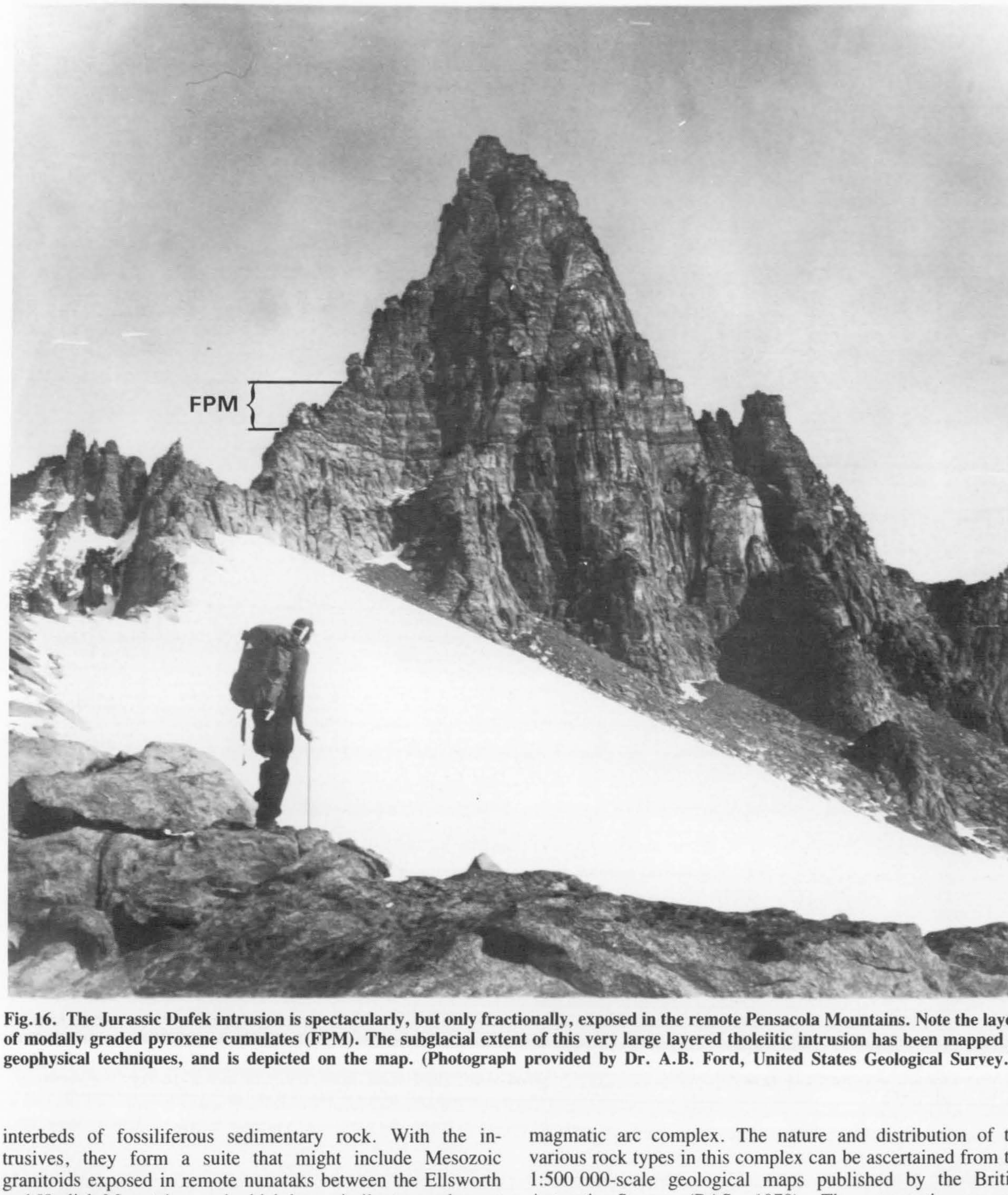

Fig.16. The Jurassic Dufek intrusion is spectacularly, but only fractionally, exposed in the remote Pensacola Mountains. Note the layers of modally graded pyroxene cumulates (FPM). The subglacial extent of this very large layered tholeiitic intrusion has been mapped by geophysical techniques, and is depicted on the map. (Photograph provided by Dr. A.B. Ford, United States Geological Survey.)

interbeds of fossiliferous sedimentary rock. With the intrusives, they form a suite that might include Mesozoic granitoids exposed in remote nunataks between the Ellsworth and Horlick Mountains, and which have similar trace-element geochemical characteristics (Pankhurst & others, 1991).

It is unclear what caused early Jurassic tholeiitic magmatism on such a huge scale in Antarctica. A number of authors have related it to the break-up of Gondwana, but this process took several tens of millions of years. In any case, most of the intrusions are quite remote from the Antarctic margins from whence the Gondwana fragments were rifted.

Mesozoic units

Almost all of the map's Mesozoic units except the Jurassic tholeiitic volcanics (**Mvt**) noted above are confined to West Antarctica, most outcrops being in the Antarctic Peninsula. Units **Mm**, **Mg**, **Mv**, and **Ms** are closely intermingled in the Antarctic Peninsula and comprise what Thomson & others (1983) describe as the remains of a Mesozoic/Cainozoic magmatic arc complex. The nature and distribution of the various rock types in this complex can be ascertained from the 1:500 000-scale geological maps published by the British Antarctic Survey (BAS, 1979). The magmatic arc was produced on Antarctica's proto-Pacific margin by subduction of the Pacific plate beneath the Antarctic plate. The processes involved are simple in concept but complicated in detail, as discussed by Thomson & others (1983) and Barker & others (1991).

