TECTONICS OF ANTARCTICA: A REVIEW*

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ABSTRACT. Despite the extensive ice cover, the exposed bedrock geology allows the recognition of an ancient shield in East Antarctica consisting mainly of Precambrian metamorphic and intrusive rocks, a series of orogenic belts along the margin of the East Antarctic shield and through West Antarctica, and Cenozoic volcanic provinces. Five distinct orogenic belts have been recognized and range in age from late Precambrian to late Mesozoic-early Cenozoic. The orogenic belts are progressively younger away from the shield, although there is considerable overlap in some areas. On the basis of the data available, tentative conclusions are drawn about the evolution of the orogenic belts in terms of plate tectonics. The absence of ophiolite suites and paired metamorphic belts leads to reliance on deformation and calc-alkaline volcanism as the indicators of compressive plate margins. The relations between East and West Antarctica remain the major problem in Antarctic tectonics.

INTRODUCTION

The major subdivision of Antarctica into two regions, one broadly similar to the Andes and the other consisting of old continental crust overlain by undeformed sedimentary strata, was recognized early in the 20th century (Nordenskjöld, 1913).

All the major geologic subdivisions of the Antarctic Peninsula (fig. 1) except the upper Paleozoic metasedimentary Trinity Peninsula Series were recognized by the Swedish South Polar Expedition 1901 to 1903 (Andersson, 1906). Nordenskjöld (1905) described two structural zones in the Antarctic Peninsula-Scotia Sea area, a cordilleran belt consisting of folded strata unconformably overlain by undeformed rocks (now known to be Paleozoic and Mesozoic, respectively) and intruded by plutons and a platform to the east comprising only slightly deformed Mesozoic and Cenozoic sedimentary strata overlain by Tertiary basalts. Although these results clearly demonstrated similarities with South America, a comparison already noted by Arctowski (1895), the extension of the structural trends into the base of the Peninsula was uncertain. Later studies in Marie Byrd Land, where a folded metasedimentary series is intruded by granitic plutons, led Wade (1937) to postulate that the Andean structures reappear in West Antarctica.

Geological investigations in East Antarctica prior to the International Geophysical Year, 1957-1958, were confined to a number of national expeditions which touched only the periphery of the continent except in the Ross Sea sector where the Transantarctic Mountains were traversed on foot. The basic structure there of a crystalline basement overlain along the Transantarctic Mountains by undeformed Paleozoic (Permian) sediments and intruded by dolerite sills was recognized, and the Transantarctic Mountains were regarded as a horst structure (Priestley and David, 1912). The main horst was believed to be of late Cretaceous or early Tertiary age (Gould, 1935), and the volcanic

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activity of Ross Island and the Victoria Land coast an expression of continued instability associated with the horst. The Cambrian strata now known to occur widely along the Transantarctic Mountains were recognized only in archeocathathid-bearing limestone erratics collected from widely separated localities. The deformed metasedimentary strata of north Victoria Land were described, though their position in the geologic column was uncertain.

A marked erosional scarp in the Transantarctic Mountains, the geography of the Ross and Filchner Ice Shelves, and the geologic contrasts between East and West Antarctica suggest that there is a major structural break extending across the continent. The structural relations between East and West Antarctica were a persistent topic in the early literature (Davies, 1956; Fairbridge, 1952; Gould, 1935; Taylor, 1940; Wade, 1937) (see Adie, 1957a, 1958; Anderson, 1965; Harrington, 1965 for more recent comprehensive bibliographies). With the advent of systematic geological exploration in the Antarctic Peninsula following the establishment of the Falkland Islands Dependencies Survey (now the British Antarctic Survey) in 1943 and in East Antarctica with the International Geophysical Year 1957-58, further advances have been made in understanding the tectonics of Antarctica; however, the relations
between East and West Antarctica still remain the major problem in Antarctic tectonics (for example, Hamilton, 1967; Craddock, 1972b).

*Bedrock morphology and crustal structure.*—Bedrock exposures amount to about 5 percent of the land area of Antarctica (fig. 1), and therefore subglacial morphology of the continent is important in the broad interpretation of the geology. Bedrock morphology has been determined by reconnaissance gravity and seismic traverses and in more detail by airborne radio echo sounding (Bentley, 1964a, 1964b, 1972).

If the Antarctica ice sheet melted, East Antarctica, after isostatic adjustment, would be largely above sea level except for the two shallow embayments identified in Wilkes Land (fig. 2). However, extensive areas in East Antarctica still lack data (see Bentley, 1972). The Gamburtsev Mountains are the only major subglacial mountains discovered so far. West Antarctica would consist of three major islands or archipelagoes, Marie Byrd Land, Eights Coast, and the Antarctica Peninsula, with the Ellsworth Mountains and a block extending southward possibly forming a fourth. A basin with a maximum depth of 2500 m, the Byrd Subglacial Basin, extends from the Ross Sea through West Antarctica and opens into the Amundsen and Bellingshausen Seas and possibly also the Ronne Ice Shelf. The Ellsworths block may be directly connected to East Antarctica; however, a very narrow but deep (1650 m) trench separates it from the Thiel Mountains. The trench apparently

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**Fig. 2.** Distribution of land and sea after removal of ice and assuming isostatic rebound. Large areas of East Antarctica lack data. (Modified from Bentley, 1972.)
trends southwestward and therefore would pass to the polar plateau side of the Transantarctic Mountains. The significance of this trench in defining the geologic boundary between East and West Antarctica is uncertain. Another, but shallower, trench with depths greater than 1000 m extends along the Transantarctic Mountains front from 170°W to northwest of the Thiel Mountains and may (Russian Antarctic Atlas—Sovetskaya antarkticheskaya ekspeditsiya, 1966) or may not (Bentley, 1972) join the other trench.

Data on the deep crustal structure have been summarized by Woollard (1962) and Adams (1972) and are presented in table 1. The crustal thickness of the northern Antarctic Peninsula is inferred to be about 30 km (Griffiths and others, 1964). The continent is believed to be close to isostatic equilibrium.

The Scotia Sea area (for a recent summary, see Dalziel and Elliot, 1973) has also been regarded as part of Antarctica. The islands of the North and South Scotia Ridges are isolated fragments of continental crust, whereas the South Sandwich Islands form a typical island arc bordered to the east by a deep oceanic trench (fig. 3). A north-south oriented spreading center has been identified in the eastern Scotia Sea (Barker, 1972a, 1972b), and, no doubt, the intense seismic and volcanic activity of the South Sandwich Islands is related to it. Also a recently active northeast-southwest oriented spreading center is located in the Drake Passage (Barker, 1972b). A possible former oceanic trench along the South Shetland Islands may be related to this spreading center as may also the late Tertiary to Recent volcanism and the positive gravity and magnetic anomalies of that area (Davey, 1972; Griffiths and others, 1964).

There are no oceanic trenches bordering any other part of the continent, and the other mid-ocean ridges surrounding the continent must be migrating away.

**EAST ANTARCTIC SHIELD**

Crystalline rocks mainly of Precambrian age and forming the igneous and metamorphic shield of East Antarctica are the only rock types exposed between Queen Maud Land (2°W) and Horn Bluff (150°E), except for the Permian strata in the foothills of the Prince Charles Mountains. The basement in the Transantarctic Mountains consists of late

<table>
<thead>
<tr>
<th>Method</th>
<th>East Antarctica</th>
<th>West Antarctica</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface wave dispersion</td>
<td>35-40 km</td>
<td>25-30 km</td>
</tr>
<tr>
<td>Seismic sounding (Kogan, 1972)</td>
<td>40 km (Queen Maud Land)</td>
<td></td>
</tr>
<tr>
<td>Bouguer gravity anomalies</td>
<td>42 km</td>
<td>32 km</td>
</tr>
<tr>
<td></td>
<td>60 km (Gamburtsev Mtns)</td>
<td>28 km (Ross, Ronne, Filchner Ice Shelves; Byrd Subglacial Basin)</td>
</tr>
</tbody>
</table>
Fig. 3. Sea floor magnetic anomalies in the Scotia Sea area. (Reproduced from Barker, 1972a, with permission.)
David H. Elliot

Table 2
Metamorphic rocks of the East Antarctic shield

<table>
<thead>
<tr>
<th>Parent rocks</th>
<th>Metamorphic rocks</th>
<th>Percentage of exposed basement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic volcanic rocks</td>
<td>Calc-magnesian and magnesian schists and gneisses; related migmatites and granites</td>
<td>60-70</td>
</tr>
<tr>
<td>Intermediate volcanic rocks</td>
<td>Ultrametamorphic charnockites and enderbites*</td>
<td></td>
</tr>
<tr>
<td>Pelitic and psammitic sediments</td>
<td>Quartzites, aluminous schists, and gneisses</td>
<td>20-25</td>
</tr>
<tr>
<td>Carbonate rocks</td>
<td>Calc-silicate marbles</td>
<td>5-10</td>
</tr>
</tbody>
</table>

*Charnockite — hypersthene-bearing granite  
Enderbite — plagioclase (commonly antiperthitic)-rich charnockite (after Ravich, 1972; Ravich, Klimov, and Soloviev, 1965)

Precambrian and early Paleozoic orogens (Beardmore and Ross Orogens), together with isolated areas of older crystalline basement, and is overlain by the largely undeformed late Paleozoic-early Mesozoic platform cover (Beacon Supergroup). In the Weddell Sea sector, there are scattered outcrops of Precambrian or Beacon platform cover.

The exposed crystalline basement is mainly a high-grade metamorphic terrain (fig. 4) consisting of gneiss of wide compositional range, schist, quartzite, marble, and plutonic rocks ranging from gabbro to granite (table 2). Charnockites and related rocks of both igneous and metamorphic origin are characteristic of the East Antarctic shield.

A lower and an upper structural stage have been recognized (Ravich, 1972). The lower stage is represented by two broad areas, one in Enderby Land (see also Kamenev, 1972; Kizaki, 1972; Trail and McLeod, 1969a, 1969b) and the other in eastern Wilkes Land (about 110°-150°E). These areas are characterized by enderbite and charnockite as well as granulite facies paragneiss. Cratonization (igneous and metamorphic processes leading to a stable craton) of the lower stage was completed in the early Proterozoic. Linear belts of lower structural stage rocks were also involved in upper structural stage tectonism (for example, Queen Maud Land; see also Juckes, 1972; Worsfold, 1967) and suffered regressive metamorphism to amphibolite grade, and locally to greenschist grade. The upper structural stage (table 3) consists of complex fold systems within which there are local outcrops of the lower stage. Metamorphism did not exceed the amphibolite grade, and therefore these areas lack enderbites and charnockites; however, migmatites and associated intrusions are common.

The youngest rocks involved in the process of cratonization are the metasedimentary rocks of greenschist facies in the southern Prince Charles Mountains (Soloviev, 1972a) which are regarded as Middle Proterozoic

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1 Structural stage is used in the same sense as it is used by Ravich (1972); the stages are time-structural units and represent assemblages of rocks that acquired their main structural characteristics by a certain time.
Fig. 4. Geology of the East Antarctica shield. (Modified from Craddock, 1972a.)
(Ravich, 1972). These rocks, which include the only known iron formation in Antarctica, are predominantly sequences of quartzite, phyllite, schist, and marble with only minor metavolcanic rocks. Younger rocks, of Late Proterozoic or Riphean (Eocambrian) age, include the Sandow Group (Ravich, Klimov, and Soloviev, 1965) which crops out in Wilkes Land (100°E). It consists of thin sequences of clastic sediment, ranging from conglomerate to shale, and metamorphosed to the greenschist grade.

The ages and times of deformation of the rocks constituting the igneous and metamorphic basement are still rather uncertain. Craddock (1970a) and Krylov (1972) have summarized the geochronologic data. Grindley and McDougall (1969) recognized three orogenic periods, and more recently Ravich, Grikurov, and Khain (in press) have distinguished six major cycles of tectogenesis in the Gondwanaland shields (table 4). There are, unfortunately, only a limited number of U-Pb and Pb-Pb dates and very few published Rb-Sr isochron dates.

### Table 3
Location of rocks assigned to the upper structural stage of the East Antarctic shield

<table>
<thead>
<tr>
<th>Western Queen Maud Land</th>
<th>Klimov, Ravich, and Soloviev, 1964</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sør-Rondane Mountains</td>
<td>Neethling, 1969</td>
</tr>
<tr>
<td>Queen Fabiola Mountains</td>
<td>Roots, 1969</td>
</tr>
<tr>
<td>Prince Olav Coast</td>
<td>Van Autenboer and Loy, 1972</td>
</tr>
<tr>
<td>Southern Prince Charles Mountains</td>
<td>Tatsumi and Kizaki, 1969</td>
</tr>
<tr>
<td>Northern Victoria Land (Wilson Group)</td>
<td>Tatsumi and Kizaki, 1969</td>
</tr>
<tr>
<td>Miller Range (Nimrod Group)</td>
<td>Soloviev, 1972b</td>
</tr>
<tr>
<td>Shackleton Range (Metamorphic Complex)</td>
<td>Trail and McLeod, 1969b</td>
</tr>
<tr>
<td></td>
<td>Gair and others, 1969</td>
</tr>
<tr>
<td></td>
<td>Grindley, 1963</td>
</tr>
<tr>
<td></td>
<td>Gunner, 1969</td>
</tr>
<tr>
<td></td>
<td>Clarkson, 1972</td>
</tr>
<tr>
<td></td>
<td>Stephenson, 1965</td>
</tr>
</tbody>
</table>

### Table 4
Tectonic cycles of the East Antarctic shield and Gondwanaland cratons

<table>
<thead>
<tr>
<th>Date (b.y.)</th>
<th>Rock type, location</th>
<th>Grindley and McDougall (1969) Date (b.y.)</th>
<th>Orogeny</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.6-3.8</td>
<td>Enderbite, Enderby Land</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.6-2.8</td>
<td>Not yet recognized in Antarctica (except, possibly, a 3.0 b.y. granite in western Queen Maud Land, Halpern, 1970)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.6-1.8</td>
<td>Migmatites, Enderby Land and Wilkes Land</td>
<td>1.0-1.05</td>
<td>Nimrod Orogeny</td>
</tr>
<tr>
<td>1.0-1.2</td>
<td>Migmatites, Wilkes Land</td>
<td>0.62-0.68</td>
<td>Beardmore Orogeny</td>
</tr>
<tr>
<td>0.7-0.8</td>
<td>Migmatites, Wilkes Land</td>
<td>0.45-0.52</td>
<td>Ross Orogeny</td>
</tr>
<tr>
<td>0.45-0.55</td>
<td>Charnockite, Queen Maud Land</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The Transantarctic Mountains have been excluded here.
(In part modified from Ravich, Grikurov, and Khain, in press)
A platform cover (Ritscher Supergroup) consisting of undeformed, titled, or locally folded strata of Precambrian age crops out in western Queen Maud Land (Neethling, 1969, 1972; Roots, 1969) (table 5). The undeformed rhyolitic rocks at the northeast corner of the Fildes Ice Shelf may fall in the same tectono-magmatic cycle as the syenites in western Queen Maud Land (see table 5) (Eastin and Faure, 1971).

