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Antarctica, a Key to the Understanding of the Evolution of Gondwanaland

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Phil. Trans. R. Soc. Lond. B 1977 **279**, 197-205
doi: 10.1098/rstb.1977.0082

Phil. Trans. R. Soc. Lond. B. **279**, 197–205 (1977) [197]
Printed in Great Britain

Antarctica, a key to the understanding of the evolution of Gondwanaland

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The geological structure of Antarctica, regarded by du Toit as the keystone to Gondwanaland, is known to reflect earlier features, some dating from Precambrian times. Improved knowledge of the evolution of Antarctica has contributed to an understanding of the history of Gondwanaland as a whole, and to the still wider question of the development of continental crust generally over the last 600 million years.

Introduction

Alexander du Toit, the great explorer of the geological past of the Southern Hemisphere, once described Antarctica as the key piece of Gondwanaland, recognizing as he did that three continents had broken away from Antarctica as new oceans opened around it. Today, the break-up of Gondwanaland is generally accepted as an established fact, and many of the steps by which it took place have been identified and dated. Increasing geological knowledge of Antarctica has played a critical rôle in these advances; in particular because of its geological position, Antarctica has provided a means of correlating events throughout Gondwanaland as a whole and of deducing possible relations between geological developments in the super-continent and in the Pacific.

In this paper I concentrate on two groups of related phenomena; changes which preceded the disruption of Gondwanaland, many of which influenced the way in which the break-up developed, and the contrast between events which have occurred since late Precambrian times in the interior and those which took place in the marginal parts of the supercontinent. Two conclusions seem to emerge. Firstly, that continental break-up and sea floor spreading within the supercontinent were preceded by other types of large-scale change which perhaps formed an essential preliminary to the dispersion of fragments of Gondwanaland. Secondly, that the Pacific seaboard of Gondwanaland behaved differently from the interior. These contrasts in tectonic behaviour were expressed in one form or another over a long period of time extending from the late Precambrian to the present day – that is to say for some 700 or 800 million years or about one sixth of the geological life of the Earth.

Late Precambrian and early Palaeozoic developments

Late Precambrian deposits in eastern Australia and in South America include thick sequences which in some districts pass upwards into Lower Palaeozoic successions. Comparable rocks are known in western Antarctica (Hamilton 1967; Grindley & McDougall 1969; Craddock 1972; Stump 1973), and in the largely submerged continental block of which New Zealand forms part (Fleming 1970; Adams 1975). Originally these deposits must have formed a more or less continuous belt along the Pacific margins of Gondwanaland. The deposits which in many regions can be shown to lie on still older continental crust (Laird, Manserch & Chappell 1971) contain shallow water members which suggest accumulation as the rim of the supercontinent was depressed below sea level. The complex of basins must have been many hundreds of kilometres in width and received sediments for long periods of time. In the Adelaide geosyncline for example, successions of predominantly shallow water deposits accumulated in gently subsiding belt at intervals between 1400 and 550 million years ago (Sprigg 1967). This belt which extends along strike for 1100 km through southeastern Australia is cut off by the southern coastline and is generally accepted as continuing in Antarctica within the Ross fold belt from northern Victoria Land to the Weddell Sea, where thick sedimentary and volcanic successions extending as far back as 1025 million years (Grindley & McDougall 1969) are preserved. Lower Palaeozoic rocks are present in places separated by clear unconformities from older rocks.

These predominantly marine deposits are flanked by thinner platform deposits which extend into eastern Antarctica. Upper Precambrian and Cambrian sediments have been reported for example from the George V and the Knox Coasts and from Dronning Maud Land (Craddock 1972). The deposits of the first two regions which once lay close to the present south Australian coast can be compared with the cover of similar age preserved in Australia west of the Adelaide geosyncline.

The development of the depressions in which thick successions were to accumulate on older crystalline basement, marked out for the first time a region in which repeated deformation was to take place during the Phanerozoic. Even though the inner margins of the late Precambrian troughs lie as much as 1000 km from the Pacific, taken as a whole, these structures extending through eastern Australia, New Zealand, western Antarctica and South America can be regarded as a marginal feature of Gondwanaland characterizing the peripheral parts of the supercontinent.

From Queensland to Venezuela the Precambrian structures were followed by a succession of Phanerozoic troughs and fold belts which developed either directly above older structures or were displaced to one side. Usually, but not always, the younger basins are the closer to the the Pacific.