Metamorphic rocks (**Mm**) in the Antarctic Peninsula area were formerly regarded as 'basement' of probable Precambrian age on which the other Mesozoic and Cainozoic units were deposited. However, geochronological investigations have not yielded any Precambrian ages, the oldest reported ages being between 426 ± 12 Ma and 410 ± 15 Ma for the emplacement of the granite precursors of granite gneiss (**Pzg$_C$**), for which ages of 331 ± 8 Ma, 311 ± 8 Ma, and 297 ± 3 Ma record an amphibolite facies metamorphism (Milne & Millar, 1989). Those authors infer that no significantly older crustal material

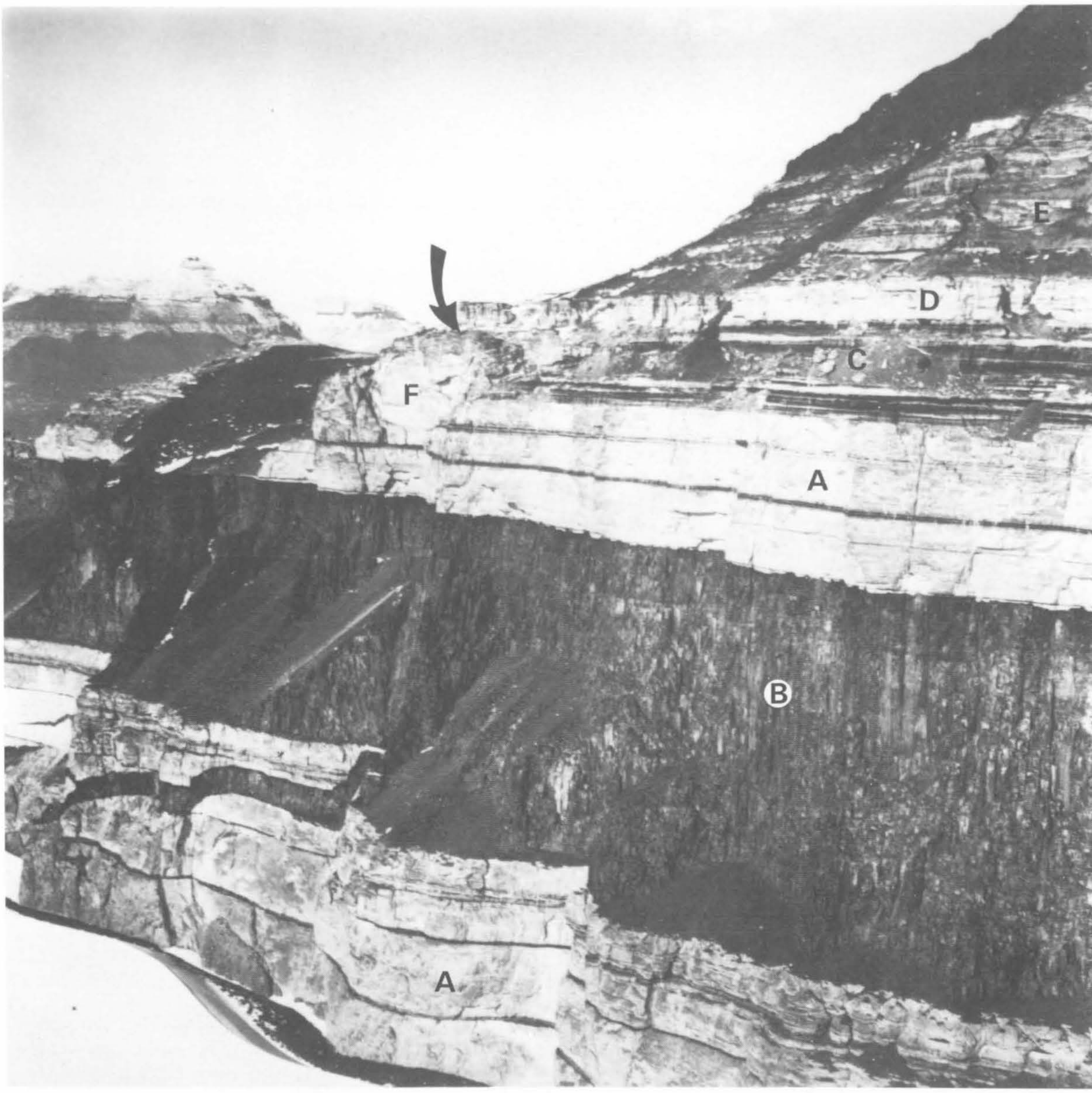

Fig.17. 150 m-thick sill of Jurassic Ferrar Dolerite (B) intruding strata of the Beacon Supergroup at Finger Mountain, south Victoria Land. A. Beacon Heights Orthoquartzite (Devonian); C. Aztec Siltstone (Devonian); D. Basal Weller Coal Measures (Permian); E. Weller Coal Measures; F. fluvial facies of the Metschel Tillite (? Late Carboniferous) exposed in a channel cut into the Beacon Heights Orthoquartzite and deposited during late Palaeozoic glaciation of Gondwana. (Photograph provided by Dr.B.C. McKelvey, University of New England, NSW.)

was involved in the metamorphism. The metamorphics are mostly mapped as 'age uncertain' on the BAS (1979) maps, but the majority of the isotopic ages quoted in the legends of these maps are Mesozoic. They are therefore mapped as Mesozoic metamorphics on the present map, although the possibility remains that there are enclaves of older metamorphics in addition to the one mapped as **Pzg**$_C$. Barker & others (1991) refer to such enclaves as 'parts of the Gondwanaland craton' and quote Pankhurst's (1983) report of a Rb-Sr whole-rock isochron age of 336 ± 34 Ma (Carboniferous) for granitic sheets in a layered migmatite near the **Pzg**$_C$ enclave.

In the central part of the Peninsula, the most widespread metamorphic rocks are almandine–amphibolite facies pink granite gneiss and biotite gneiss; amphibolites and hornblende gneisses are less common, and schists and garnetiferous gneiss comparatively rare. Mica schist, quartzite, amphibolite, marble, and chert of greenschist to amphibolite-facies grade in the South Shetland and South Orkney Islands are interpreted (Barker & others, 1991) as the remnants of a late Palaeozoic/early Mesozoic subduction complex that was accreted to the Antarctic Peninsula and South America before break-up of the Gondwana supercontinent. The origins of many of the rocks mapped as **Mm** are unclear.