In summary, a number of schemes for the tectonic subdivision of the shield have been presented (for example, Grikurov, Ravich, and Soloviev, 1972; Voronov, 1964), but as yet the radiometric data are inadequate for the delineation of geochronologic-geotectonic provinces because so many are K-Ar and Rb-Sr mineral or whole rock dates. In general the lower and upper structural stages (Ravich, 1972) appear to have been consolidated by Middle Proterozoic time. The high-grade metamorphic rocks constitute the stable shield which, except for some peripheral areas, has since Late Proterozoic time undergone only block tectonics and periods of magmatism (Soloviev, 1972a). The platform cover ranges in age from Middle Proterozoic (western Queen Maud Land) to Late Paleozoic.

BEARDMORE OROGEN

The margin of the East Antarctica shield between the Ross and Weddell Seas was the site of intermittent deformation and intrusive activity spanning the Late Precambrian to Early Mesozoic. The Beardmore Orogeny (Grindley and McDougall, 1969) is the earliest widely documented phase of activity and is recognized from the central Transantarctica Mountains to, possibly, the Shackleton Range (fig. 5; table 6, opposite p. 54). Strata deformed during this orogeny were deposited in one or more elongate basins along the margin of the East Antarctic shield. The orogeny is defined by Late Precambrian metamorphism and igneous activity, and stratigraphically by Cambrian beds unconformably overlying the deformed strata.

<table>
<thead>
<tr>
<th>Group</th>
<th>Lithology</th>
<th>Thickness m</th>
<th>Age, m.y.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trollkjeltrygg Group</td>
<td>Basic and intermediate lavas and tuffs</td>
<td>1360</td>
<td>Straumsnutane Formation at top gives isochron date of 848 ± 28 (Eastin, ms)</td>
</tr>
<tr>
<td></td>
<td>Sandstone</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Boulder beds and interbedded pyroclastics</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jutul Volcanics</td>
<td>Basic and intermediate flows</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td>Ahlmannrygg Group (4 formations)</td>
<td>Clastic red beds Sandstone, mudstone, graywacke Siltstone, arkose Subgraywacke, siltstone, arkose</td>
<td>1700-1900</td>
<td>Cut by diabase sills dated at 1700 ± 130 and 825 ± 20, and by syenites dated at 1050 ± 70 (Allsopp and Neethling, 1970)</td>
</tr>
</tbody>
</table>
Fig. 5. The Upper Precambrian Beardmore Orogen.
<table>
<thead>
<tr>
<th>Period</th>
<th>Stratigraphic Unit</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cretaceous-Cenozoic</td>
<td>Uplift and erosion</td>
<td>South Victoria Land</td>
</tr>
<tr>
<td>Jurassic</td>
<td>Uplift and erosion</td>
<td>North Victoria Land</td>
</tr>
<tr>
<td>Late Paleozoic/early Mesozoic (Gondwanian Orogeny)</td>
<td>Deformation — open to tight folding, local overturning to West</td>
<td>Victoria Group</td>
</tr>
<tr>
<td>Ordovician-Permian</td>
<td>(not recognized)</td>
<td>Victoria Group (Devonian)</td>
</tr>
<tr>
<td>Middle Paleozoic</td>
<td>(not recognized)</td>
<td>Victoria Group</td>
</tr>
<tr>
<td>Early Paleozoic</td>
<td>Uplift and erosion deformation — open folding, local overturning to West, granite intrusion (355 m.y.)</td>
<td>Victoria Group</td>
</tr>
<tr>
<td>Cambrian-Ordovician</td>
<td>Blacklock Glacier Group</td>
<td>Victoria Group (Anshull Limestone, etc.)</td>
</tr>
<tr>
<td>Late Precambrian</td>
<td>Uplift and erosion deformation — tight to nodal folding</td>
<td>Victoria Group</td>
</tr>
<tr>
<td>pre-Late Precambrian</td>
<td>Uplift and erosion deformation — tight to nodal folding</td>
<td>Victoria Group</td>
</tr>
</tbody>
</table>

Note: The table outline is incomplete and does not include all the information provided in the image.
Stratigraphy.—In Late Precambrian time thick sequences of graywacke and shale, locally overlain by acidic volcanic rocks, were deposited in the region of the Transantarctic Mountains (fig. 5). Nowhere is a stratigraphic or structural contact with older Precambrian basement observed, and only in the Nimrod Glacier area is the sequence seen to conformably overlie other strata (Grindley and Laird, 1969; Laird, Mansergh, and Chappell, 1971). There, 510 m of schist, marble, and quartzite, the Cobham Formation, underlies a 6700-m-thick metagraywacke-argillite sequence, the Goldie Formation. The Goldie Formation, which crops out as far south as the Beardmore Glacier (Grindley, 1963; Oliver, 1964), consists of quartzofeldspathic to arkosic graywacke, argillite, quartzite, and subordinate quartz sandstone; carbonate rocks and volcanic strata have not been recorded. Features typical of turbidites are widespread (Laird, Mansergh, and Chappell, 1971). The Goldie here is overlain with angular unconformity by Cambrian limestone (Laird, Mansergh, and Chappell, 1971).

Similar metasediments (Teall Graywacke) crop out in south Victoria Land, though locally they are represented by schists and gneisses (Warren, 1969; Grindley and Warren, 1964; Gunn and Warren, 1962). In north Victoria Land similar strata, the Robertson Bay Group, are about 5000 m thick (Crowder, 1968; Gair and others, 1969; Harrington and others, 1964, 1967). Metagraywacke, phyllite, and argillite are the predominant lithologies; slate, sandstone, polymict conglomerate, and limestone are found locally. Thick basaltic sills and spilitic basalt flows have been recorded near the upper Mariner and Tucker Glaciers (LeCouteur and Leitch, 1964; Riddolls and Hancox, 1968). Low-grade metasedimentary rocks, the Berg Group, crop out further west in Wilkes Land (156°E) (Klimov and Soloviev, 1958; Ravich, Klimov, and Soloviev, 1965) and contain acritarchs assigned to the Precambrian (Itchenko, 1972). Grindley and Warren (1964) suggest the Berg Group may be older than, but related to, the Robertson Bay Group.

In the eastern Queen Maud Mountains metagraywacke-argillite sequences are known as the Duncan Formation (McGregor, 1965; McGregor and Wade, 1969) and the LaGorce Formation (Minshew, ms; Mirsky, 1969), and near the Amundsen and Scott Glaciers they are overlain by massive felsic metavolcanic strata (Fairweather and Wyatt Formations). Volcanic structures have largely been eliminated by subsequent metamorphism or strong cataclasis. Although lavas may be present, most of the rocks are likely to be of pyroclastic origin; intrusions may also be present. The metavolcanic strata unconformably overlie the clastic sediments in the Nilsen Plateau (Minshew, ms; Mirsky, 1969), but Katz and Waterhouse (1970) observed an interfingering relation near the head of the Scott Glacier and favor interpreting the volcanics as older. Rather similar metavolcanics crop out in the Thiel Mountains (Ford and Sumison, 1971; Schmidt and Ford, 1969).

A very thick (10,000 + m) turbidite sequence, the Patuxent Formation, (Schmidt and Ford, 1969; Schmidt and others, 1965) crops out
extensively in the Pensacola Mountains. Graywacke and argillite are the
dominant rock types, together with minor coarse sandstone and intra-
formational conglomerate. Basaltic flows and pillow lavas are inter-
bedded in the sequence, which is also intruded by diabase sills and minor
felsic plugs and sills (Gorecki Rhyolite). The Gorecki Rhyolite has
yielded a Rb-Sr isochron date of 1210 ± 76 m.y. (Eastin, ms). The
Patuxent is overlain unconformably by Cambrian limestone.

Further northeast in the Shackleton Range, possible equivalent
strata are the Turnpike Bluff Group (Clarkson, 1972), a sequence of
quartzite, slate, subordinate conglomerate, sandstone, and limestone of
unknown but great thickness.

Deformation and intrusive activity.—In the central Transantarctic
Mountains the late Precambrian strata have been deformed either into
upright to recumbent isoclinal folds or into tight and symmetric, asym-
metric, and overturned folds. The folds plunge up to 20° and trend
regionally parallel or subparallel to the present mountain chain. Axial
plane slaty cleavage is widespread. There have been no systematic studies,
and hence the structure is rather poorly known. Laird, Mansergh, and
Chappell (1971) indicate that the stronger deformation in the Nimrod
Glacier area is associated with the earlier Beardmore Orogeny rather
than the later early Paleozoic Ross Orogeny. Oliver (1972) has sug-
gested tentatively that both the Beardmore and Ross Orogenies are re-
corded in the structures of the Goldie Formation near the mouth of
the Beardmore Glacier. Katz and Waterhouse (1970) record tightly
folded structures striking east in the LaGorce Formation. Axial planes
generally dip south, as do the thrust planes or bedding plane faults.
Locally a strong vertical axial plane cleavage strikes southeast.

A minimum age of sedimentation for the metasedimentary rocks
from the Nilsen Plateau is given by an isochron date of 728 ± 27 m.y.
(table 7). The metavolcanics from the Wisconsin Range and plutonic
rocks from the Nilsen Plateau and the Wisconsin Range all give late
Precambrian isochron dates (table 7). The Wisconsin Range Batholith
(Murtaugh, 1969), part of which crops out in the Nilsen Plateau (Mc-
Lelland, unpub. ms), ranges in composition from quartz-diorite to
granite. Both foliated and massive phases are present, and the foliation
in the gneissic phases is parallel to the northeasterly trends of the ad-
jacent country rocks. The Nimrod Group in the Miller Range has also

<table>
<thead>
<tr>
<th>Location</th>
<th>Lithology</th>
<th>Date</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Miller Range</td>
<td>Nimrod Group gneisses</td>
<td>about 600</td>
<td>Gunner and Faure, 1972</td>
</tr>
<tr>
<td>Nilsen Plateau</td>
<td>Gneissic granodiorite</td>
<td>611 ± 17</td>
<td>Eastin, ms</td>
</tr>
<tr>
<td>Wisconsin Range</td>
<td>Wisconsin Range Batholith</td>
<td>627 ± 22</td>
<td>Faure, Murtaugh, and</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Montigny, 1968</td>
</tr>
<tr>
<td>Thiel Mountains</td>
<td>Metavolcanic rocks</td>
<td>632 ± 102</td>
<td>Eastin, ms</td>
</tr>
<tr>
<td>Wisconsin Range</td>
<td>Metavolcanic rocks</td>
<td>633 ± 13</td>
<td>Montigny and Faure, 1969</td>
</tr>
<tr>
<td>Nilsen Plateau</td>
<td>Metasedimentary rocks</td>
<td>728 ± 27</td>
<td>Eastin, ms</td>
</tr>
</tbody>
</table>
yielded data suggesting re-equilibration at this time (table 7). The meta-
volcanic and metasedimentary rocks, as well as some intrusive bodies in
the Nilson Plateau, have also given dates consistent with resetting during
the Ross Orogeny.

A similar situation prevails in the Thiel Mountains where meta-
volcanic rocks give a late Precambrian date (table 7). Rb-Sr, K-Ar, and
Pb data on plutonic rocks indicate intrusion during the late Precambrian
and early Paleozoic, with resetting of older dates during the younger
Ross event (Schmidt and Ford, 1969).

The Patuxent Formation in the Pensacola Mountains also is in-
tensely deformed. In the eastern and central outcrop areas the near
vertical strata exhibit isoclinal folding about axes that plunge gently
either north or south and a near vertical axial plane cleavage; in the
western outcrops, the strata exhibit symmetrical folds with steeply dip-
ing limbs. The structural grain is parallel or subparallel to the moun-
tain range. The age of this deformation is bracketed only by the un-
conformable relations of the Patuxent with the overlying Middle Cam-
brian limestone and by the 1.2 b.y. date of the Gorecki Rhyolite. Thus
assignment of a late Precambrian age to the deformation is only tenta-
tive. The igneous rocks associated with the Patuxent Formation show
evidence of isotopic resetting during later thermal events (Eastin, ms)
but no direct radiometric indication of the Beardmore Orogeny.

Structures in the Turnpike Bluff Group in the Shackleton Range
trend east-west and are presumed to be of Precambrian age because of
the contrast in the degree and style of deformation of the adjacent
Cambro-Ordovician(? beds (Clarkson, 1972; Stephenson, 1966).

Summary.—The thick graywacke-shale sequences have been described
as one or more late Precambrian depositional basins; however, it is by
no means certain that the Patuxent Formation and the Robertson Bay
Group were deposited contemporaneously with the sequences in the
central Transantarctic Mountains. Further, the deformation of the
Patuxent Formation and the Turnpike Bluff Group, whose structures
trend at right angles to those of the Patuxent, may not have been syn-
chronous with the Beardmore Orogeny. Also, the Robertson Bay Group
was possibly first deformed in the mid-Paleozoic Borchgrevink Orogeny.

