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The geology of Antarctica: a review

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Geological field work in Antarctica and the off-lying islands during the past two decades has contributed materially to the establishment of the stratigraphical succession in both East and West Antarctica. The tectonic evolution of Antarctica is discussed in relation to the known stratigraphical and structural data for the continent, and the rôle of Antarctica in several reconstructions of the former supercontinent of Gondwanaland critically examined. In this context, various aspects of the palaeogeography, palaeoclimatology, geochronology and stratigraphy of Antarctica is reviewed.

During the past two decades, field work in both East and West Antarctica has contributed materially to the understanding of the stratigraphy and structure of this continent. Since the International Geophysical Year, 1957–8, there has been a rapid accumulation of detailed geological information, and an even greater increase in the diversity of correlations and interpretations of existing data.

Has this resulted directly from the pure thirst for basic geological knowledge of the continent that was virtually unknown at the turn of the century? Is this because Antarctica has featured so prominently in reconstructions of the former supercontinent of Gondwanaland? Or, is it because this continent and its surrounding oceans are still a relatively unknown sphere to which current earth theories can be applied with a view to understanding the global setting of tectonics?

In the early years of the twentieth century the geology of Antarctica was almost synonymous with the stratigraphical term 'Beacon Sandstone' and the current view at that time was that a major rift extending from the Ross Sea to the Weddell Sea separated East from West Antarctica. Today, however, the geological scene is dominated by detailed comparisons between the various aspects of the geology of Antarctica and those of the other Southern Hemisphere continents, and thought is centred on the use of terms such as 'plate tectonics', 'sea-floor spreading', 'fracture zones' and 'subduction'.

Irrespective of the technological advances in the exploration of Antarctica, due credit must be given to the field observations of the early geologists who laboured under immense difficulties, often manhauling, in a hostile environment to achieve their objectives. Today there are the distinct advantages of rapid transport into the field by aircraft, helicopters and motor toboggans, with the aid of sophisticated logistic support. Geological parties can now be placed in the field within hours to investigate specific problems; they can easily be moved from one area to another and even be withdrawn to civilization at the slightest whim!

Much of the early field observation in Antarctica is as valid today as it was at that time; only the interpretation has been modified in the light of current theories. In particular, the field geology of the Swedish South Polar Expedition, 1901–3, and the British Antarctic Expedition, 1910–13, has stood the test of time. The field observations of the great Antarctic geologists, David, Mawson, Griffith Taylor, Priestley, Debenham, Nordenskjöld, Andersson and Bodman have never been bettered; and, if the work of today's Antarctic geologists can withstand the test of another half century, they will have succeeded in their contribution to knowledge.

Geologists of many nationalities have mapped and investigated various problems in different parts of Antarctica – in the Transantarctic Mountains, the coastal outcrops of East Antarctica, in the interior of Dronning Maud Land, the Antarctic Peninsula and Marie Byrd Land. In the last 20 years this work has been substantially supported by national governments and encouraged by the Scientific Committee on Antarctic Research (Adie 1964, 1972*a*), which has played an active coordinating rôle and influenced the investigation of many diverse problems.

Stratigraphy

Reconnaissance geological mapping, strengthened by detailed mapping in key areas, has been responsible for the establishment of satisfactory stratigraphical columns for both East and West Antarctica (tables 1 and 2). The spatial distribution of the stratigraphical units identified in these regions has been compiled by Craddock (1970*b*) into a small-scale geological map of Antarctica.

Table 1. Generalized stratigraphy of East Antarctica

		(Glaciation)	
Cenozoic		McMurdo Volcanics	
Jurassic		Ferrar Group	
Jurassic–Carboniferous	Beacon Supergroup	Victoria Group	
Devonian	Beacon Supergroup	Taylor Group	
[Carboniferous–Devonian]		[Admiralty Intrusives (350 Ma)]	
		Kukri Peneplain	
Ordovician–Cambrian		Granite Harbour Intrusives	Ross orogeny (475–500 Ma)
		~~	
Cambrian	Ross Supergroup	Robertson Bay Group Byrd Group Koettlitz Group Skelton Group	
	Ross Supergroup	~~~~~	
Upper Precambrian	Ross Supergroup	Beardmore Group	
		~~	Nimrod orogeny (630–1000 Ma)
Precambrian		Nimrod Group (1000 Ma) Wilson Group	

From both the stratigraphical and structural data there is a sharp contrast between East and West Antarctica, the former having been referred to as the Gondwana Province and the latter as the Andean Province (Adie 1962). East Antarctica, the true continental shield region, comprises a Precambrian metamorphic and crystalline basement (the oldest rocks have been dated at 3000 Ma) which has suffered a number of fold phases, the latest identifiable Precambrian one being the Nimrod orogeny (630–1000 Ma). The younger rocks of the Upper Precambrian–Cambrian Ross Supergroup were also folded during the Ross orogeny (475–500 Ma) and in many localities intruded by the synorogenic Granite Harbour Intrusives. Throughout the Transantarctic Mountains and elsewhere these older rocks are bevelled by the Kukri Peneplain, and the later almost horizontal Devonian–Jurassic Beacon Supergroup sediments rest on this erosional surface.