The granitoids of map unit **Mg** range in age from late Triassic to possibly early Cainozoic, and are widely distributed through the Antarctic Peninsula, Marie Byrd Land, and southwest of the Ellsworth Mountains. There are also nepheline syenite intrusives in western Dronning Maud Land (longitude 0°) that have yielded Jurassic K-Ar ages. This unit is essentially an amalgam of three suites: (1) the Dronning Maud Land syenites (about which little is known; see Ravich & Soloviev, 1969), (2) granitoids to the southwest of the Ellsworth Mountains (possibly associated with the widespread early Mesozoic tholeiitic magmatism, see above), and (3) granitoids in the

Fig.18. Flat-lying Kirkpatrick Basalt of Jurassic age, and the extrusive counterpart of the Ferrar Dolerite, in the Mesa Range of northern Victoria Land. A stratigraphic thickness of about 800 m of lavas is exposed in this region. (Photograph provided by Dr D.H. Elliot, Byrd Polar Research Institute, Ohio State University, U.S.A.)

Antarctic Peninsula/Marie Byrd Land area thought to be related to subduction of the Pacific plate (or its predecessors) beneath the Antarctic plate.

The oldest isotopic date obtained from this last suite is 209 ± 3 Ma (i.e. late Triassic), and the youngest granitoids are of Cainozoic age. The granitoids are regarded as the exposed roots of the ancient magmatic arc complex and have been compared with granites in South America's Andean Cordillera, a major mineral province with important deposits of copper, gold, silver and other metals. Comparisons between the Andean Cordillera and the Antarctic Peninsula carry the simplistic implication that the peninsula might be similarly endowed with mineral wealth. A number of mineral occurrences in the Antarctic Peninsula (Rowley & others, 1983; 1991) are associated with granitoids, especially the younger granitoids most of which are exposed at higher erosion levels than the older plutons. It is therefore quite likely that mineralized rocks associated with the older plutons have been eroded away.

Diverse rhyolitic to basaltic volcanics accompanied by tuffs, agglomerates, and volcanogenic sedimentary rocks (map symbol **Mv**) constitute a third element in the Antarctic Peninsula magmatic arc complex. Their middle Jurassic to early Cretaceous (about 170 to 120 Ma) age range partly overlaps with that of the Mesozoic tholeiites (**Mvt**), discussed above. Elliot (1986) appears to have inferred that the former rocks are part of a magmatic arc relative to which the latter occupy a 'back-arc' situation. Some of the mineral occurrences noted above are found at contacts between the volcanic rocks and Mesozoic granitoids.

One of the Mesozoic sedimentary formations represented on the map by symbol **Ms** is the middle or late Jurassic Latady Formation from the southeast end of the Antarctic Peninsula. It consists of slate, siltstone, and mudstone, with subordinate sandstone and coal, and rare conglomerate, and is the product of deposition of debris derived by erosion of the nearby volcanic arc. Along the east coast of the Antarctic Peninsula, **Ms** includes variously metamorphosed breccias, shales, sandstones, conglomerates, and volcanogenic rocks, and Late Cretaceous strata on an island at about 66°S and 59°W. On the west side of the peninsula, **Ms** represents the Fossil Bluff Formation, a tightly folded sequence of late Jurassic to early Cretaceous shallow-marine tuffaceous sedimentary rocks, pyroclastics, andesitic lavas, mudstones, sandstones (some plant-bearing), conglomerates, and local thin coals. It is extensively exposed on the east coast of Alexander Island and contains a mixed fauna of ammonites, belemnites, brachiopods, bivalves, and fish remains.

In the northern Antarctic Peninsula region, **Ms** represents Jurassic/Cretaceous terrestrial sediments with mudstone layers which contain well-preserved plant fossils first discovered by the 1901–1904 Swedish South Polar Expedition (see Truswell, 1991, for details). It also includes late Jurassic to early Cretaceous marine sediments, and poorly consolidated early Cainozoic marine or shallow-water sedimentary rocks on Seymour Island, directly east of James Ross Island. In this general vicinity, there are also late Cretaceous conglomerates with interbedded sandstones, dark sandy mudstones and shales, thin black fossiliferous limestones, and tuffaceous sandstones and vitric tuffs. Fossils include small ammonites, bivalves, and plant remains. In her review of Antarctic fossil plants, Truswell (1991) observed that the Mesozoic latitude of the Antarctic Peninsula was not much different to that of today, and that the peninsula now has a climatic regime that prevents virtually all plant and animal life. If Mesozoic climatic, seasonal and daylight conditions resembled those of today, it follows that the Mesozoic plants now found as fossils must have had special (but as yet unknown) physiological responses to grow in such conditions.

Cainozoic units

Cainozoic sedimentary sequences on Seymour Island have yielded important vertebrate fossils, including penguins and other birds, whales, fishes, and most recently marsupials (see Colbert, 1991), as well as invertebrates and plants. Spectacular claims about intercontinental faunal linkages have been based on these vertebrate fossils (see Woodburne & Zinsmeister, 1984), but whilst there are obvious links with South American faunas, links to Australia, and indeed to the Antarctic mainland, have yet to be demonstrated.

Cainozoic volcanic rocks and active volcanoes (**Czv**) are common in the Antarctic Peninsula, Marie Byrd Land, and in the Transantarctic Mountains adjacent to the Ross Sea, but are represented in East Antarctica only by the isolated 360 m high volcanic cone at Gaussberg (longitude 89°E) — discovered in 1902 by the Imperial German Antarctic Expedition led by von Drygalski. This volcano consists of olivine leucitite (Fig. 19) (Sheraton & Cundari, 1980) thought to have been erupted subglacially about 55 000 years ago (Tingey & others, 1983). Although the tectonic setting of Gaussberg is still poorly understood, it may be significant that rocks of very similar chemical and isotopic composition in Western Australia have proved to be prospective for diamonds.

The Marie Byrd Land volcanic province (LeMasurier & Rex, 1982, 1983, 1991) is a 750 km-long tract of highly alkaline, basaltic and felsic, late Cainozoic volcanic rocks with oceanic island geochemical characteristics notwithstanding a relatively large proportion of felsic rocks (which commonly overlie the basaltic ones). The province is thought to lie on one flank of a major intra-continental rift, and the volcanism to have occurred when West Antarctica was glaciated. Le Masurier & Rex (1982, 1983, 1991) relate the volcanism to the development of the subglacial topography of Marie Byrd Land, but are unable to link it to any particular plate tectonic event, although they believe it was triggered by extensional tectonism.