Long continued subsidence of basins along the margin of the East
Antarctic shield with concomitant deposition of thick graywacke-shale
sequences derived, probably, from the craton was terminated in the late
Precambrian by eruption of felsic extrusive rocks. In the Pensacola
Mountains thick pillow basalts are interbedded in the sequence and
suggest, possibly, an active continental margin in that area. However, the
apparent general absence of volcanic detritus in all the graywacke se-
quences favors an Atlantic-type margin (Mitchell and Reading, 1969).
In later stages a compressive margin was initiated, and subsequently cal-
alkaline magmas were generated. The sedimentary and volcanic strata
were deformed, metamorphosed to a low grade, and intruded by batho-
liths. Uplift and erosion followed, and a surface of low relief was formed on which Cambrian marine strata were deposited.

ROSS OROGEN

A 500 m.y. thermal event is recorded across much of the East Antarctic crystalline basement. Only along the Ross-Weddell Sea margin is there a record of orogenesis, the Ross Orogeny (Gunn and Warren, 1962), marked by deformation and batholith intrusion.

The Beardmore Orogeny was succeeded by a period of erosion along much of the Transantarctic Mountains; in Early Cambrian time a broad epicontinental sea formed, and there was extensive carbonate deposition which was overlapped and followed by clastic sedimentation and eruption of felsic volcanic rocks. In the late Cambrian to Ordovician, these rocks were deformed and intruded by granitic batholiths during the Ross Orogeny (fig. 6). The Ross Orogen is overlain by underformed Devonian strata.

Stratigraphy.—Lower Paleozoic strata were deposited in shallow water representing both near shore clastic environments and a carbonate platform. The carbonate platform is best developed between the Byrd and Nimrod Glaciers where the Cambrian strata (Byrd Group) unconformably overlie the Beardmore Group. The Byrd Group (Laird, 1963; Laird, Mansergh, and Chappell, 1971; Grindley and Laird, 1969) consists of very thick carbonates interbedded with and overlain by clastic sediments. The 9000-m-thick carbonate sequence, the Shackleton Limestone, includes thick limestone breccias and quartzites at or near the base; the breccias contain clasts of granite and metasedimentary rocks similar to the Goldie Formation. Quartz- and limestone-pebble conglomerate, sandstone, and shale are also interbedded. The Shackleton Limestone includes archeocyathid bioherms of Early Cambrian age (table 8), which are particularly abundant in the lower part of the sequence. Much of the Cambrian may be represented by beds overlying the fossiliferous strata. To the east of the carbonate belt a clastic sequence of quartz- and limestone-pebble conglomerate, argillite, graded sandstone, and impure limestone crops out. Spilitic and felsic volcanics are also interbedded. The conglomerate locally contains metasedimentary rocks similar to the Goldie Formation and limestone similar to the Shackleton Limestone. The clastics (Starshot and Dick Formations, Douglas Conglomerate) are regarded in part equivalent to the Shackleton Limestone (see also Skinner, 1964), but the relations are not clear. Laird, Mansergh, and Chappell, (1971) suggest the shoreline lay a short distance to the west.

Only in the Argentina Range and near Whichaway Nunataks is there additional evidence of Lower Cambrian carbonates (table 8).

Elsewhere the shallow marine platform is represented by either mixed carbonate-clastic or entirely clastic sequences with or without interbedded volcanic strata. In the Skelton Glacier area, south Victoria Land, as much as 3000 m of limestone with subordinate quartzite, sandstone, and slate crop out (Flory and others, 1971). Farther north the metamorphic grade rises and probable equivalent strata form the Koett-
Fig. 6. The Lower Paleozoic Ross Orogen. Sedimentary and volcanic strata in West Antarctica included here may be in part either older or younger.
<table>
<thead>
<tr>
<th>Location</th>
<th>Formation or Group</th>
<th>Fauna</th>
<th>Age</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>North Victoria Land</td>
<td>Sledgers Fm.</td>
<td>Brachiopods, trilobites, hyolithids, gastropods</td>
<td>Late Cambrian</td>
<td>Laird and others (1972)</td>
</tr>
<tr>
<td>Nimrod Glacier area</td>
<td>Shackleton Lst.</td>
<td>Archeocyathids</td>
<td>Early Cambrian</td>
<td>Hill (1964)</td>
</tr>
<tr>
<td>Beardmore Glacier</td>
<td>Shackleton Lst.</td>
<td>Archeocyathids</td>
<td>Cambrian</td>
<td>Young and Ryburn (1968)</td>
</tr>
<tr>
<td>Leverett Glacier</td>
<td>Leverett Fm.</td>
<td>Trilobite faunaule</td>
<td>Late Middle Cambrian</td>
<td>Palmer and Gatehouse (1972)</td>
</tr>
<tr>
<td>Ellsworth Mtns.</td>
<td>Heritage Group</td>
<td>Archeocyathids, trilobites, molluscs</td>
<td>Late Cambrian</td>
<td>Webers (1972)</td>
</tr>
<tr>
<td>Pensacola Mtns.</td>
<td>Nelson Lst.</td>
<td>Brachiopods, trilobites</td>
<td>Late Middle Cambrian</td>
<td>Palmer and Gatehouse (1972)</td>
</tr>
<tr>
<td>Argentina Range</td>
<td>limestones</td>
<td>Archeocyathids, trilobites, molluscs</td>
<td>Early Cambrian to Late Middle Cambrian</td>
<td>Palmer and Gatehouse (1972)</td>
</tr>
<tr>
<td>Whichaway Nunataks</td>
<td>erratics</td>
<td>Archeocyathids</td>
<td>Early Cambrian</td>
<td>Hill (1965)</td>
</tr>
<tr>
<td>Shackleton Range</td>
<td>erratics derived from Blaiklock Gl. Group</td>
<td>Brachiopods</td>
<td>Cambro-Ordovician</td>
<td>Thomson (1972b)</td>
</tr>
</tbody>
</table>

Fm. = Formation  
Lst. = Limestone
litz Marble (Gunn and Warren, 1962, Warren, 1969). Some of the other metasedimentary rocks of this area, such as the augen gneisses described by Smithson, Fikkan, and Toogood (1970) and Smithson and others (1972), may belong here or in the Beardmore Orogen.

Lower Paleozoic, probably Cambrian, strata are sparsely represented in the Queen Maud Mountains; outcrops occur at the head of the Beardmore Glacier (see table 8) and in the Shackleton Glacier area constitute the Henson Marble and Taylor Formation (McGregor, 1965; McGregor and Wade, 1969). The Taylor consists of quartzite, calcareous sandstone, marble, and felsic volcanic rocks and may therefore be equivalent to the Starshot and Dick Formations. The 2000-m-thick Leverett Formation (table 8) in the Horlick Mountains also consists of interbedded limestone, sandstone, and shale, with rhyolitic pyroclastics and conglomeratic sandstone prominent near the top (Minszew, ms; Mirsky, 1969). In the Pensacola Mountains (Schmidt and Ford, 1969; Schmidt and others, 1965) the Cambrian Nelson Limestone (table 8), which unconformably overlies the Patuxent Formation, consists of a thin, basal red bed sequence followed by thin- and thick-bedded limestone and argillaceous limestone. It is overlain by a volcanic unit, the Gambacorta Formation, which includes rhyolitic flows, breccias, and pyroclastic rocks, and volcanogenic sandstone and conglomerate. The Gambacorta Formation has given an isochron date of 568 ± 39 m.y. (Eastin, ms). It intertongues at the top with a thin-bedded fine-grained clastic sequence (Wiens Formation).

Farther to the northeast in the Shackleton Range the ?Cambro-Ordovician Blaiklock Glacier Group (table 8) consists of 6000 m of (?) marine sandstone and grit with subordinate conglomerate, micaceous shale and sandstone, and slate (Clarkson, 1972). The lower formation of 760 m of sandstone is separated from the 5300-m-thick upper, lithologically more variable, formation by an unknown thickness of unexposed strata.

A Cambrian shallow marine clastic sequence, the Bowers Group, also crops out in north Victoria Land (table 8). It consists of rocks ranging from coarse polymict conglomerate through sandstone and quartzite to mudstone, with subordinate carbonate beds and lenses, and basic volcanic flows and breccias (Crowder, 1968; Dow and Neall, 1972; Laird and others, 1972; Sturm and Carryer, 1970). A shallow marine or intertidal depositional environment has been inferred for part of the middle formation, the Sledgers Formation (Laird and others, 1972). The uppermost formation, the Camp Ridge Quartzite, is a very thick conglomerate unit, and Laird and others (1972) describe the Bowers Group as a whole as a regressive sequence. Sediment thickness is estimated at 25 km, but this is, perhaps, the result of repetition of the sequence.

Cambrian strata also occur in the very thick and conformable Precambrian to Permian sequence in the Ellsworth Mountains (Craddock, 1969). The 6700-m-thick Heritage Group, consisting of conglomerate, quartzite, sandstone, slate, phyllite, and argillite, includes fossiliferous
Upper Cambrian (table 8) limestone beds near the top. The immense thickness implies that the basal part may be Precambrian, and that the underlying carbonate sequence, the Minaret Group, is also that age. These beds may be in part equivalent to the upper Precambrian graywacke-shale sequences, but the relations are unclear. Similarly the relations of the Cambrian strata to the beds in the Transantarctic Mountains are unclear.

Deformation and intrusive activity.—The Bowers Group of northern Victoria Land, like the older Robertson Bay Group, was apparently deformed principally during the mid-Paleozoic Borchgrevink Orogeny (p. 69). However granitic plutons and batholiths assigned to the Ross Orogeny crop out west of the Cambrian strata (Adamson, 1971; Gair and others, 1969; Nathan and Skinner, 1972; Skinner and Ricker, 1968). The age of most of these rocks is based on K-Ar dates which may have been reset during the Ross Orogeny (table 9).

The basement metasedimentary rocks (Skelton Group; Gunn and Warren, 1962) in south Victoria Land exhibit a higher degree of metamorphism and more complex deformation than has been recorded elsewhere for the Ross Orogen. Recent work (Lopatin, 1972; Smithson, Fikkan, and Toogood, 1968, 1970; Smithson, Murphy, and Toogood, 1969; Smithson and others, 1972; Murphy and others, 1970) suggests the existence in Victoria Valley of three periods of deformation characterized by isoclinal folds. Fold axes trend north (F₁ and F₂) and northwest (F₃). It is not yet possible to relate the different periods of deformation specifically to the Beardmore or to the Ross Orogeny, except in that the third period of folding (F₃) belongs to the Ross Orogeny. The metamorphic rocks are in the uppermost amphibolite facies but only in the greenschist facies in the Skelton Glacier area where only two folds systems have been recognized. Both syntectonic (Larsen Granodiorite) and post-tectonic (Irizar Granite) plutonic bodies occur and constitute part of the Granite Harbor Intrusive Complex. Radiometric data indicate a preponderance of dates in the range 470 to 500 m.y. with a total range of 425 to 525 m.y. (table 9). Smithson, Fikkan, and Toogood (1970) regard the age of the youngest deformation as most likely to be in the range 450 to 480 m.y.

The Shackleton Limestone (Byrd Group) in the Nimrod Glacier area was folded about horizontal axes trending north or north-northwest and has axial planes subvertical to steeply dipping to the east (Laird, Mansegh, and Chappell, 1971). Axial plane cleavage is developed locally. One major syncline and several subsidiary folds have been recognized. The beds are near vertical or overturned further to the north. Structures with trends markedly different from the regional trends are observed in some areas, particularly in the Starshot Formation adjacent to the Byrd Glacier where fold axes are oriented between east and northeast (Skinner, 1964). Data on Cambrian strata in the Queen Maud Mountains are available only for the Leverett Formation, which is a homoclinal sequence dipping about 45° north.
<table>
<thead>
<tr>
<th>Location</th>
<th>Rock types</th>
<th>Method</th>
<th>Date (m.y.)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>North Victoria Land</td>
<td>gneisses and granitic rocks</td>
<td>K-Ar, Rb-Sr</td>
<td>420-565</td>
<td>Gair and others, 1969</td>
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<tr>
<td></td>
<td></td>
<td>Rb-Sr isochron</td>
<td>530</td>
<td>Faure and Gair, 1970</td>
</tr>
<tr>
<td></td>
<td></td>
<td>K-Ar</td>
<td>408-461</td>
<td>Nathan, 1971</td>
</tr>
<tr>
<td>South Victoria Land</td>
<td>Granite Harbour Intrusive Complex</td>
<td>K-Ar, Rb-Sr</td>
<td>425-525</td>
<td>Warren, 1969</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rb-Sr isochron</td>
<td>490 ± 14</td>
<td>Jones and Faure, 1969</td>
</tr>
<tr>
<td></td>
<td></td>
<td>K-Ar</td>
<td>451-461</td>
<td>McDougall and Ghent, 1970</td>
</tr>
<tr>
<td></td>
<td>Skelton Group, and dikes intruding metasediments</td>
<td>K-Ar</td>
<td>459-482</td>
<td>McDougall and Ghent, 1970</td>
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<tr>
<td>Miller Range and</td>
<td>Nimrod Group</td>
<td>K-Ar</td>
<td>471-528</td>
<td>Grindley and McDougall, 1969</td>
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<tr>
<td>Beardmore Gl. area</td>
<td></td>
<td></td>
<td></td>
<td>McDougall and Grindley, 1965</td>
</tr>
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<td></td>
<td>Hope Granite</td>
<td>K-Ar</td>
<td>450-478</td>
<td>Gunner, 1971a, ms</td>
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<tr>
<td></td>
<td></td>
<td>Rb-Sr isochron</td>
<td>463 ± 17</td>
<td></td>
</tr>
<tr>
<td>Queen Maud Mountains</td>
<td>Queen Maud Batholith</td>
<td>K-Ar, Rb-Sr</td>
<td>405-470</td>
<td>McGregor and Wade, 1969</td>
</tr>
<tr>
<td>Horlick Mountains</td>
<td>Wisconsin Range Batholith</td>
<td>K-Ar, Rb-Sr</td>
<td>450-520</td>
<td>Mirsky, 1969</td>
</tr>
<tr>
<td>Wisconsin Range</td>
<td></td>
<td>Rb-Sr isochron</td>
<td>479 ± 10</td>
<td>Eastin, ms</td>
</tr>
<tr>
<td>Nilsen Plateau</td>
<td>Wisconsin Range Batholith</td>
<td></td>
<td>452 ± 14</td>
<td>Eastin, ms</td>
</tr>
<tr>
<td>Thiel Mountains</td>
<td>quartz monzonite, plutons and volcanics</td>
<td>Rb-Sr isochron</td>
<td>409 ± 4</td>
<td>Eastin, ms</td>
</tr>
<tr>
<td>Pensacola Mountains</td>
<td>granite, granite gneiss</td>
<td>Rb-Sr isochron</td>
<td>555 ± 26</td>
<td>Eastin, ms</td>
</tr>
</tbody>
</table>
Plutonic bodies mapped as Hope Granite and part of the Granite Harbour Intrusive Complex crop out both in and near the Miller Range and extensively along the foothills of the central Transantarctic Mountains where they intrude the Goldie Formation. The intrusions range in composition from quartz-diorite to granite. Radiometric data (table 9) indicate early Paleozoic emplacement of the plutons and isotopic re-equilibration of the Nimrod Group at that time.