There is a long stratigraphical hiatus between the eruption of the Jurassic Ferrar Group volcanic rocks and the Cenozoic McMurdo Volcanics (Adie 1965). Had there been any degree of sedimentation during this period, there is now little evidence of its former existence on land.

Table 2. Generalized stratigraphy of the Antarctic Peninsula

Pleistocene	(Glaciation)	
Pliocene	Pecten conglomerate	
Upper Miocene	camptonite dykes (15 Ma) o Alexander Island	
Upper–Middle Miocene	James Ross Island Volcanic Group (+dyke swarms)	
Late Miocene	Seymour Island Series	Andean Intrusive Suite (45–70 Ma)
Upper Cretaceous	Snow Hill Island Series Cape Longing Series	
Middle Cretaceous		acid–basic intrusions (90–110 Ma)
Lower Cretaceous–Upper Jurassic	Fossil Bluff Formation of Alexander Island	
Upper Jurassic	andesite–rhyolite volcanic group	acid intrusions (130–140 Ma)
Middle Jurassic	Mount Flora plant beds Church Point plant beds basal conglomerate	
Middle–Lower Jurassic		acid intrusions (160–180 Ma)
Post-Carboniferous	volcanic rocks	
(?) Carboniferous	Trinity Peninsula Series	
Devonian		granitic intrusions (370 Ma)
Early Palaeozoic	volcanic rocks	
(?) Early Palaeozoic or late Precambrian	metamorphic complex	

In contrast, West Antarctica bears all the characteristic features of the South American Andes. Nowhere have rocks of the true metamorphic basement complex (similar to the one in east Antarctica) been found though a 'metamorphic complex' of possible early Palaeozoic age is known in Palmer Land. Although the Antarctic Peninsula now occupies the position of a late Palaeozoic geosyncline, its evolution has been one primarily of volcanism and plutonism. The folded (?) Carboniferous Trinity Peninsula Series greywacke-facies sediments fringe the northern part of the Antarctic Peninsula, are present along the east coast and in central Alexander Island, and also occur in Marie Byrd Land. At least four phases of volcanism have been identified in the Antarctic Peninsula (Adie 1972*b*), the most important and widespread being the Upper Jurassic andesite–rhyolite volcanic group (table 2). Perhaps the most important aspect of the evolution of the Antarctic Peninsula is plutonic intrusion. Five main phases have been radiometrically dated by Rex (1972), the youngest and most widespread being the late Cretaceous–early Tertiary Andean Intrusive Suite (Adie 1955).

Many stratigraphical features analogous to those described above have also been recorded from Marie Byrd Land but perhaps the most striking one is the huge Cenozoic volcanic province which occupies the area of the Executive Committee Range. Not only is there a series of freshly exposed lava and ash cones but there is also considerable evidence that subglacial eruption occurred in many places. A probable extension of this late volcanism has been observed on the western extremity of Alexander Island, and it could be related to similar activity in the South Shetland Islands.

The Ellsworth Mountains, which are located in an intermediate position between the Transantarctic Mountains and Marie Byrd Land, are anomalous in the overall structural scheme. Stratigraphically, these mountains are allied to the general scheme for East Antarctica but their structural trend is almost east–west and almost normal to the structural trends in both East and West Antarctica. Their true tectonic place has not yet been fully resolved but Craddock (1970*c*) has suggested that they belong to the Ellsworth orogen which also encompasses the Whitmore and Pensacola Mountains areas.

Recent volcanism of sharply contrasting chemistry has occurred at only two localities on the continent: at Ross Island in East Antarctica and at Deception Island in the South Shetland Islands, the former being potassic and the latter richly sodic.

Structure and tectonics

There is a marked structural contrast between East and West Antarctica, but it is clear that there is some degree of structural parallelism with the western margin of the continental shield of East Antarctica defined by the Transantarctic Mountains. In the coastal regions of East Antarctica the structural grain defined by fold-axis trends is difficult to interpret with any degree of certainty because it has been undoubtedly disrupted by large-scale block faulting. The widespread reconnaissance surveys by the Russians have clearly demonstrated this conclusion. Furthermore, their deep seismic shooting in the hinterland mountains of Dronning Maud Land has proved major horst and graben structures governed by meridional faults with vertical throws in the order of 10 km. In one locality virtually undeformed and unmetamorphosed Precambrian sediments have been mapped in one of the upthrown blocks.