The volcanic rocks on the western side of the Ross Sea are on the other flank of the rift structure to which the Marie Byrd Land province is thought to be related, and constitute the McMurdo Volcanic Province, extending northwards from Ross Island to the Balleny Islands. They are generally alkaline in composition with the active Mount Erebus on Ross Island (Fig.20) being largely composed of kenyte; felsic volcanics are less abundant than in Marie Byrd Land. The province's rocks are on average younger than those in Marie Byrd Land, although there is a significant age overlap. Marine geophysical surveys (Cooper & Davey, 1987) have revealed a line of submarine volcanic cones along a rift structure between Ross Island and northern Victoria Land. The tectonic setting of the McMurdo Volcanic Province is not clear apart from the possible association with a postulated transcontinental rift (which obviously will not extend to the Balleny Islands). If the volcanism was linked to uplift of the Transantarctic Mountains — itself one of Antarctica's major geological enigmas — it would be expected to extend along the whole range and not terminate at Ross Island. It was probably triggered by interaction between oceanic crust in the Ross Sea and the continental crust of East Antarctica, but this remains to be worked out in detail.

The basaltic **Czv** volcanics in the Transantarctic Mountains at latitude 87°S and longitude 153°W were erupted subglacially and are probably not related to the McMurdo volcanics. They have yielded a K-Ar age of about 20 Ma, which is taken as a minimum age for glaciation of this part of the continent.

The plate tectonic settings of the Cainozoic volcanic rocks in the Antarctic Peninsula region are varied, but broadly related to interaction between oceanic crust of the Pacific plate and continental crust of the peninsula (see Barker & others, 1991, for discussion). This makes the area Antarctica's only active (or convergent) plate margin. The Deception Island volcano (63°S; 61°W) at the west end of the South Shetland Islands

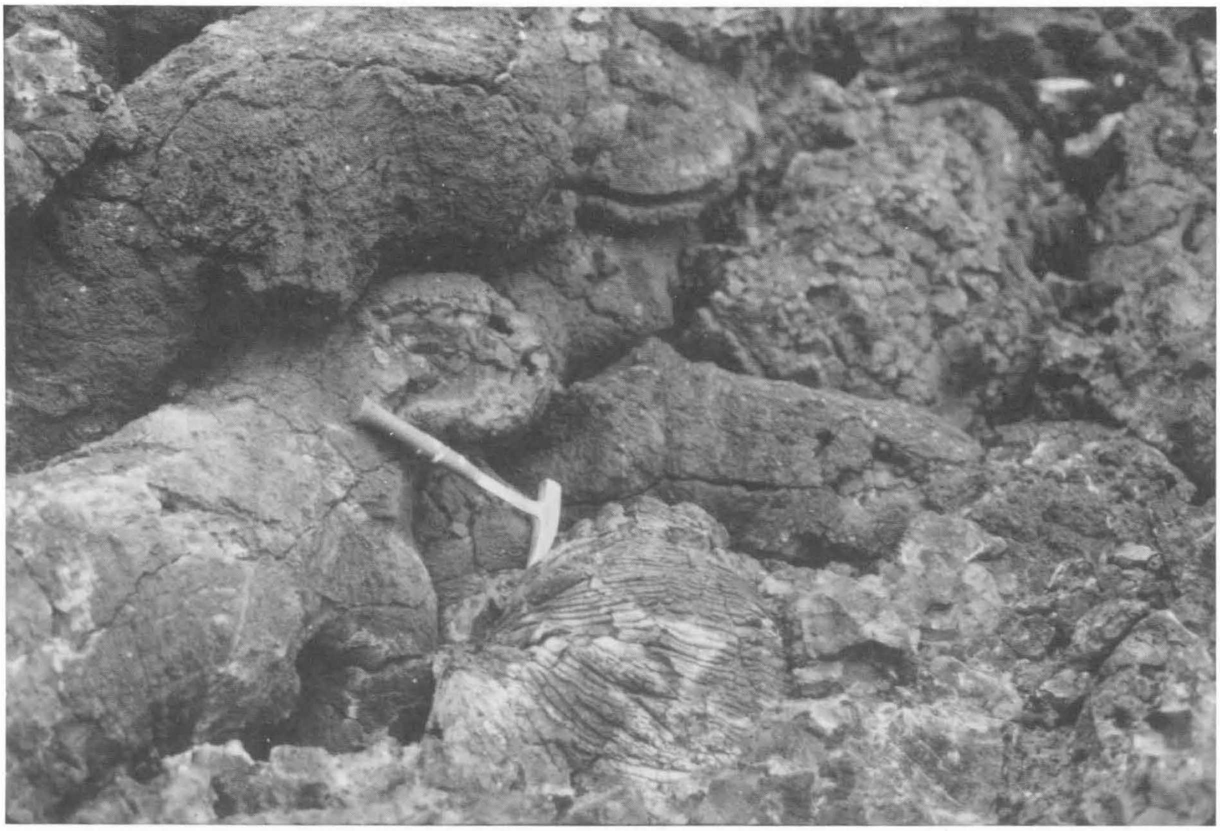

Fig.19. Olivine leucitite pillow-lavas exposed on the flanks of Gaussberg on the edge of the East Antarctic ice cap at about 90°E. This isolated volcanic cone was discovered in 1901 by the Imperial German Expedition led by Erich von Drygalski.

consists of a lower complex of palagonite tuffs and agglomerates with interspersed lava flows overlain by lavas that range in composition from olivine tholeiite to basaltic andesite and rhyodacite (see description in LeMasurier & Thomson, 1990). Its volcanism is a consequence of subduction of the Drake (micro)plate beneath the Antarctic Peninsula at the well-defined sea-floor trench north of the main island group. It is in essence a relic of the long-continued Mesozoic/Cainozoic magmatic arc in West Antarctica, described by Barker & others (1991).

Other examples of modern volcanism in the Antarctic Peninsula region include: olivine basalts at Seal Nunataks off the eastern coast at latitude 65°S; alkali olivine basalts, and palagonite breccias and tuffs in the James Ross Island area; and similar rocks on Alexander Island, some of which overlie glacially striated bedrock pavements, and thus provide limited evidence of subglacial eruption.