In the Shackleton Glacier area and to the southeast, the Queen Maud Batholith, a composite batholith ranging from gabbro to granite, forms most of the foothills. Pre-, syn-, and post-tectonic phases have been recognized (McGregor, 1965; Burgener, ms). These plutonic rocks intrude the Taylor Formation and equivalents of the Henson Marble in the Shackleton Glacier area. Isotopic equilibration of the plutonic rocks occurred between 470 and 405 m.y.; the young dates, which include some for gneissic phases, possibly indicate slower cooling rather than a separate event because lower levels in the batholith are exposed. Furthermore, some of the gneissic phases may have been emplaced during the Beardmore Orogeny.

Granitic rocks in the Horlick Mountains constitute the Wisconsin Range Batholith, much of which may have been emplaced during the Beardmore Orogeny (see p. 56). Early Paleozoic K-Ar and Rb-Sr dates (table 9) may only indicate isotopic resetting of older dates; however, isochron dates of 479 ± 10 m.y. and 452 ± 14 m.y. suggest emplacement of some plutons during the Ross Orogeny. Similarly, isochron data for the Thiel Mountains suggest emplacement during the Ross Orogeny, and mineral dates show isotopic resetting of older intrusions (table 9).

The Cambrian limestones and overlying sedimentary and volcanic rocks of the Pensacola Mountains were deformed into large open symmetrical folds with axes trending northerly and plunging gently south (Schmidt and others, 1965). Some subsidiary folds are asymmetric and locally overturned to the west. Axial plane cleavage is developed in the more strongly deformed argillaceous beds. Rhyolitic porphyry plugs and sills intrude the deformed sequence and are probably comagmatic with the rhyolitic strata of the Gambacorta Formation. A small stock of granite and granite gneiss intruding the Patuxent Formation was emplaced in the Early Paleozoic (table 9). In the Argentina Range to the northeast, the limestones have a variable dip and strike between northeast and north-northwest (Schmidt and Ford, 1969), but there is no direct evidence of the time of deformation.

The Blaiklock Glacier Group in the Shackleton Range dips either to the southwest or easterly and possibly has been folded about a north-south axis (Clarkson, 1972). The age of this deformation remains uncertain. Similarly the time of deformation, other than pre-Permian, of the possibly correlative Urfjell Group in western Dronning Maud Land remains uncertain (Aucamp, Wolmarans, and Neethling, 1972).
West Antarctica.—Rocks that may be related to the Ross Orogen in that they yield Early Paleozoic radiometric data crop out sparingly in Marie Byrd Land and Thurston Island. Further, the acoustic basement penetrated in the Ross Sea (Hayes and others, 1973) consists of marble lithologically comparable with the Koettlitz Marble of south Victoria Land.

In Marie Byrd Land (Klimov, 1967; Lopatin and Orlenko, 1972; Wade and Wilbanks, 1972) a thick sequence (4800 m) of metasediment, mainly graywacke, quartzite, slate, and phyllite, contains a few poorly preserved acritarchs assigned a Riphean age by Itchenko (1972) and has yielded metamorphic dates ranging between 445 and 475 m.y. (Krylov, Lopatin, and Mazina, 1970) (table 10, opposite p. 86). The regional strike of structures in the metasediments is northwesterly, and axial plane cleavage is widespread. A possibly correlative graywacke-shale sequence overlain by metavolcanic rocks has been reported from the Ruppert Coast (Klimov, 1967). In addition, metavolcanic rocks ranging in composition from basic to acid form scattered outcrops along the coast of eastern Marie Byrd Land and on Thurston Island and are regarded as Paleozoic (Craddock, 1972a; Klimov, 1967; Lopatin and Orlenko, 1972); although included here and in figure 6 their age is uncertain. It should be emphasized that the age and time of deformation of these rocks are open to question because of the sparsity of data.

Gneiss complexes that may be more strongly metamorphosed equivalents of the metasedimentary sequence crop out in the Fosdick Mountains and at isolated outcrops eastward to Thurston Island (Klimov, 1967; Lopatin and Orlenko, 1972; Wade, 1969). In the Fosdick Mountains (Klimov, 1967; Lopatin and Orlenko, 1972; Wilbanks, 1972) gneisses, migmatites, and other granitic rocks form an amphibolite-grade metamorphic complex of metasedimentary origin. All rocks are strongly foliated; the gross structure of the eastern end of the range has been interpreted as a south plunging antiform (Wilbanks, 1972), whereas toward the west superimposed younger deformation with northwest trends obliterates older structures. An infrastructure-superstructure relationship has been inferred (Wilbanks, 1972) for the metamorphic complex and adjacent metasediments. Mesozoic dates (Halpern, 1972; Krylov, Lopatin, and Mazina, 1970) from this area may have been reset, though Halpern (1972) tentatively relates the Fosdick Mountains gneisses and schists to Cretaceous orogeny. Limited radiometric data available for the Ruppert Coast and Thurston Island (Craddock, 1972a) indicate closing of isotopic systems in the range 420 to 500 m.y., but it is by no means certain that all the metamorphic complexes were first formed at this time.

The possibility of Precambrian and lower Paleozoic rocks and orogenies occurring in the Antarctic Peninsula and South Orkney Islands has long been advocated (Adie, 1954, 1969a, 1969b, 1972; Grikurov, 1972;
Grikurov and Lopatin, in press), but no definitive stratigraphic or radiometric data are yet available.

Summary.—In Early Cambrian time an epicontinental sea formed across the planed down roots of the Beardmore Orogen in the Transantarctic Mountains. The thick archecocytid bioherms suggest the shoreline was very low and little sediment was being transported into the part of the basin now observed. The shoreline, which is inferred to have been on the adjacent part of the craton, migrated away from the craton, so that by the late Cambrian thick marine clastic sequences, possibly derived from now rising land, were deposited. The later stages were also accompanied by felsic volcanism. The epicontinental sea was wide and extended well into West Antarctica. The thick graywacke-shale sequence of (?) Early Paleozoic age in Marie Byrd Land may have been deposited off the edge of this epicontinental sea; however, it seems more likely that it would have been derived from a land mass in West Antarctica. It is possible that the epicontinental sea formed an Atlantic-type margin and that there was collision in early Paleozoic time with continental crust or an island arc, although the latter is less likely because of the absence of volcanic detritus. Associated subduction led to the early acidic volcanism in the Transantarctic Mountains and later deformation, metamorphism, and batholith intrusion. Whatever the dynamic situation along the Transantarctic Mountains and in West Antarctica, the Ross Orogeny is recorded over much of the East Antarctic basement in both mineral and whole rock K-Ar and Rb-Sr dates (see Craddock, 1972a) and in an isochron date on charnockites (McQueen and others, 1972).

BORCHGREVINK OROGEN

The occurrence of metamorphic and igneous rocks in north Victoria Land yielding radiometric dates significantly younger than those of the Ross Orogeny, has led to the recognition of a mid-Paleozoic event termed the Borchgrevink Orogeny (Craddock, 1970c, 1972b) (fig.7). A pre-orogenic depositional phase has not yet been recognized, though mid-Paleozoic shallow marine clastic sediments unaffected by the Borchgrevink Orogeny crop out in the Ellsworth and Transantarctic Mountains (table 6). The orogen is defined stratigraphically by overlying undeformed Permian and Triassic sediments.

Stratigraphy.—The strata probably deformed during this orogeny are the Robertson Bay and Bowers Groups. They consist, respectively, of a very thick graywacke, shale, and basic volcanic sequence of probable late Precambrian age and a thick shallow marine sequence of Cambrian age (see p. 55 and p. 61). However, strata deposited during the mid-Paleozoic but without clear relation to the Borchgrevink Orogeny crop out in the Ellsworth, Pensacola, and Transantarctic Mountains. These sediments are predominantly quartz-rich clastics deposited in a shallow marine environment.
Fig. 7. The mid-Paleozoic Borchgrevink Orogen.
The Taylor Group in the Transantarctic Mountains forms the lower part of the Beacon Supergroup (Barrett, Grindley, and Webb, 1972) which ranges from Devonian or older to Jurassic and constitutes most of the platform cover of the East Antarctic metamorphic basement. The Taylor Group was laid down on the eroded roots of the Ross Orogen and is best developed in south Victoria Land where it consists of about 1400 m of quartzose sandstone with conglomerate and feldspathic and lithic sandstone at the base, and red and green siltstone locally at the top. Elsewhere, between south Victoria and the Shackleton Glacier, the Taylor is represented by up to 500 m of cross-bedded quartzose sandstone. The variegated siltstones at the top of the sequence contain fish remains and plant microfossils that are regarded as Late Middle Devonian (White, 1968) or Late Devonian (Helby and McElroy, 1969; McKelvey and others, 1972; Ritchie, 1969); the Taylor Group may include strata as old as Silurian. Marine conditions probably prevailed until the late Devonian when freshwater lakes and rivers were established (Barrett, Grindley, and Webb, 1972). Paleocurrent analysis and sandstone petrography suggest derivation of the basal New Mountain Sandstone from a metamorphic terrain similar to the East Antarctic shield but lying to the east in the Ross Sea area (Barrett and Kohn, in press), whereas all other strata were derived dominantly from the East Antarctic craton to the west.

A thin marine clastic sequence (Horlick Formation) with an abundant Lower Devonian invertebrate fauna (Boucot and others, 1967) crops out in the Ohio Range (Long, 1965). Sediments were derived from the East Antarctic craton.

The strata deformed in the Ross Orogeny in the Pensacola Mountains are unconformably overlain by a thick sequence (2300 m) of marine and non-marine clastic sediments, the Neptune Group (Schmidt and Ford, 1969). The unfossiliferous Neptune Group is disconformably overlain by the Dover Sandstone which consists of 1200 m of cross-bedded quartzose sandstone of probable upper Devonian age (J. M. Schopf, in Schmidt and Ford, 1969). In the Ellsworth Mountains the Cambrian Heritage Group is overlain conformably by a clastic sequence (Crashsite Quartzite) consisting of 3200 m of quartzite with minor interbedded argillite and conglomerate (Craddock, 1969). The upper part of the Crashsite contains Lower Devonian brachiopods (Boucot and others 1967).

The mid-Paleozoic strata suggest a shallow marine environment extending from the Weddell Sea to south Victoria Land, bordered by the East Antarctic craton and, at least during the early stages, rising land in the Ross Sea area.

*Deformation and igneous activity.*—The upper Precambrian Robertson Bay Group (Crowder, 1968; Gair and others, 1969; Harrington and others, 1967) is strongly deformed about near-horizontal fold axes which strike predominantly northwest. The folds are tight but only
rarely isoclinal. Fold amplitudes range up to several hundred meters, and wavelengths up to 5 km. Axial plane cleavage in argillaceous rocks is common. Metamorphism was slight; prehnite-pumpellyite and lower greenschist facies have been recorded. K-Ar metamorphic dates of 410 and 420 m.y. have been obtained from two phyllites.

The Bowers Group is also strongly folded about axes that trend mainly northwest but swing to near north in the northernmost outcrops (Dow and Neall, 1972; Gair and others, 1969). A major syncline with dips up to 80° has been observed for over 160 km in the Camp Ridge Quartzite. Locally the beds on the western limb are overturned and dip east.

The Robertson Bay Group is cut by a number of large undeformed, post-tectonic intrusions known as the Admiralty Intrusives (Grindley and Warren, 1964). These range in composition from hornblende-biotite-granodiorite to biotite–granite, with associated aplitic and granophyric dike phases (Gair and others, 1969; Riddolls and Hancock, 1968; Sturm and Carryer, 1970). Granodiorite is the most abundant rock type. Limited K-Ar data (Gair and others, 1969; Nathan, 1971) establish intrusion in the 300 to 385 m.y. range.

The Gallipoli Porphyries, a 270-m-thick sequence of porphyritic rhyolitic rocks of probably extrusive origin, overlie granite assigned to the Granite Harbour Intrusive Complex and underlie Jurassic basalts. A Rb-Sr isochron date of 375 ± 40 m.y. (Faure and Gair, 1970) suggests they are probably the extrusive equivalents of the Admiralty Intrusives.