In Coats Land, at the northwesterly extension of the Transantarctic Mountains, the Shackleton Range and Theron Mountains are horsts defined by major east–west fault systems. Likewise, in Victoria Land, block faulting with east–west bounding faults is an important feature superimposed on the fold systems of the Nimrod and Ross orogenies.

The early work in Victoria Land indicated that the geology of this well-exposed part of the continent was dominated by a basement of Precambrian rocks capped by the almost horizontal Beacon Supergroup sediments which were intruded by thick Ferrar dolerite sills. The distribution of these rocks also implied there had been major faulting parallel to the coast and less important transverse faulting (frequently occupying the glaciers). This led to the concept of the great 'Antarctic Horst' and the 'Inland Plateau', a horst and graben system that supposedly

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dominated the structure of East Antarctica, and the corollary of the Weddell Sea–Ross Sea graben separating East and West Antarctica. Geophysical work by the Americans in Marie Byrd Land has now demonstrated conclusively that such a graben feature does not exist but that an apparent erosional feature of considerable sub-sea-level depth extends from the head of the Ross Ice Shelf westward to the vicinity of the Amundsen Sea, and separates much of Marie Byrd Land as a major island archipelago from continental Antarctica.

The arcuate geographical configuration of the Antarctic Peninsula is undoubtedly related to the major Triassic folding which was responsible for the southwest to northeast trending fold axes in the Trinity Peninsula Series sediments. A similar fold episode apparently affected the metasediments of the Ford Ranges in Marie Byrd Land. However, in the northeast Antarctic Peninsula and in Alexander Island, a possibly end Tertiary folding with almost north–south axial trends has deformed the Cretaceous sediments, adding complexity to the overall structural interpretation. There is little doubt that major block faulting, perhaps also in the late Tertiary, has in part been responsible for the present-day topography of the Antarctic Peninsula. The accumulated evidence for such vertical movements is overwhelming and comparable to similar tectonism in the South American Andes. In this context, the origins of the Antarctic Peninsula plateau and George VI Sound still need to be resolved.

In his proposed tectonic scheme for the whole of Antarctica, Craddock (1972*c*) has drawn on the field observations of many geologists and he has attempted a logical interpretation, often with limited data. He has defined *four* main orogens abutting the East Antarctic shield and decreasing in relative age towards the Western Hemisphere. The oldest and perhaps the most important one is the Ross orogen which embraces the zone deformed mainly by the Ross orogeny and follows the Transantarctic Mountains. Of subsidiary importance are the Borchgrevink and Ellsworth orogens, which could be open to question and further research. Much of West Antarctica, including the Antarctic Peninsula and western Marie Byrd Land, is included in the Andean orogen.

An alternative but more complex approach to the tectonics of Antarctica has been proposed by Grikurov, Ravich & Soloviev (1972) and their resultant scheme was based primarily on broader historical–geological principles. The respective merits of these schemes clearly depend on the use to which the interpretations will ultimately be put, but perhaps it should be borne in mind that inevitably each and every investigator will achieve his own scheme depending on the weight placed on the available evidence.

In most tectonic interpretations for Antarctica great emphasis has been placed on fold episodes and it seems that relatively little attention has been paid to the rôle of large-scale faulting. Evidence for this is largely obscured by the cover of the Antarctic ice sheet and geophysical techniques will ultimately have to be resorted to for positive proof. Nevertheless, there is a consensus of opinion that the rôle of both vertical or block faulting and tear faulting, with dislocations of some hundreds of kilometres, has been under-rated in the interpretation of Antarctic tectonics. Major fracture zones and sea-floor spreading centres can be readily detected by geophysical techniques in the oceans surrounding Antarctica, but these do not satisfactorily explain the tectonic relationship between East and West Antarctica, the apparently anomalous structural setting of the Ellsworth Mountains, the very existence of the higher Transantarctic Mountains or the opening of the Weddell Sea. Is it therefore not a tenable hypothesis that a major tear fault separates East from West Antarctica and that the Ellsworth Mountains are a rotated sliver of crust torn from East Antarctica during this major dislocation?

In a more detailed way, Grikurov (1972) has examined the tectonics of the Antarctandes region (the Andean orogen of Craddock (1970*c*)), concluding that there are *four* clearly identifiable structural complexes; these still need to be reconciled with the scheme proposed by Craddock.

Geochronology

Radiometric dating (mainly by whole-rock and mineral K-Ar and Rb-Sr methods) has contributed largely to the unravelling of stratigraphical and tectonic problems of Antarctica. Although much still remains to be done in this field, the early synthesis of results by Ravich & Krylov (1964) and the more recent ones by Craddock (1970*a*) and Krylov (1972) have highlighted the importance of radiometric dating, its application to the solution of various geological problems and the major voids in coverage.