As noted previously, many Cainozoic glacial deposits are not shown on the map. Nevertheless, attention is drawn to the late Cainozoic (probably Pliocene) diatomite-rich deposits (**Czs**) at Marine Plain in the Vestfold Hills (longitude 79°E) (Fig.21), which provide evidence for a climate significantly warmer than today's (Quilty, person. communic.). Quilty has also discovered fossil remains of a new species of dolphin in this deposit. Also important for elucidating the Cainozoic glacial history of Antarctica, and especially its Quaternary part, are **Czs** deposits in the 'Dry Valleys' (Fig.22) area of the Transantarctic Mountains west of Ross Island. These moraines, lake beds, conglomerates, and glaciomarine sediments from the fjordal lower parts of the valleys provide a geological record of the complex interaction between eastwards flowing outlet glaciers from the East Antarctic ice cap, local mountain glaciers, and ice in the Ross Sea/Ross Ice Shelf embayment. Sea level was the main control on whether this Ross embayment ice either floated or was grounded. The Cainozoic sequences in the Dry Valleys region have been drilled at a number of localities in the last two decades for the purpose of investigating Antarctic glacial history (see McGinnis, 1981; Barrett, 1989; Denton & others, 1991; McKelvey, 1991). Palaeontological age control from fossil diatoms, foraminifera, and shells is supported by K-Ar dating of intrusive and interlayered volcanic rocks, and by ^{14}C dating of shells and algal deposits.

Similar rocks in the Beardmore Glacier region are likewise attributed to fjordal sedimentation, but are distinctive because they contain fossil wood remains, some of them apparently in growth position. How wood came to be growing at such high latitudes at a time when Antarctica was apparently glaciated on much the same scale as today, is a question that vexes plant physiologists and causes disputes between glacial geologists (see Truswell, 1989, 1991, for discussion).

Not shown on the map are the many outcrops at high levels in the Transantarctic Mountains of glacial drift of the Sirius Formation. This unit contains Pliocene marine diatom fossils which are inferred to have been derived from marine sedimentary basins now deeply buried beneath the East Antarctic ice cap. This hypothesis implies that sediment was deposited in the basins during the Pliocene, and that the basins were therefore not then ice covered, a situation that would have required substantial deglaciation (see Webb & others, 1984). Curiously, no invertebrate macrofossils have been found in the Sirius Formation.

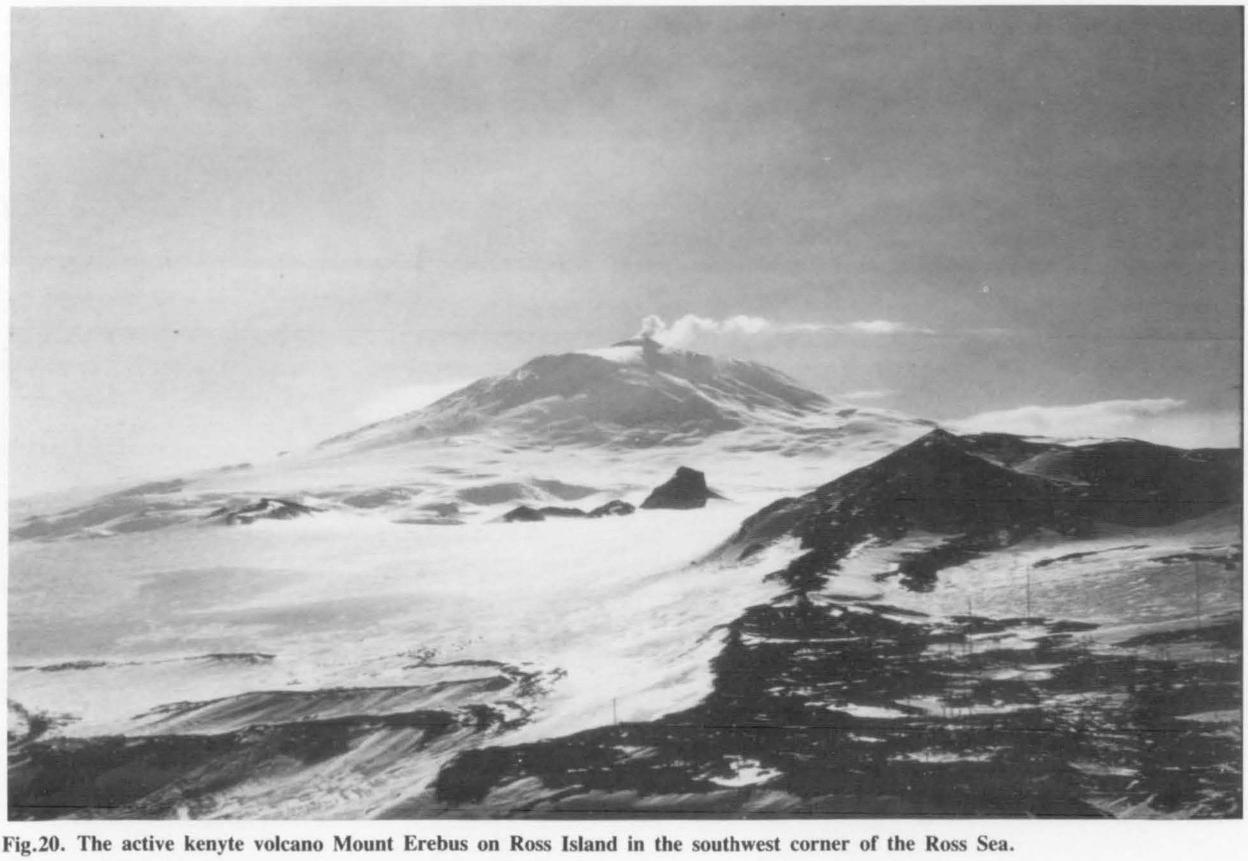

Fig.20. The active kenyte volcano Mount Erebus on Ross Island in the southwest corner of the Ross Sea.

Fig.21. Diatomaceous deposits at Marine Plain in the southern Vestfold Hills, East Antarctica. Dolphin fossils have been recovered from these Pliocene deposits.