West Antarctica and Antarctic Peninsula.—Evidence of mid-Paleozoic events are scattered through West Antarctica. A Rb-Sr isochron date of 352 ± 21 m.y. for quartz-diorite from the Fosdick Mountains, Marie Byrd Land (Halpern, 1968) constitutes the best evidence for intrusive activity of this age. Igneous and metamorphic rocks between Marie Byrd Land and Thurston Island have yielded whole rock and mineral K-Ar and Rb-Sr dates falling between 310 and 355 m.y. (Craddock, 1972a; Wade, 1972). A single K-Ar date of 370 m.y. has been reported by Adie (1972) for the Antarctic Peninsula, but no data on field relations are available. Rex and Baker (1973) refer to an isochron of 300 ± 50 m.y. for schists and gneisses from Signy Island in the South Orkney Islands. These rocks also give K-Ar mineral dates in the range 200 to 180 m.y. (Grikurov, Krylov, and Silin, 1967; Miller, 1960). The schists on Elephant and Clarence Islands have been correlated with the South Orkneys metamorphic complex (Dalziel, 1972a) and may therefore also be mid-Paleozoic.

Summary.—There is no definite evidence of a pre-orogenic depositional phase. The extent to which the Robertson Bay and Bowers Groups were involved in the Ross Orogeny is unclear, and it is possible that the K-Ar dates on the phyllites were isotopically reset by emplacement of the Admiralty Intrusives. Nevertheless, the Admiralty Intrusives, together with radiometrically dated igneous and metamorphic rocks in West Antarctica and the South Orkney Islands, suggest an active con-
tineal margin with generation of calc-alkaline magmas and regional metamorphism of preexisting crustal rocks. Uplift during the orogeny exposed a gneiss terrain in the Ross Sea area which shed detritus now forming the basal part of the Taylor Group. Uplift was not vigorous and prolonged because much of the sediment deposited in the inland sea between south Victoria Land and the Ellsworth and Pensacola Mountains is a relatively mature quartz sandstone. However, the Neptune Group in the Pensacola Mountains represents less stable conditions and erosion of adjacent highlands.

GONDWANIAN OROGEN

Early Mesozoic deformation is recorded marginal to the East Antarctic shield only in the Pensacola Mountains (Ford, 1972a), where it is known as the Weddell Orogeny. Deformation of similar age in the Ellsworth Mountains is described as the Ellsworth Orogeny (Cradock, 1972b) and is also recognized in the Antarctic Peninsula (Dalziel and Elliott, 1973). Following Dalziel and Elliott (1973) the early Mesozoic deformation affecting the Antarctic sector of the “Pacific” margin of Gondwanaland will be described as the Gondwanian Orogeny, a term first used by Du Toit (1987).

The stratigraphic record (tables 6 and 10) of this orogen (fig. 8) is scattered. Thick graywacke-shale sequences were deposited in the Antarctic Peninsula area, whereas shallow marine and non-marine strata accumulated in the Ellsworth, Pensacola, and Transantarctic Mountains. The non-marine strata in the Transantarctic Mountains are undeformed pre- and syntectonic platform sediments of the Victoria Group (Beacon Super-group). Radiometric data indicating igneous and metamorphic rocks of this age are sparse. The deformed strata in the Antarctic Peninsula are overlain unconformably by Upper Jurassic sediment, and this gives a minimum age to the deformation.

Stratigraphy.—A thick graywacke-shale sequence on Alexander Island (Bell, 1973b; Grikurov, 1972), the Trinity Peninsula Series on the northern Antarctic Peninsula (Aitkenhead, 1965; Elliot, 1966, 1967), the Miers Bluff Formation in the South Shetland Islands (Dalziel, 1972b), and the Graywacke-Shale Formation of the South Orkney Islands (Dalziel, 1971) are quartzose graywacke-shale sequences generally regarded on rather sparse evidence as contemporaneous and of late Paleozoic age. In addition, Fraser and Grimley (1972) correlate a thick siltstone-shale sequence and associated basic volcanics in the southern Antarctic Peninsula with the Trinity Peninsula Series. The quartzose graywackes of the Sandebugten Series on South Georgia have been grouped in the past with the Trinity Peninsula Series, but structural and petrographic data now suggest they are much younger (Dalziel and others, 1973a; see p. 75).

The Trinity Peninsula Series is the most extensive of these sequences and has been estimated to be more than 13,000 m thick. Quartzose graywacke and shale form thick interbedded sequences and predominate
markedly over other rock types which include conglomerate, conglomeratic mudstone, arkose, quartzite, siltstone, carbonaceous shale, limestone, chert, and greenschist (Adie, 1957b; Aitkenhead, 1965; Elliot, 1965, 1966; Fleet, 1965, 1968). Conglomerate clast lithology and sandstone petrology suggest a largely granitic provenance with subordinate sedimentary and metamorphic rocks. The greenschists are likely to have been basic volcanic rocks. Other sequences are broadly similar but generally lack the varied minor constituents. Thick sequences of acidic volcanic rocks, largely lavas, are inferred to overlie conformably the siltstone-shale sequence of the southern Antarctic Peninsula. Basalts and pillow lavas are abundant in parts of the sequence on Alexander Island, and some of the sandstones have a significant proportion of volcanic detritus (Bell, 1973b; Grikurov, 1972). Plant microfossils recovered from the Trinity Peninsula Series at Hope Bay and from the Alexander Island sequence suggest a Carboniferous age (Grikurov and Dibner, 1968).

Glacial and shallow marine strata of late Paleozoic age, which were deformed in the Gondwanian Orogeny, crop out in the Ellsworth and Pensacola Mountains. The glacial marine beds, which are related to those of the Transantarctic Mountains, form the 915-m-thick Whiteout Conglomerate and the 315-m-thick Gale Mudstone (Cradock, 1969; Frakes, Mathews, and Crowell, 1971; Schmidt and Williams, 1969). The Whiteout Conglomerate is overlain conformably by the Permian Polarstar Formation, which consists of 1500 m of interbedded arenaceous and argillaceous rocks probably deposited in a shallow marine environment (Cradock and others, 1965). The Gale Mudstone, however, is not in contact with the 200-m-thick carbonaceous floodplain sequence (Pecora Formation) of Permian age (Williams, 1969) which crops out in the Pensacola Mountains.

The Victoria Group in the Transantarctic Mountains (Elliot, in press) lies disconformably on the Taylor or with nonconformity or angular unconformity on Precambrian and Lower Paleozoic basement. It ranges in thickness from a few meters in north Victoria Land to 2300 m in the Beardmore area. There the lowest beds in the Victoria Group consist of glacial strata overlain by a black shale unit which was probably deposited in an environment similar to the Baltic Sea. The black shale is succeeded by a massive deltaic sandstone which grades up into a well-developed floodplain sequence with abundant carbonaceous material, including coal. In south Victoria Land, the thin glacial beds are overlain directly by carbonaceous beds of a floodplain environment. Equivalent strata elsewhere are rather similar carbonaceous floodplain deposits; these beds either rest directly on basement rocks or their lower contact is not exposed. Plant microfossils establish an Early Permian (Sakmarian) age for the late stages of glaciation (Schopf, 1971; Barrett and Kyle, in press), though strata in the Pensacola and Ellsworth Mountains may be older (Frakes, Mathews, and Crowell, 1971). The carbonaceous strata are assigned to the Middle and Upper Permian on
Fig. 8. The upper Paleozoic-lower Mesozoic Gondwanan Orogen.
the basis of the abundant *Glossopteris* flora (Rigby and Schopf, 1969) and conchostracans (Doumani and Tasch, 1965).

Strata younger than the Permian coal measures are confined to the area between Scott Glacier and north Victoria Land and comprise a thick sequence of coarse and fine clastic sediment which again represents alluvial plain deposition. The upper parts of this younger clastic sequence are found only in the Beardmore area and in both south and north Victoria Land where they may rest directly on lower Paleozoic basement. In the Beardmore area, volcanic detritus is increasingly abundant up section, and volcanioclastic strata including airfall tufts constitute the only rock types in the uppermost part. A lower Triassic vertebrate fauna (Elliot and others, 1970; Kitching and others, 1972) has been recovered from basal beds overlying the coal measures in the Beardmore area. The upper part of the sequence contains the *Dicroidium* flora and plant microfossils of Middle and Late Triassic age (Helby and McElroy, 1969; Norris, 1965; Rigby and Schopf, 1969; Townrow, 1967).

Tholeiitic igneous rocks are associated with Beacon strata everywhere except the Prince Charles Mountains. Sills of the Ferrar Dolerite are ubiquitous in the Transantarctic Mountains, and comagmatic basaltic lavas cap the Beacon in the Beardmore Glacier area and Victoria Land and also occur in western Queen Maud Land. The Ferrar Group has been dated radiometrically between 191 and 147 m.y., and thin sedimentary interbeds in the Kirkpatrick Basalt contain Jurassic plants, fish, and an invertebrate fauna (for summary see Elliot, in press).

*Orogenesis.*—The probable Upper Paleozoic sequences of the Antarctic Peninsula and the South Orkney Islands are all strongly folded and show evidence of polyphase deformation. In the Trinity Peninsula Series and Miers Bluff Formation the structural trends are parallel or sub-parallel to the length of the Peninsula, and the strata are overturned to the southeast. The gross structure of the Trinity Peninsula Series has been described as an anticlinorium (Aitkenhead, 1965; Elliot, 1965, 1966), and there are at least two major *en-echelon* anticlines present. Overturned strata and isoclinal folding probably occur regionally, and slaty cleavage subparallel to axial surfaces is common. The Miers Bluff Formation forms part of a refolded southeast-facing recumbent fold which has a gently west-dipping axial surface (Dalziel, 1972b). The Graywacke-Shale Formation, which is exposed on Laurie and Fredricksen Islands, South Orkney Islands, strikes east-west in the central part of Laurie Island but north-south at the eastern end; late stage folds trending north-northwest occur at the western end (Dalziel, 1971). The metamorphic grade attains the greenschist facies only in the Trinity Peninsula Series.

Outcrops of the Trinity Peninsula Series are sparse south of 64°S but still display vertical or steep dips and isoclinal folds trending parallel to the Peninsula. The strata on the Wilkins Coast were probably deformed in early Mesozoic time. The siltstone-shale sequence is folded about north-northwest axes and has been subjected to regional meta-
morphism which increases to the southwest where the rocks have been metasomatized and migmatized and have also been intruded by synkinematic plutons. The structural grain in these rocks is discordant to the regional trends in the Peninsula. There are few data available for the sequence on Alexander Island.

Early Mesozoic mineral dates are recorded from the metamorphic complex of the South Orkney Islands (Grikurov, Krylov, and Silin, 1967; Miller, 1960), but these may be the result of partial argon loss in the "Andean" orogeny (Dalziel, 1972a). Recent radiometric dating has demonstrated an episode of early Jurassic intrusive activity in the Antarctic Peninsula (Adie, 1972) which may be related to the Gondwanian Orogeny.

The entire Precambrian to Permian sequence of the Ellsworth Mountains was deformed in the early Mesozoic. Folds are commonly tight and asymmetric to overturned. Cleavage near parallel to axial planes of folds is widespread and best developed in the pelitic rocks although even the coarser clastics exhibit a fracture cleavage. Fold axes and other structural elements are parallel or sub-parallel to the mountain range and from south to north swing from northwest to near north. Isolated outcrops of deformed strata to the south and west, which are tentatively correlated with the Ellsworth sequence, have been intruded by Upper Triassic to Lower Jurassic plutons (Craddock, 1972a, 1972b; Halpern, 1968).

Permian and older strata in the Pensacola Mountains were deformed into broad open folds in the central part of the outcrop area; eastward deformation decreases, but westward the intensity increases, and folds are tight and locally overturned to the west (Ford, 1972a). Fold axes trend near north-northeast. The age of deformation is regarded as latest Permian to Middle Jurassic; however, indirect relationships of radiometrically dated Mesozoic diabase suggest it is latest Permian to Late Triassic (Ford, 1972a).

In the rest of the Transantarctic Mountains evidence of the Gondwanian Orogeny is found, possibly, in the marked paleocurrent reversal between the Permian and Triassic strata of the Victoria Group. Furthermore a consideration of the depositional basins of the Victoria Group suggests that episodic uplift of the Gondwanian Orogen was an important control in their evolution (Elliot, in press).

Along the coast of West Antarctica, in eastern Marie Byrd Land, Thurstson Island, and Eighty Coast, radiometric data on igneous and metamorphic rocks suggest an event or events of Late Paleozoic to Early Mesozoic age (Craddock, 1972b; Halpern, 1972, 1973).

Summary.—The Gondwanian Orogen was initiated by the development in the Antarctic Peninsula area of depositional basins in which thick graywacke-shale sequences accumulated. At least the later stages of basin-filling were probably contemporaneous with deposition of glacial beds in a subsiding epicontinental basin developed in the Ellsworth-Pensacola Mountains area. This epicontinental sea lay off the end of a
major non-marine depositional basin that stretched from the Nimrod Glacier area to the Ellsworth Mountains. The evolution of this non-marine basin and the basin that developed subsequently in the Transantarctic Mountains suggest strong control by a rising geanticline in West Antarctica (Elliot, in press). The graywacke-shale sequences were deposited on the Pacific side of this geanticline, whereas the marine and non-marine strata were laid down on the continental side. Deformation, very low grade regional metamorphism, and minor intrusive activity mark the Early Mesozoic orogenesis. However continued uplift of the orogenic belt is reflected in the paleocurrent reversal between the Permian and Triassic strata in the central Transantarctic Mountains. Furthermore acidic volcanism was initiated at this time and eventually dominated the rock record in the central Transantarctic Mountains in Late Triassic time; associated plutonism is recorded in West Antarctica. The Gondwanian Orogen might be analogous to an Andean type plate margin, although contemporaneous submarine volcanism is apparently well developed only in the Alexander Island sequence, and calccalkaline volcanism only in the southern Antarctic Peninsula. There was probably little underthrusting associated with this orogeny (Dalziel and Elliot, 1973).