Krylov (1972) has identified *thirteen* age groups which apparently coincide with tectono-magmatic events in Antarctica: 3000, 2000–1700, 1600–1500, 1200–1000, 900–800, 700–600, 570–440, 380–360, 260–220, 200–160, 120–90, 55–30 and 10–0 Ma. He commented initially on the methods used to achieve these results, their degrees of accuracy and overall validity. Moreover, he has attempted to place these events in a global context, discussing certain aspects that require additional field research.

In the Antarctic Peninsula, Rex (1972) has dated a number of samples by K-Ar and Rb-Sr methods with a view to establishing an absolute chronology for the stratigraphical column already worked out on the basis of field relations. His main contribution is the recognition of *five* major intrusive phases (table 1) which were of prime importance in the building of the Antarctic Peninsula.

Palaeogeography and palaeoclimate

From the stratigraphical record of East Antarctica, especially the Transantarctic Mountains where the most complete succession is present, it is clear that there have been major changes in past climates. As in the other Southern Hemisphere continents, the major refrigeration during the Permo-Carboniferous is represented by the widespread occurrence of terrestrial tillites. At one stage during this period, Antarctica occupied a central position over the South Pole while Gondwanaland underwent continental glaciation over a fairly long period of time (Adie 1975) and most of the glacial debris was deposited *in situ*. However, some of the detritus must have been transported towards the continental margins to be deposited in the marine environment of the adjacent seas. Is it not feasible that some of the pebbly mudstones which are common in the Trinity Peninsula Series of the Antarctic Peninsula are the marine equivalents of these glacial strata in the same way that there are both terrestrial and marine phases of the Dwyka Tillite in South Africa?

With the passage of time, the climate ameliorated and in the Permian, with the appearance of the *Glossopteris* flora, coals were widely deposited in terrestrial basins under cold humid conditions. But by the end of the Triassic, desert conditions had entirely replaced the cool-temperate climate and this is borne out by the typical lithologies and the associated fauna. Labyrinthodonts and other tetrapods (such as *Lystrosaurus*), the remains of which have only recently been discovered in the Transantarctic Mountains, heralded the onset of desiccation. This was indeed a short-lived phase which was terminated by widespread volcanism in Lower Jurassic times.

The late Mesozoic and Tertiary witnessed a gradual climatic deterioration and there is evidence that the first local ice caps began to form in the higher-relief areas of Antarctica about 15 Ma ago. Amalgamation of these, associated with severe cooling and increased precipitation, led to the present-day Antarctic ice sheet, which probably reached its maximum extent during the mid-Pleistocene.

Antarctica and Gondwanaland

In the earliest hypotheses of continental drift involving the fragmentation and disruption of Gondwanaland, Antarctica played a subdued rôle simply because of the lack of data. Early reconstructions of Gondwanaland, such as those of Du Toit and King, depended solely on stratigraphical correlations, sedimentological comparisons and the matching of fold systems. In more recent years, mainly due to the active interest of the geophysicists, more sophisticated techniques have been applied to solving these problems. The computer matching of continental shelf margins, together with more detailed tectonic, structural, stratigraphical, petrological, geochemical and palaeomagnetic approaches, has been applied with varying degrees of success depending on whether the 500 or 1000 fathom (915 or 1830 m) isobath was used in the reconstruction.

The work of Smith & Hallam (1970) and Craddock (1970*d*) provided useful working models but these have raised numerous problems which have been critically examined by later authors. Perhaps the detailed analysis and reconstruction by Dietz, Holden & Sproll (1972) is the most satisfactory to date because they have examined this problem from the standpoint of Antarctica being the centre piece of the jig-saw and the individual relationships of the other continents to Antarctica. Even so, they have been quick to point out anomalous overlaps and divergences of continental shelf margins, the difficulty of placing large fragments of submerged (?) continental crust in any reconstruction and most important of all the relative position of the Antarctic Peninsula. They have pointed out the need for better bathymetric maps of the coastal regions of the southern continents to define accurately the continental margins, and the fact that palaeomagnetic studies may prove invaluable in untangling the tectonic rotation of the Antarctic Peninsula in relation to the opening of the Weddell Sea (Barker & Griffiths 1977).

There can be no doubt that recent important geological discoveries in Antarctica such as the widespread extent of the Permo-Carboniferous tillites, the Permian coal deposits and the associated *Glossopteris* flora, and the Triassic tetrapods in the Transantarctic Mountains have added crucial evidence towards the solution of this fascinating problem of continental drift and plate tectonics, but it is clear that much still remains to be done in the vast unexplored expanses of Antarctica.

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