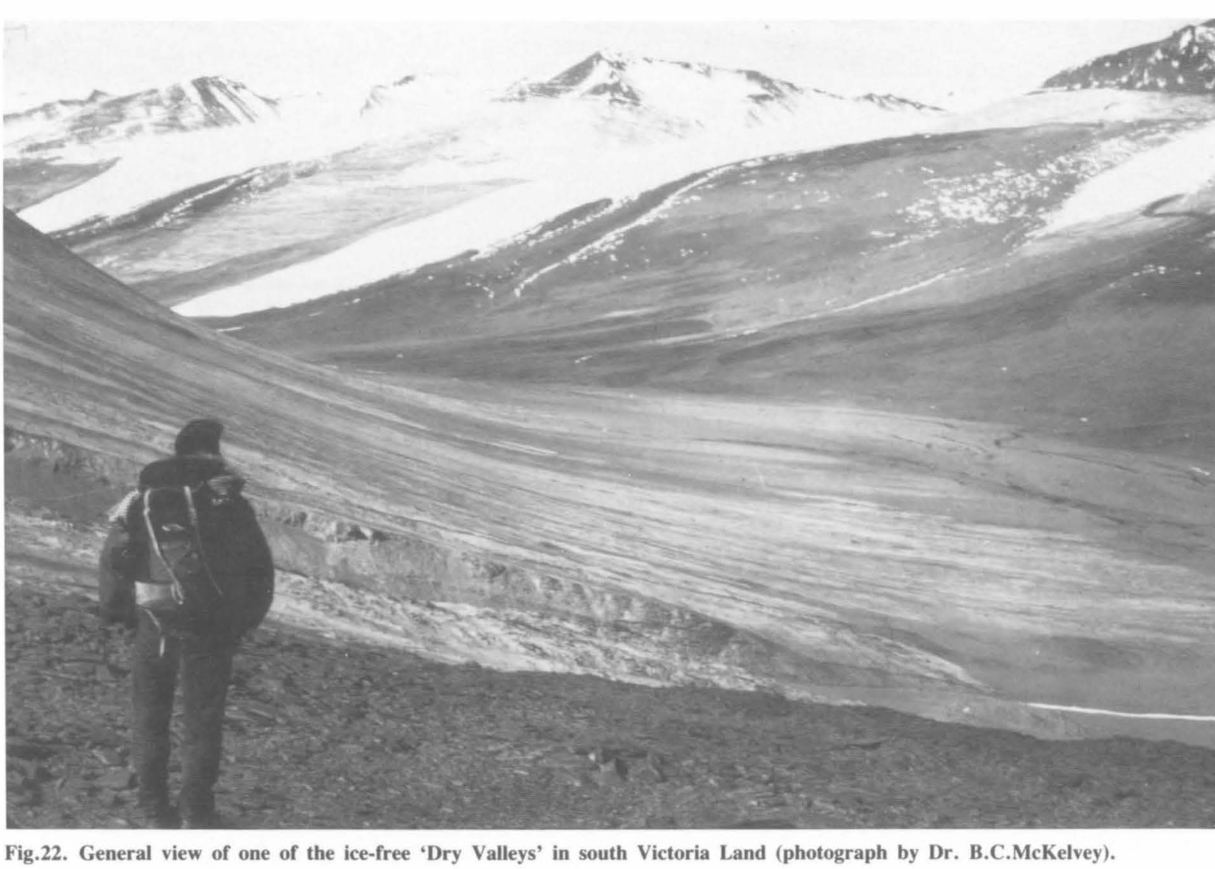

Fig.22. General view of one of the ice-free 'Dry Valleys' in south Victoria Land (photograph by Dr. B.C.McKelvey).

THE CONTINENTAL MARGINS

Although the geology of Antarctica's continental margins is not depicted on the map, the subject (reviewed by Anderson, 1991), is deserving of comment in view of the scientific effort and resources devoted in recent years to marine geological and geophysical investigations and surveys of them. Included in this effort are two legs of the Ocean Drilling Program: one (113) in the Weddell Sea region in 1987 (Barker, Kennett & others, 1988); and the second (119) in Prydz Bay at the mouth of the Amery Ice Shelf (70°E; 70°S) in 1988 (Barron, Larsen & others, 1988). Various segments of Antarctica's predominantly passive continental margins formed at different times as the various Gondwana landmasses rifted and, with the onset of seafloor generation and spreading, eventually moved away towards their present positions. These segments have different geological histories with, for example, the margin where India was once attached dating back to 125 Ma, and with that opposite Australia to about 80 Ma. However, the recent (from about 40 Ma to the present) history of the entire margin is dominated by the effects of the continuing Cainozoic glaciation. Thus, the early history of the margin segments will have features in common with that of the margin of the formerly adjacent landmass, whereas the later history will be in complete contrast. This picture assumes that rifting was symmetrical, which probably was not the case everywhere; in addition it does not apply to the active or convergent margins in the Antarctic Peninsula region.

Shown on the map at about longitude 147°E is the location of a marine core, which recovered a non-marine organic-rich siltstone with a well-preserved spore/pollen assemblage of Early Cretaceous age (Domack & others, 1980). Similar assemblages have been recovered from sea floor deposits elsewhere on the Antarctic margin, but exposed rocks of this age are only known from the Antarctic Peninsula region. The siltstone was probably deposited in a rift valley that formed where sea floor was later generated and continental separation eventually occurred.

ANTARCTIC GLACIATION

The history of Antarctica's modern glaciation can be traced from several lines of geological evidence, although agreement between them is commonly less than complete. Evidence from the continental record includes the dating of glacigene sediments, the mapping of lake and moraine levels, and isotopic dating of volcanic rocks within sequences of glacial sediments or overlying striated glacial pavements. Evidence from the marine realm is provided by submarine sediments, oxygen isotope and biostratigraphic attributes of marine microfossils, and sediments on the deep ocean abyssal plains. However, the disturbance of sedimentary sequences on the continental shelves by repeated advances and retreats of the continental ice cap has reduced their value as sources of information about Antarctic glacial history (see Anderson, 1991).