**ANDEAN OROGEN**

Strata involved in, or related to, the late Mesozoic-early Cenozoic Andean Orogeny (Craddock, 1972b) crop out along the Pacific margin of Antarctica and in the Scotia Sea area (fig. 9). The bulk of the strata are Jurassic and Cretaceous, and only locally are there Tertiary representatives. Pre-orogenic depositional basins are known only in South Georgia and eastern Ellsworth Land; elsewhere sedimentary basins developed in response to uplift of the orogenic belt. Regional metamorphism is largely absent, and deformation is only locally significant, but intrusive activity is very widespread; in these aspects the Andean orogen differs from the earlier orogens. A detailed summary is given in Dalziel and Elliot (1973).

**Stratigraphy.**—Thick graywacke-shale sequences are found in South Georgia where a (?) quartzose graywacke unit, the Sandebugten “Series”

2 and a graywacke sequence with andesitic detritus and interbedded basaltic lavas, the Cumberland Bay “Series”, crop out. The Sandebugten, although formerly compared with the Trinity Peninsula Series, is now considered (Dalziel and others, 1973a) to be nearly the same age as the Cumberland Bay Series. Strata similar to and along the strike of the Cumberland Bay Series crop out on Annenkov Island off the coast of South Georgia and contain a Lower Cretaceous (Aptian) invertebrate fauna (Wilckens, 1947).

Late Mesozoic sequences on the east side of the Peninsula consist of sedimentary and volcanic strata of probable Jurassic age and upper Cretaceous and Tertiary shallow marine beds, whereas on the west coast the marine beds are Late Jurassic and Early Cretaceous in age.

Unconformable relations with older strata (Trinity Peninsula Series) have been observed at only four localities in the northern Antarctic

2 The term “Series” has only lithostratigraphic significance.
Peninsula of which that at Hope Bay (table 11) is the most important (Aitkenhead, 1965; Bibby, 1966; Dalziel, 1972b; Fleet, 1968). The flora from the Hope Bay volcanic and sedimentary sequence, although generally regarded as Middle Jurassic (Halle, 1910), is probably early Late Jurassic (J. M. Schopf, personal commun., 1974) by comparison with the flora from strata dated by ammonites on the Lassiter Coast (Williams and others, 1972). Sedimentary strata underlie volcanic rocks at few localities, and the volcanic rocks, which may be as much as 3000 m thick, form the bulk of the Jurassic record. They consist of lavas and tuffs of andesitic to rhyolitic composition; ash flow tuffs have been reported and may constitute a significant part of the section. Possible feeder dikes and plutons related to these extrusive rocks have been recognized (Fleet, 1968).

Extensive exposures of volcanic rocks of Middle and Late Jurassic age (Dewar, 1970; Fuenzalida, Araya, and Hervé, 1972; Thomson, 1972a) crop out on the west coast of the Peninsula as far south as Marguerite Bay and possibly form much of the core of the Peninsula to the south. Andesite lavas and pyroclastic rocks predominate over other lithologies which include both basaltic and rhyolitic rocks and volcanogenic sediment. Neither the base nor the top of the sequence has been observed, and the volcanic strata may range into the Cretaceous.

On the Lassiter Coast a 600-m-thick sequence of shale, siltstone, and minor sandstone which is overlain by 1000 m of dacitic and andesitic lavas, tuffs, and ashflow tuffs has been dated as Late Jurassic by the contained invertebrate fauna (Williams and others, 1972). Felsic volcanic rocks, both flows and tuffs, together with shales, sandstones, and conglomerates which have a significant component of volcanic detritus, crop out in eastern Ellsworth Land (Laudon and others, 1969). The sediments contain Middle and Upper Jurassic invertebrate faunas (Quilty, 1970, 1972; Stevens, 1967).

Felsic volcanic rocks cut by K-Ar dated Cretaceous felsite dikes are known from the Jones Mountains (Craddock, Bastien, and Rutford, 1964), and some other undated volcanic strata in Marie Byrd Land are regarded as Jurassic (Craddock, 1972a, 1972b).

Table 11
Stratigraphic succession at Hope Bay

<table>
<thead>
<tr>
<th>Thickness, m</th>
<th>Lithology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper Jurassic volcanic strata</td>
<td>210+ Rhyolitic tuffs and lavas, agglomerate, interbedded chert.</td>
</tr>
<tr>
<td>Jurassic sedimentary strata</td>
<td>90 Mudstone, shale, subordinate sandstone. Shales contain a rich Jurassic flora.</td>
</tr>
<tr>
<td></td>
<td>120 Conglomerate with sandstone and mudstone intercalations</td>
</tr>
</tbody>
</table>

Anglular unconformity

Late Paleozoic strata

Graywacke-shale sequence
(Trinity Peninsula Series)
Fig. 9. The upper Mesozoic-lower Cenozoic Andean Orogen.
The James Ross Island area forms part of an apparently extensive Late Mesozoic-Cenozoic sedimentary basin on the southeast side of the Antarctic Peninsula (Dalziel and Elliot, 1973). The Cretaceous sequence has been estimated at 5000 m thick. The lower 1500 m, which crops out on the northwest side of James Ross Island, includes numerous conglomeratic beds. The upper part, the Snow Hill Island Series, is much more widespread and is generally a finer-grained clastic sequence. Ammonite faunas (Howarth, 1958, 1966; Spath, 1953) establish a Campanian age, but the former existence of Lower Cretaceous strata in adjacent areas has been postulated (Bibby, 1966; Elliot, 1966). The Seymour Island Series rests with slight angular unconformity on the Campanian strata. It is a clastic sequence of shale, sandstone, and conglomerate, and granitic pebbles indicate that by this time Andean plutons were exposed to erosion. Floral and faunal remains have been regarded as Late Oligocene-Early Miocene (Dusén, 1908; Wiman, 1905); however, an Eocene age has recently been postulated (Simpson, 1971).

Isolated outcrops of clastic sediments as far south as the Bowman Coast are assigned a Cretaceous age on their enclosed faunas or by lithologic identification (Bibby, 1966; Elliot, 1966; Fleet, 1966; Thomson, 1967). Conglomeratic strata in a possibly analogous position crop out on the South Orkney Islands (Adie, 1964; Thomson, 1973); invertebrate and plant fossils suggest a tentative age of Jurassic or Cretaceous.

Cretaceous strata on the Pacific side of the Peninsula crop out on Livingston and Snow Islands in the South Shetlands and on Alexander Island. The Byers Peninsula sedimentary and volcanic strata on Livingston Island have been assigned a Late Tithonian to Late Barremian age (Valenzuela and Hervé, 1972). Volcanic sequences elsewhere in the South Shetlands, generally regarded as Upper Jurassic or Cenozoic, may include Cretaceous strata. Sequences on Alexander Island at Belemnite Point and Ablation Point are largely clastic sediments with a large volcanic component; invertebrate faunas establish a Late Jurassic age (Adie, 1964; Howarth, 1958). Farther south, a thick, shallow-marine clastic sequence, the Fossil Bluff Series, has been assigned a Late Jurassic-Early Cretaceous age (Taylor, 1972; Thomson, 1972c). The sequence consists of conglomerate, sandstone, and mudstone derived from the east and constitutes deltaic and interdeltaic environments of a shoreline facies (Horne, 1967, 1968, 1969). Volcanic detritus is abundant in much of the succession.

Tuffaceous strata in western Alexander Island which have yielded a 70 m.y. K-Ar date from the base of the sequence are regarded by Grikurov, Krylov, and Silin (1967) as effusive equivalents of the Andean igneous complex.

Deformation and plutonism.—Only the strata in South Georgia and at the base of the Antarctic Peninsula exhibit significant deformation, and regional metamorphism is practically nonexistent. Pre-, syn-, and post-tectonic plutonism is very widespread and locally the deeper levels of the orogen may be exposed as, possibly, in the orthogneisses of Marguerite Bay.
The Sandebugeten and Cumberland Bay sequences on South Georgia are strongly deformed about northwest-southeast trending axes. Folds are tight and asymmetric to overturned, and slaty cleavage is widespread (Skidmore, 1972; Trendall, 1953, 1959). Folds in the Cumberland Bay strata verge north-northeast, and the sequence is thrust over the Sandebugeten in which the fold vergence is dominantly to the south-southwest; despite differences in vergence the structural relations indicate simultaneous deformation (Dalziel and others, 1973a). Deformation can be dated only as post-Aptian on South Georgia; however, correlation with South America indicates that it was pre-Coniacian (Dalziel, deWit, and Palmer, 1974). These rocks represent part of a marginal basin that is better exposed in the southernmost Andes (Dalziel, deWit, and Palmer, 1974).

In the Antarctic Peninsula post-Aptian deformation is also shown by the open folding and (?) thrusting (see Katz, 1973) to the east of the shallow marine and deltaic strata of the Fossil Bluff Series (Horne, 1967). The deformed graywacke-shale sequence regarded by Horne as Mesozoic is here considered to be Paleozoic (see Bell, 1973b; Grikurov, 1972).

The Jurassic strata on the Lassiter Coast were deformed into open to isoclinal folds with northeast-southwest axes and are locally overturned to the southeast (Williams and others, 1972). Axial plane cleavage is well developed. Further to the west in Ellsworth Land, the Jurassic beds are isoclinally folded about west-northwest axes, commonly have an axial plane cleavage, and are cut by numerous thrust faults (Laudon and others, 1969). Deformation predates or is in part synchronous (Williams and others, 1972) with plutonism. Plutons in Ellsworth Land are dated as mid-Cretaceous (Halpern, 1967).

Elsewhere the Jurassic and Cretaceous strata are, at most, gently folded except adjacent to major faults such as along the northwest part of James Ross Island where the Campanian beds are near vertical. Fold axes are generally parallel to the trend of the Peninsula.

Plutonic rocks constitute a major part of the Antarctic Peninsula and are also recorded on the South Shetlands. A post-Aptian gneissic igneous complex of uncertain origin apparently cuts the Cumberland Bay sequence on South Georgia (Trendall, 1959), but it has not been dated. Plutons probably occur in the submerged southern part of the South Orkney platform (Harrington, Barker, Griffiths, 1972). Elephant and Clarence Islands lack intrusions; however, the (?) Paleozoic metamorphic complex has yielded Late Cretaceous and Tertiary K-Ar dates (Dalziel, 1972a; Grikurov and others, 1970) which may be the result of updating by very young intrusions (Rex and Baker, 1973). Intrusions crop out in the South Shetlands and are very widespread on the Antarctic Peninsula where they range from gabbro to alkali-granite. The intrusions never reach batholithic proportions, but this is probably a function of the level of erosion. The intrusions cut the Trinity Peninsula Series, the Upper Jurassic volcanic strata, and the Jurassic sedimentary and volcanic sequences at the base of the Antarctic Peninsula. Radiometric dat-
ing (Adie, 1972; Fleet, 1968; Grikurov, Krylov, and Silin, 1966, 1967; Halpern, 1965, 1967; Rex, 1972; Scott, 1965) now indicates intrusion between Early Jurassic and Early Cenozoic, and five separate episodes of plutonic activity have been postulated (table 12). The plutonic rocks have been considered part of a normal calc-alkaline suite (Adie, 1955) in which intermediate compositions are most abundant. Block faulting, gentle folding, and tilting accompanied emplacement of the Andean plutons.

Late Mesozoic plutonic bodies are also widespread in Marie Byrd Land and the Eights Coast. Radiometric data have been compiled by Craddock (1972a), and additional data have been given by Halpern (1972) and Wade (1972). Dates fall between 166 and 88 m.y. with the majority in the ranges 88 to 115 and 130 to 150 m.y. Few of these are whole rock isochron dates. The plutons range from quartz diorite to granite, and their abundance in Marie Byrd Land suggests batholiths at shallow depth.

Summary.—Pre-orogenic depositional basins developed in South Georgia and eastern Ellsworth Land. That in South Georgia has been compared with a marginal basin developed between an island arc and the adjacent continental landmass (Dalziel, deWit, and Palmer, 1974), whereas that in eastern Ellsworth Land apparently developed in an intracratic environment a considerable distance from the continental margin. Abundant calc-alkaline volcanism in late Jurassic time, however, is suggestive of an Andean-type continental margin. This volcanism is, no doubt, related to the abundant plutonism that occurred episodically into mid-Cenozoic time. Although deformed strata are absent over most of the Antarctic Peninsula and West Antarctica, the large volumes of calc-alkaline magma suggest active subduction. Uplift associated with evolution of the plate boundary led to formation of sedimentary basins on either side of the rising cordillera and concomitant deposition of molasse sequences seen now principally in the James Ross Island area and Alexander Island. Intermittent uplift continued into the Cenozoic,

<table>
<thead>
<tr>
<th>Table 12</th>
<th>Mesozoic and Early Cenozoic intrusive episodes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Radiometric date (m.y.)</td>
</tr>
<tr>
<td>Early Tertiary</td>
<td>45-60</td>
</tr>
<tr>
<td>Late Cretaceous</td>
<td>70-75</td>
</tr>
<tr>
<td>Mid Cretaceous</td>
<td>90-110</td>
</tr>
<tr>
<td>Late Jurassic</td>
<td>130-140</td>
</tr>
<tr>
<td>Early to Mid Jurassic</td>
<td>160-180</td>
</tr>
</tbody>
</table>
but a new tectonic regime was established with the onset of Cenozoic basic volcanism.

CENOZOIC VOLCANIC PROVINCE

Volcanic rocks, dominantly basic, crop out extensively in Victoria Land, West Antarctica, and the Antarctic Peninsula (fig. 10), and the South Sandwich Islands (fig. 3). Isolated outcrops also occur in the central Transantarctic Mountains and on the East Antarctic coast at about 90°E (fig. 4). A variety of tectonic environments are indicated by the volcanic rocks. The landforms developed demonstrate the youth of many of these volcanic piles, but the onset of volcanicity is poorly dated. Active volcanoes or those recently active as shown by fumarolic activity are indicated on figure 10.