There appears to be general agreement that glaciers existed on Antarctica about 40 Ma ago and that continental-scale glaciation developed by about 30 Ma, but there is debate about whether this was a stable or a dynamic situation. There is abundant evidence of Quaternary fluctuations of the Antarctic ice cap (see Fig.23), and no obvious reason why this should not have been the case in earlier times. The interpretation of fossil diatoms in the Sirius Formation as evidence — albeit indirect — for substantial deglaciation of Antarctica in the Pliocene (Webb & others, 1984; but see also Denton & others, 1991) appears to be supported by the presence of *in situ* fossil wood in Sirius Formation sediments near the Beardmore Glacier, which requires at least ice-free refugia (see Truswell, 1991). It is generally assumed that the East Antarctic ice cap (which rests on bedrock that is predominantly above sea level and is classed as a continental ice cap) formed before, and was more stable than, the 'marine' West Antarctic ice cap which rests on bedrock that is below sea level (Denton & others, 1991).

The history of Antarctica's Cainozoic (and continuing) glaciation has some relevance to national and international community concerns about the possible consequences of climate change/global warming brought about by elevated levels of atmospheric CO_2. One such concern relates to sea level and whether it will rise as a result of the melting of the Antarctic ice cap in response to global climatic warming. Currently there is a widespread belief that such warming will lead to increased evaporation of sea water in the oceans around Antarctica, which will cause increased precipitation over, and therefore expansion of, the ice cap. This extraction of water from the oceans is expected to balance the thermal expansion of the oceanic water mass that would follow global atmospheric warming, with the result that little change in sea level is expected in the next one hundred years or so. However, sea level could suddenly rise were a large-scale surge of a substantial part of the Antarctic ice sheet to occur, as considered by Budd & McInnes (1978) and postulated for part of the Amery Ice Shelf ice drainage system by Allison (1979) and Wellman (1982). The moraine sheet shown in Figure 24 may have been deposited by such a surge.

A detailed climatic record dating back to 160 000 years is being compiled from glaciological studies of ice cores from the world's continental ice sheets and may prove useful in efforts to predict future climate. It has some potential for extension to about 400 000 years, but insights into the earlier Quaternary and Cainozoic climates will involve geological studies for which calibration of the late Quaternary geological record of climate against the ice core data will be required, as will integration of the marine and terrestrial geological records of past climate.

ANTARCTIC RESOURCES

Several references have been made in these notes to speculation about Antarctica's resource potential. The possible occurrence of platinum group metals in the Dufek intrusion (DeWit, 1985) is a case in point. Nonetheless, it is generally agreed that the exploitation of mineral deposits on the Antarctic continent will remain uneconomic for many decades if not for ever, and that the known occurrences of banded iron formation, copper mineralization, and coal are of academic interest only (see

Fig.23. A 'tidemark' of glacial drift on the walls of a cirque on Mount Menzies in the southern Prince Charles Mountains, East Antarctica, indicates a higher level of glacial cover in the past.

Fig.24. An 8 m-thick sheet of moraine overlying patterned ground on Mount Ruker in the southern Prince Charles Mountains. It may have been deposited during a surge of the nearby Fisher Glacier (see Wellman, 1982).

Rowley & others, 1983, 1991; Quilty, 1984; Rose & McElroy, 1987; Splettstoesser & Dreschoff, 1990). There is no reason to believe that Antarctica is any more or less endowed with mineral wealth than the other continents; however, the limited bedrock outcrop, the absence of erosional processes involving water (which precludes mineral exploration by stream-sediment geochemical methods), and the polar climatic and seasonal regime are all serious impediments to mineral development.

The possibility that petroleum deposits on the Antarctic continental shelf might be developed is less remote, although at least several decades away (Behrendt, 1983, 1991). At present, the seas around Antarctica are biologically very productive and, if this was the case throughout the Cainozoic glaciation, it is possible that Cainozoic glacial marine deposits on the shelf could be rich in biological debris and potentially a source for petroleum. On the other hand, advances and retreats of the continental ice caps over the offshore margins probably had a 'bulldozer' effect and profoundly disturbed the shelf sediments, causing petroleum accumulations to disperse. The petroleum prospectiveness of glacial marine sediments is not well known, but production from similar rocks of Palaeozoic age is reported from Oman (Levell & others, 1988).

The fact that no substantial petroleum accumulations are known from the Antarctic shelf may merely reflect the lack of serious, systematic, exploration. However, minor petroleum occurrences or traces have been encountered in drill holes of the Deep Sea Drilling Project (DSDP)(McIver, 1975), Cenozoic Investigations of the Ross Sea (CIROS)(Barrett, 1989), as well as during a marine dredging and coring project. The economics of petroleum exploration and exploitation in Antarctic waters are very discouraging, and problems such as icebergs, stringent environmental safeguards, remoteness from markets, and limited accessibility need to be addressed. Recent accidents involving petroleum production platforms and supertankers serve to underline these difficulties.

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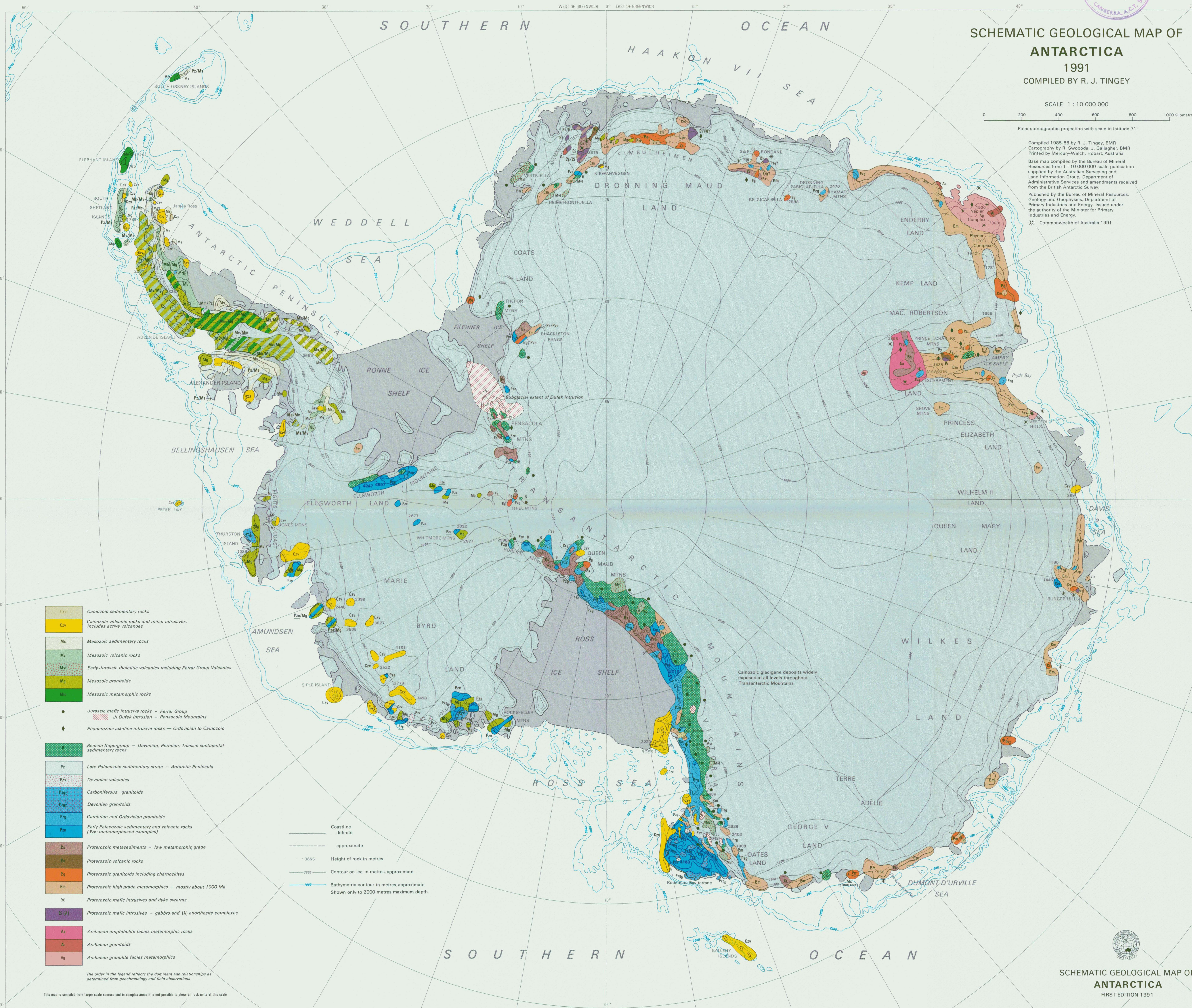
SCHEMATIC GEOLOGICAL MAP OF
ANTARCTICA
1991
COMPILED BY R. J. TINGEY
SCALE 1 : 10 000 000
0 200 400 600 800 1000 Kilometres
Polar stereographic projection with scale in latitude 71°
Compiled 1985-86 by R. J. Tingey, BMR
Cartography by R. Swoboda, J. Gallagher, BMR
Printed by Mercury-Walch, Hobart, Australia
Base map compiled by the Bureau of Mineral Resources from 1 : 10 000 000 scale publication supplied by the Australian Surveying and Land Information Group, Department of Administrative Services and amendments received from the British Antarctic Survey.
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SOUTHERN OCEAN
HAAKON VII SEA
WEDDELL SEA
BELLINGSHAUSEN SEA
AMUNDSEN SEA
ROSS SEA
DAVIS SEA
DUMONT D'URVILLE SEA
ANTARCTIC PENINSULA
DRONNING MAUD LAND
COATS LAND
ENDERBY LAND
KEMP LAND
MAC. ROBERTSON LAND
PRINCESS ELIZABETH LAND
WILHELM II LAND
QUEEN MARY LAND
WILKES LAND
TERRE ADÉLIE
GEORGE V LAND
OATES LAND
VICTORIA LAND
MARIE BYRD LAND
ELLSWORTH LAND
RONNE ICE SHELF
FILCHNER ICE SHELF
ROSS ICE SHELF
TRANSANTARCTIC MOUNTAINS
ELLSWORTH MOUNTAINS
PENSACOLA MTNS
SHACKLETON RANGE
PRINCE CHARLES MTNS
AMERY ICE SHELF
Subglacial extent of Dufek intrusion
Cainozoic glacigene deposits widely exposed at all levels throughout Transantarctic Mountains
Czs Cainozoic sedimentary rocks
Czv Cainozoic volcanic rocks and minor intrusives; includes active volcanoes
Ms Mesozoic sedimentary rocks
Mv Mesozoic volcanic rocks
Mvt Early Jurassic tholeiitic volcanics including Ferrar Group Volcanics
Mg Mesozoic granitoids
Mm Mesozoic metamorphic rocks
Jurassic mafic intrusive rocks – Ferrar Group
Ji Dufek Intrusion – Pensacola Mountains
Phanerozoic alkaline intrusive rocks — Ordovician to Cainozoic
B Beacon Supergroup – Devonian, Permian, Triassic continental sedimentary rocks
Pz Late Palaeozoic sedimentary strata – Antarctic Peninsula
Pzv Devonian volcanics
Pzgc Carboniferous granitoids
PzgD Devonian granitoids
Pzg Cambrian and Ordovician granitoids
Pze Early Palaeozoic sedimentary and volcanic rocks (Pze -metamorphosed examples)
Ps Proterozoic metasediments – low metamorphic grade
Pv Proterozoic volcanic rocks
Pg Proterozoic granitoids including charnockites
Pm Proterozoic high grade metamorphics – mostly about 1000 Ma
Proterozoic mafic intrusives and dyke swarms
Pi (A) Proterozoic mafic intrusives – gabbro and (A) anorthosite complexes
Aa Archaean amphibolite facies metamorphic rocks
Ai Archaean granitoids
Ag Archaean granulite facies metamorphics
The order in the legend reflects the dominant age relationships as determined from geochronology and field observations
This map is compiled from larger scale sources and in complex areas it is not possible to show all rock units at this scale
Coastline definite
approximate
3655 Height of rock in metres
2500 Contour on ice in metres, approximate
1000 Bathymetric contour in metres, approximate
Shown only to 2000 metres maximum depth
SCHEMATIC GEOLOGICAL MAP OF
ANTARCTICA
FIRST EDITION 1991