South Sandwich Islands.—These volcanic islands, which close off the Scotia Sea to the east, constitute an island arc lying west of an oceanic trench and above an active subduction zone for which earthquake hypocenter data indicate activity to a depth of about 200 km (Lander, 1973). Baker (1968, 1972) has drawn attention to the unusual character of this island arc in that basalts and their derivatives are the principal rock types. These rocks are high in alumina, mainly quartz normative, and many of them are comparable, in their very low potash content, to oceanic tholeiites. However, a transition to calc-alkaline volcanism is noted by Baker for some rocks. The oldest dated sample is 4.0 m.y., but the sea floor magnetic anomalies related to the spreading center in the eastern Scotia Sea (Barker, 1972a) suggest that volcanism may have begun at least 8 m.y. ago.

Antarctic Peninsula.—The James Ross Island volcanic group on the Weddell Sea side of the northern Antarctic Peninsula (Baker, González-Ferrán, and Vergara, 1973; Nelson, 1966) consists of at least five eruptive phases each consisting of palagonite breccias overlain by lavas (hawaiites, Baker, 1972). Chemically the analyzed samples plot in the field of alkalic basalts, but normatively they contain both olivine and hypersthene and therefore correspond to olivine tholeiites (Baker, 1972). K-Ar dates on the lavas range from 4.6 ± 0.4 to 1.4 ± 0.2 m.y. (Rex, 1972). Alkaline basic rocks of similar aspect form the Seal Nunataks to the south and are all dated at less than 1.0 m.y. (Rex, 1972).

The Cenozoic volcanic record on the northwestern side of the Peninsula is more extensive but less well known. Significant thicknesses of basalts assigned a Tertiary age crop out on Anvers Island (Hooper, 1962), but the principal described outcrops are in the South Shetland Islands (Barton, 1966; Hawkes, 1961a,b; Hobbs, 1968) where the only active volcanoes of this area are located. On King George Island (Barton, 1966; Hawkes, 1961a) four main sequences of lavas, pyroclastic rocks, and volcanioclastic sediments of Eocene to Miocene age (Barton, 1966; Orlando, 1964) have been recognized. The lavas have been described as calc-alkaline (González-Ferrán, 1972; Hawkes, 1961a), as a high-alumina basalt series (Katsui, 1972), and as mainly basaltic andesites of tholeiitic affinities although some are calc-alkaline andesites (Baker, 1972). The younger
volcanic rocks on the southeast side of the island include alkali olivine basalt, andesite (zhawaiite), and agglomerate and show a more alkaline trend (Baker, 1972). Deception Island and Bridgeman Island lie to the southeast but apparently along the fault zone (Griffiths and others, 1964) defining the southeastern margin of the South Shetlands. Deception Island is a composite volcano of lavas and pyroclastics ranging from olivine basalt to trachyte (Baker, Davies, and Roobal, 1969; Hawkes, 1961b; and others). Baker (1972) considers that these mildly undersaturated hypersthene-olivine normative lavas belong to the soda branch of the alkali basalt-trachyte trend, and that chemically they resemble the James Ross Island Volcanic Group.

The dating of most volcanic rocks regarded as Cenozoic is uncertain. Published radiometric data are confined to two Eocene and one Oligocene K-Ar date from islands just off the Antarctic Peninsula (Rex, 1972). In general, there is much more evidence of late Cenozoic volcanism on the South Shetland Islands than elsewhere. Block tectonics seem to control the more recent volcanic eruptions (González-Ferrán, 1972), particularly along the southeastern margin of the South Shetland Islands.

Alexander Island, Ellsworth Land, and West Antarctica.—The Cenozoic volcanic rocks in Marie Byrd Land have been divided by LeMasurier (1972) into a basal unit of subhorizontal flows and palagonitized tuffs and breccias, overlain by stratovolcanoes consisting of flows and pyroclastics, and finally small parasitic cones. The basal unit is entirely of alkali basalt composition and reaches flood basalt proportions. The flows attain several hundred meters in thickness, whereas the hyaloclastite breccias may be as much as 2000 m thick. The stratovolcanoes consist mainly of felsic flows and pyroclastics of alkaline composition and include anorthoclase trachyte, phonolite, and other rock types (González-Ferrán and González-Bonorino, 1972; LeMasurier, 1969). The parasitic cones are largely alkali basalt. Some olivine basalts contain numerous ultramafic nodules (González-Ferrán and Vergara, 1972). Volcanism may have begun as early as Eocene (LeMasurier, 1972), but most of the stratovolcanoes, because of their state of dissection, are probably late Cenozoic, and inactive fumaroles have been reported from Mt. Hampton (LeMasurier, 1969).

The different elevations of the volcanic erosion surface and alignment of the stratovolcanoes suggest a rectangular fault block system, which is considered analogous to the East African Rift System and to Iceland (LeMasurier, 1971).

Palagonite tuffs and breccias and olivine basalt flows crop out in the Hudson Mountains (Wade and LaPrade, 1969; Wade and Wilbanks, 1972), Jones Mountains (Craddock, Bastien, and Rutford, 1964) where the oldest flows are dated at 7 to 10 m.y. (Rutford and others, 1972), eastern Ellsworth Land (Laudon, 1972) where they are dated at 6 m.y. (Halpern, 1968), and southwestern Alexander Island (Bell, 1973a). Peter I Island is also a young volcanic center at least 13 m.y. old (Craddock,
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Table 10: Stratigraphy and geologic history of West Antarctica, Antarctic Peninsula, and part of the Scotia Arc.
and consists of rocks ranging from olivine basalt to trachyandesite (Craddock, Bastien, and Rutford, 1964).

East Antarctica.—Outside Victoria Land, a late Cenozoic cone, Gaussberg, at about 90°E consists of highly potassic leucite basalt dated at 20 and 9 m.y. (Craddock, 1972a). At the head of the Scott Glacier (fig. 10) olivine basalt lavas and pyroclastics form part of a dissected volcanic pile (Doumani and Minshew, 1965; Minshew, ms).

The McMurdo volcanic province, which includes Ross Island and areas to the west and southwest, consists largely of subaerial lavas and pyroclastics which form impressive stratovolcanoes, such as the still active Mt. Erebus (Giggenbach, Kyle, and Lyon, 1973), together with numerous parasitic cones (Treves, 1969, 1970; Cole and Ewart, 1968). The rocks range from olivine-pyroxene basalt to anorthoclase trachyte (Cole and Ewart, 1968; Treves and Stuckless, 1973). They are all strongly undersaturated with normative nepheline between 6 and 30 percent (Goldich and others, 1973). Small cinder cones of basalt are also widely distributed in Taylor and Wright Valleys, south Victoria Land. Volcanism was initiated at least 15 m.y. ago (Treves and Stuckless, 1973).

Further north, Nathan and Schulte (1967, 1968) have described an arcuate belt of late Cenozoic stratovolcanoes which includes Mount Ov- lording and the recently active Mount Melbourne. Alkali basalt, trachy- basalt, trachyandesite, phonolite, and trachyte have been described; however, the analyzed rocks are quartz normative despite the apparent alkaline mineralogy.

In the Hallett volcanic province (Hamilton, 1972) thicknesses as great as 2500 m of palagonite breccias and basaltic pillow breccias are overlain by subaerial flows and pyroclastics of trachytic and basaltic composition. Various alkali basalt and trachyte types, including anorthoclase trachytes, have been recognized, and both silica-enriched and silica-deficient differentiation trends noted.

Summary.—The South Sandwich Islands apparently represent the early stages in island arc development (Baker, 1968), and their tectonic situation is in marked contrast to that of volcanic rocks elsewhere in Antarctica.

A now inactive spreading center located in the Drake Passage has magnetic anomalies associated with it that are at least as old as 20 m.y.; it is possible that the Cenozoic volcanism predating the present alkaline trends in the South Shetland Islands is related to a former southeast-dipping subduction zone. The mildly alkaline volcanism, which continues to this day in the active volcano of Deception Island, is related to a regime of block tectonics and possible opening of a marginal basin in the Bransfield Strait (Davey, 1972). Strontium isotopic ratios indicate derivation of the Deception Island volcanics from the mantle (Faure, Shultz, and Carwile, 1971).

The alkaline basaltic volcanics in West Antarctica also have mantle strontium isotopic ratios (Jones and Walker, 1972), and again the tectonic environment has been one of vertical movements. Tectonism, up-
lift and/or subsidence, has been relatively active in late Cenozoic time (LeMasurier, 1971, 1973), and it would appear that West Antarctica is undergoing a period of rifting.

The McMurdo and Hallett volcanic provinces with the possibly correlative basaltic rocks from the Scott Glacier suggest strongly a connection with the Cenozoic uplift of the Transantarctic Mountains (Victoria Orogeny of Gunn and Warren, 1962); however, this is by no means proven. In addition, these major volcanic areas are close to the pronounced change in crustal thickness between East Antarctica (40 km) and the Ross Sea area (28 km).

TECTONIC EVOLUTION AND
RELATIONS BETWEEN EAST AND WEST ANTARCTICA

Despite the extensive ice cover, Antarctica can be divided broadly into the East Antarctic shield consisting of a Precambrian to Lower Paleozoic metamorphic complex and West Antarctica which is made up largely of Paleozoic and Mesozoic orogenic belts. Five orogenies which range from late Precambrian to late Mesozoic-early Cenozoic are documented in dispersed places from the Transantarctic Mountains through West Antarctica and the Antarctic Peninsula. Cenozoic volcanic provinces are located in the Scotia Arc, Antarctic Peninsula, West Antarctica, and Victoria Land, and in diverse tectonic settings. Many of the details of the relations between and within tectonic units, particularly older events in West Antarctica and the Borchgrevink and Gondwanian orogens, have not been resolved.

Tectonic interpretations of Antarctica with a "stabilist" philosophy in which West Antarctica and the Antarctic Peninsula are considered to be ancient Precambrian terrains modified by epeirogenic processes have been presented by Grikurov (1972), Grikurov, Ravich, and Soloviev (1972), and Grikurov and Lopatin (in press). Others (for example Craddock, 1972b, in press; Hamilton, 1967; Stump, 1973) have regarded the development of Antarctica in terms of lateral accretion of geosynclinal belts onto the ancient Precambrian shield, with perhaps one or more of the belts being in part epeirogenic. Plate tectonic interpretations have so far been applied mainly to the Antarctic Peninsula (Dalziel and Cortés, 1972; Dalziel and Elliot, 1973; Katz, 1973), and to West Antarctica by Katz (1973) and Stump (1973).

Paleomagnetic data do little to resolve the problem of former relations between East Antarctica and other parts of the continent. Paleopole positions are limited to the Cambrian, Ordovician, Jurassic, and Late Cenozoic for East Antarctica (Creer, 1970; McQueen and others, 1972), to the Cretaceous for Marie Byrd Land (Scharnberger and Scharon, 1972), and to the Cretaceous or Tertiary for the Antarctic Peninsula (Creer, 1970; Dalziel and others, 1973b). The Antarctic Peninsula paleopoles are all relatively close to the present pole position, but the interpretation is hampered by lack of radiometric dating. However, the data are not inconsistent with those that can be inferred for East Antarctica
from a consideration of sea-floor magnetic anomalies between Antarctica and Australia and paleopoles for Australia; these suggest a polar position for East Antarctica for the late Mesozoic and Cenozoic. The paleopoles from Marie Byrd Land are rather scattered and give a mean pole position at lat 36°S, long 116.3°E (southwest corner of Australia). This has been interpreted to show that Marie Byrd Land and New Zealand were located away from Antarctica and Australia in the Late Cretaceous and have since then drifted, as indicated by the South Pacific sea floor magnetic anomalies, into their present positions. Evidence of the closing of an ocean basin between Marie Byrd Land and the rest of Antarctica during the Cenozoic is lacking, and the alkaline volcanics of Marie Byrd Land imply an entirely different tectonic regime at least for the late Tertiary. Craddock (in press) also has suggested a marginal basin separating East and West Antarctica in Late Cretaceous time.

The swing in the trend of the Antarctic Peninsula has been related to oroclinal bending (Hamilton, 1966) but if it occurred it was probably pre-Late Cretaceous (Dalziel and others, 1973b). Similarly the very marked swing in structural trends in eastern Ellsworth Land may be the result of oroclinal bending in post-Jurassic time. Craddock (in press) regards this as possibly of Late Cretaceous age. Paleomagnetic data are lacking for the substantiation of these “oroclines”; Ford (1972b) has postulated a major transcurrent, possibly right lateral, fault along the south side of Ellsworth Land which might be associated with the (?) orocinal bending.

The East Antarctic shield consists mainly of granulite and amphibolite facies metamorphic rocks together with intrusions of wide compositional range but predominantly granitic. Charnockitic rocks of both igneous and metamorphic origin are widespread. Radiometric data, structural trends, and rock types suggest a complex history which has, no doubt, included several orogenies. As yet, the data are insufficient to delineate separate orogens.

The Beardmore Orogen is the earliest that can be separated on the basis of deformed and regionally metamorphosed strata intruded by granitic batholiths. A single depositional basin or a series of closely spaced basins occupied the Transantarctic Mountains and received their sediment fill from the East Antarctic craton. Basic volcanic rocks are interbedded in the graywacke-shale sequences only in the Pensacola Mountains and north Victoria Land, but there is some question as to the true age of these beds. In the central Transantarctic Mountains the graywacke-shale sequence is overlain by thick felsic volcanic strata, suggesting the basin was filled or uplifted contemporaneously with the onset of igneous activity. Outpourings of felsic volcanic rocks were perhaps accompanied by intrusion adjacent to the presently exposed areas, and subsequently in late Precambrian time deformation and batholith emplacement occurred. The deformation and calc-alkaline igneous rocks suggest subduction and a compressive plate margin. The orogen is delimited by Cambrian strata lying unconformably on the graywacke-
shale sequence. The inclusion in this orogen of the sequences in the Shackleton Range, Pensacola Mountains, and north Victoria Land is open to debate.

In early Cambrian time the Transantarctic Mountains became the site of an extensive carbonate platform developed on the eroded Beardmore Orogen. Shallow marine clastic sequences occur at either end of the mountain belt and in the central part where the carbonate sequence is thickest. There, the clastics overlie the carbonates and may reflect the early stages of uplift of the orogen. The shoreline is inferred to have been on the East Antarctic shield side, and carbonate platforms may have extended some distance across West Antarctica as suggested by the marble recovered from the Ross Sea (Hayes and others, 1973) and the shallow marine sequence in the Ellsworth Mountains. However, the earliest deformation recorded in the Ellsworth sequence is Early Mesozoic; therefore, the absence of Late Precambrian and Early Paleozoic deformation is indicative of a tectonic history different from that in the Transantarctic Mountains and most of West Antarctica and supports the concept that the Ellsworth rocks may not now be in the same position relative to East Antarctica as that occupied in Precambrian and Paleozoic time.

A possible lower Paleozoic graywacke-shale facies is represented in Marie Byrd Land (compare Craddock, 1972b, who regards it as possibly upper Paleozoic), although the true age and time of deformation remain uncertain. It is also possible that West Antarctica has been welded onto the East Antarctic shield, the suture being along the line of abrupt change in crustal thickness which parallels the Transantarctic Mountains (Smithson, 1972). Such a suture adjacent to the Transantarctic Mountains has been disputed by McGinnis (1973) who interprets the pronounced gravity gradient but smooth magnetic profile there in terms of changes in crustal rock types. However, the geographic separation of the rocks with Early Paleozoic dates in West Antarctica from the Transantarctic Mountains might be more easily explained by considering Marie Byrd Land a separate block welded on by plate convergence during the late Precambrian or early Paleozoic.

The Early Paleozoic Ross Orogeny is marked by widespread intrusions which reach batholithic proportions. Deformation and metamorphism are severe only in south Victoria Land where the rocks attain the amphibolite grade. Nowhere have high pressure metamorphic rocks or members of the ophiolite suite been recorded, nor have they been recorded yet from any other orogenic belt in Antarctica. Precambrian rocks in the Transantarctic Mountains and across much of the shield were affected by Early Paleozoic events. The orogen is bounded stratigraphically by flat-lying Devonian strata in the Transantarctic Mountains.

The Beardmore and Ross orogens might be regarded as a closely connected pair in which the areas of graywacke-shale deposition migrated away from the East Antarctic shield; the apparent locus of deformation,
metamorphism, and intrusion remained essentially the same, although the active margin of the plate had moved further away from the shield.

By mid-Paleozoic time the Ross Orogen had been planed down, and both shallow marine and nonmarine strata were deposited in the Transantarctic and Ellsworth Mountains, although only in the Ellsworths did marine strata accumulate to a significant thickness. Paleocurrent data and petrology of the Taylor Group of the Transantarctic Mountains indicate that a gneiss terrain was being eroded in the Ross Sea area. This was also a time of plutonic intrusion in north Victoria Land; deformation and low-grade metamorphism of the Robertson Bay and Bowers Groups is also regarded as mid-Paleozoic and belonging to the Borchgrevink Orogeny. The difference in style of deformation of the Robertson Bay and Bowers Groups might be a function of rock type, or alternatively they might record different periods of deformation; furthermore, the deformation might well predate the mid-Paleozoic. The structural trends in north Victoria Land line up with those of western Marie Byrd Land, but there also definitive data on the age and on the time of deformation of the pre-Cretaceous graywacke-shale sequence (tentatively discussed in this paper as part of the Ross Orogen) are lacking. What few data there are from the Ross Sea suggest basement structures trending meridionally and therefore divergent from those of the Borchgrevink Orogen, and that marble lithologically comparable with the Lower Paleozoic carbonates of south Victoria Land forms part of the basement. Nevertheless, a scattering of mid-Paleozoic dates from intrusive and metamorphic rocks suggests that north Victoria Land, West Antarctica, and the Antarctic Peninsula formed part of an active plate margin, though there was probably only a slow rate of plate closure.

The long interval of non-deposition and erosion recorded in the unconformity between the Taylor and Victoria Groups in the Transantarctic Mountains probably reflects uplift in north Victoria Land and West Antarctica following the Borchgrevink Orogeny. In the Ellsworth Mountains the marine tillites may have been deposited during the Carboniferous; the overlying Permian shallow marine strata brought to a close deposition which appears to have been continuous from Late Precambrian to Late Paleozoic time. Permian strata, predominantly non-marine floodplain deposits, in the Transantarctic Mountains fill elongate basins confined in West Antarctica by a geanticline whose uplift during the Gondwanian Orogeny is reflected in the pattern of sedimentation in the overlying Triassic strata (Elliot, in press). Along the Antarctic Peninsula thick graywacke-shale and volcanic sequences of Carboniferous to (?) Permian age accumulated on the Pacific margin of the continent.

The Lower Mesozoic structural trends in the Ellsworth Mountains are terminated abruptly to the north by the Andean Orogen within which late Paleozoic and early Mesozoic intrusions occur. The significance of the rather scattered K-Ar and Rb-Sr radiometric dates for this and other orogenies is uncertain, because they record closing of isotopic systems, not necessarily time of intrusion or metamorphism. The struc-
tural trends in the Ellsworth Mountains apparently swing eastward toward the southern end of the range. Craddock (1972b) and Ford (1972b) postulate that the trends swing round to join those in the Pensacola Mountains, and they regard the Ellsworths as autochthonous with respect to East Antarctica. However, it is difficult to reconcile the structural trends of the various parts of the Gondwanian Orogen with their present geographic distribution with one orogeny. The Lower Mesozoic structural trends together with the absence of Late Precambrian and Paleozoic deformation of the Ellsworth Mountains sequence has led to suggestions that the Ellsworth block, which is outlined by the subglacial morphology, has been moved and rotated from its original position in Gondwanaland (Elliot, 1972; Frakes and Crowell, 1968; Hamilton, 1967; Schopf, 1969). If the Ellsworths have moved, the most likely original position would have been along the east side of the Weddell Sea, but there is little evidence to either support or deny this. Craddock (in press) regards the discordant trends in the Ellsworth Mountains as related to late Cretaceous movements between East and West Antarctica.

The Gondwanian Orogeny is perhaps crucial in the understanding of the Pacific margin of Gondwanaland because it is the youngest event predating Mesozoic fragmentation (Barrett, Grindley, and Webb, 1972; Dalziel and Elliot, 1971, 1973; Elliot, in press; Halpern, 1968; Katz, 1973; and others). The geology of the Antarctic Peninsula and islands of the Scotia Sea suggests that a cordillera linked South America to Antarctica (Dalziel and Elliot, 1971, 1973), and such a reconstruction requires relative movement of parts of West Antarctica. The relations of the Antarctic Peninsula to the East Antarctic shield are far from clear, and this is compounded by uncertainties about how to reassemble the Scotia Sea-Weddell Sea area in Gondwanaland. Many reconstructions leave this area open with obvious misfits and gaps, whereas Ford (1972b) filled this area with the southern part of South America, regarding the tectonic features of the Peninsula as more closely aligned with those of South America in such a reconstruction. Regardless of the particular reconstruction favored, a large source area is required for the late Paleozoic nonvolcanic graywacke sequences of the Antarctic Peninsula and South Orkney Islands. Furthermore, deformation in the Ellsworth and Pensacola Mountains occurred within the Antarctic continent and not along its Early Mesozoic margin.

The Gondwanian Orogeny is delimited stratigraphically by the unconformable relations between Jurassic strata and the Trinity Peninsula Series at Hope Bay. The very extensive calc-alkaline volcanicity of the Antarctic Peninsula during the late Jurassic may be a post-orogenic phase related to subduction of the Andean type. Similarly, one or more of the Jurassic intrusive episodes may be related to the Gondwanian Orogeny and not the “Andean” Orogeny. Furthermore, the apparent contrast in composition of the Jurassic volcanics of the northern Antarctic Peninsula should perhaps be viewed in terms of an andesitic
volcanic chain to the west and to the east a back arc volcano-tectonic rift erupting silicic tuffs and ash-flow tuffs.

The Gondwanian Orogeny is delimited in the Pensacola Mountains by the cross-cutting gabbroic Dufek Massif of Jurassic age (Ford, 1972a). The very widespread Jurassic tholeiites (Ferrar Group) of the Transantarctic Mountains are correlative, if not comagmatic, with the Dufek Massif and together with the Tasmanian dolerites form a unique geochemical province defined by initial Sr\textsuperscript{87}/Sr\textsuperscript{86} ratios similar to crustal rocks (0.710-0.714) (Faure and others, 1972; Heier, Compston, and McDougall, 1965). The Mesozoic tholeiites of Gondwanaland have been related to rifting preceding the drifting apart of the now separate continents. A rift environment is likely for the Ferrar Goup, but although strike slip movement (possibly transform faulting, Elliot, 1972) is possible, there is no evidence of drifting; on the contrary, the occurrence of Jurassic granitic intrusions in West Antarctic and the Antarctic Peninsula suggest active or recently active subduction and compression along that margin or, which is more likely, a period of intrusion following subduction and compression. A possible explanation is that the Jurassic basalts were generated in a zone of extension and rifting on the continental side of the Gondwanian Orogen, perhaps somewhat analogous to the tectonic setting of the Columbia River Basalts or, in oceanic environments, to back-arc spreading which forms a marginal basin (Karig, 1971). The initial rifting prior to opening of the Weddell Sea may have occurred at this time.

The Andean Orogen in the Antarctic Peninsula and West Antarctic has been discussed in detail by Dalziel and Elliot (1973), Katz (1973), and others. It is characterized by widespread plutonism, but crustal shortening is confined to South Georgia and to the Jurassic sequences of eastern Ellsworth Land and the Lassiter Coast. In both areas regional yielding was away from the Pacific (toward the northeast in South Georgia and southeast at the base of the Antarctic Peninsula). Lack of data on sea floor magnetic anomalies from the southeastern Pacific renders interpretation in terms of plate tectonics uncertain. However, recent results of the Deep Sea Drilling Project (Hollister and others, 1974) suggest that the ocean floor is likely to be late Mesozoic and Cenozoic. This is consistent with the abundant late Mesozoic to early Cenozoic calc-alkaline plutonism which also suggests subduction that persisted into the Cenozoic in at least the northern Antarctic Peninsula.

Upper crustal tectonism is recorded as high angle faulting throughout the late Mesozoic and Cenozoic, during which time several episodes of plutonism occurred. The late Cretaceous and early Tertiary episodes are recorded only in the Antarctic Peninsula. Uplift of the Andean orogen was accompanied by deposition of molasse-type sequences of Jurassic-Cretaceous age in Alexander Island and Cretaceous-early Tertiary age in the northern Antarctic Peninsula, possibly related, respectively, to late Jurassic and mid-Cretaceous episodes of plutonism.
Other late Mesozoic and Tertiary basins are, no doubt, located on the continental shelves around Antarctica. Seismic and drill core data from the Ross Sea (Hayes and others, 1973; Houtz and Davey, 1973) indicate at least two Tertiary basins that may extend south beneath the Ross Ice Shelf. These basins are at least Early Tertiary, as shown by erratics of fossiliferous marine sediment recovered in the Ross Island area (Harrington, 1969; Hertlein, 1969) and may extend back into the late Cretaceous. Similar basins may be present in the Weddell Sea sector. The sedimentary fill for these basins was probably derived from the uplift of both the Andean Orogen and the Transantarctic Mountains (Victoria Orogeny of Gunn and Warren, 1962).

Seismic profiles across West Antarctica also establish the presence of stratified rocks up to 3 km thick forming the upper part of the crust in the Byrd Subglacial Basin (Bentley and Clough, 1972). Identification and correlation with exposed bedrock geology are uncertain, although the low velocity seismic layers are consistent with Cenozoic sediments and, possibly, interbedded sediments and volcanics.

The Cenozoic has been marked by the development of the Scotia Sea (Barker and Griffiths, 1972; Dalziel and Elliot, 1971, 1973), which is continuing today in the active island arc of the South Sandwich Islands. Elsewhere the Cenozoic is characterized by predominantly vertical tectonics accompanied by basaltic volcanism. Along the western side of the Ross Sea and in West Antarctica the volcanics are mainly alkaline basalts and trachytes; those in Marie Byrd Land have been compared with rift systems such as Iceland and East Africa. In the northern Antarctic Peninsula the Tertiary volcanics have tholeiitic affinities with possibly calc-alkaline trends also present. In part these may be related to the now inactive spreading center in the Drake Passage. Younger volcanic rocks are sub-alkaline and related on the northwestern side of the Peninsula to the rifting associated with the opening of the Bransfield Strait (Davey, 1972), a possible marginal basin.

The Tertiary basins have already been discussed with the Andean Orogeny. They probably contain the record of climatic cooling in the Early Cenozoic and in the Ross Sea have demonstrated the antiquity of glaciation in Antarctica (Hayes and others, 1973).

Further advances in understanding the tectonic relations between the Antarctic Peninsula, West Antarctica, and the East Antarctic shield will come with more definitive dating of the igneous and metamorphic rocks of West Antarctica, paleomagnetic studies, more refined data on the deep crustal structure of West Antarctica, and data on the age and evolution of the Weddell Sea.

If deformation of thick graywacke-shale sequences and calc-alkaline igneous activity can be interpreted as geologic evidence of former subduction zones and compressive plate margins, then there is reasonably good evidence of four if not five major episodes of plate convergence on the Pacific side of Antarctica, with an overall progressive lateral accretion away from the shield. No ophiolite suites have yet been identi-
fied, nor is there evidence of paired metamorphic belts, and therefore actualistic models are difficult to substantiate and plate tectonic interpretations are still very much open to debate.

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