In Antarctica marine sediments accumulated to the west of the Ross Orogen repeatedly during the Phanerozoic, marine Lower Palaeozoic and Permo-Carboniferous deposits being particularly important (Adie 1972; Craddock 1972). Successive periods of Phanerozoic folding have been recognized. In contrast, as is well known, any deposits laid down during the Phanerozoic in eastern Antarctica were mainly continental in character. These largely escaped folding, though faulting was of considerable importance, often determining the location of sediment-filled troughs within the craton. Grindley & McDougall have summarized the tectonics of East Antarctica since the last period of high grade metamorphism (*ca.* 1000 Ma) in the following words. 'Rejuvenations have occurred subsequently with fault movements producing mylonite zones, intrusions of stocks of granite and syenite, and deposition of continental sediments with volcanic rocks in the tectonic basins and grabens. The most intense rejuvenation undoubtedly took place during the same period (450–520 m.y.) as the Ross Orogeny in the Transantarctic mountains as shown by the predominance of radiometric dates in this time interval around the periphery of East Antarctica. There appears no need to postulate a peripheral geosyncline to explain these Paleozoic dates. Rejuvenation by block and wrench? faulting accompanied by early Paleozoic plutonic activity and tectonic uplift would appear adequate to account for the concentration of radiometric dates in the 400–500 m.y. interval' (Grindley & McDougall 1969, pp. 398–399).

In this passage discussing the tectonics of eastern Antarctica Grindley & McDougall bring out very clearly features which are typical not only of East Antarctica, but of many other parts of the interior of Gondwanaland.

One of the major achievements of the geological investigation of Antarctica has been the demonstration of the contrast between such tectonic changes in the interior (the craton of East Antarctica), and the extensive deformation within the Ross and younger orogenic belts close to the Pacific. In many ways this contrast is more clearly indicated in Antarctica than in other parts of Gondwanaland facing the Pacific. Moreover it has a still wider implication. In one direction early Palaeozoic changes were presumably related to contemporary movements of the Pacific floor relative to the continental block of Antarctica, and in the other as the geological resemblances between eastern Antarctica and southern Africa suggest, were connected with a widespread fracturing of the interior of the supercontinent. The structures thus provide an opportunity to link the pre-break-up deformation of Gondwanaland with movement of the surrounding ocean floor. This problem, one of the most fascinating in geology, is far from complete solution.

As Kennedy (1965) first emphasized, a network of Pan African mobile belts formed in Africa about 500 million years ago. Similar structures have been described from western Australia and from South America. The evidence that these formed over the same time interval as the Ross orogen, suggests that the complex of structures represents the response of Gondwanaland to stresses accompanying movements within the Pacific at that time. Not only were abundant graben formed in the interior, but igneous rocks were intruded into the crust from the mantle, extensive volcanicity occurred within Gondwanaland and further metamorphism of existing crystalline rocks took place to produce, for example, granulites of early Palaeozoic age in both Africa (the Mozambique belt for example) and East Antarctica, where many granulites near the coast have given ages around 500 Ma (Grindley & McDougall 1969). Extensive intraplate deformation developed during this event, but, at least on the evidence provided by the Antarctic and African cratons, the opening and closing of newly formed oceans was not a feature of the interior of Gondwanaland at that time. Elsewhere, however, as for instance in Laurasia between present-day northwest Europe and eastern North America, there appears to be evidence of the formation and destruction of oceans of limited size as continental blocks separated and came together during the late Precambrian and early Palaeozoic.

Antarctica brings out rather clearly a relationship which has been recognized elsewhere in Gondwanaland. Regions composed of early Precambrian rocks (over 2500 Ma old), which escaped the effects of younger Precambrian and Palaeozoic modification such as occurred during the Pan-African or Ross events, rarely contain any sign of subsequent volcanic activity other than dolerite dyke swarms. The observation that younger Phanerozoic volcanism whether on land or on ocean floors avoids early Precambrian crust but is concentrated in those parts which were modified later in the Precambrian or during the early Palaeozoic, is of great interest. It suggests that both mantle (where most volcanic rocks originate) and crust may have been permanently altered by an event such as the Pan-African or Ross episodes. Kennedy (1965) was the first to recognize that many coastlines formed by the break-up of Gondwanaland lie within Pan-African belts, and Kennedy (1964) has shown how the volcanic rocks of Africa and Arabia formed over the last 400 Ma lie (with a few exceptions, of which kimberlites are the most important) outside the blocks built of unmodified early Precambrian or Archaean rock. A map of Phanerozoic volcanicity in Antarctica shows a similar relationship. The volcanic rocks

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

occur in the Transantarctic Mountains and in western Antarctica generally, but not within the early Precambrian of the East Antarctic craton. The alkali-rich magnesian rocks of the Gaussberg Peninsula originating like kimberlites deep within the mantle, form one of the few exceptions to this rule. With this exception from East Antarctica, known Upper Palaeozoic and Younger Phanerozoic volcanic rocks are confined to regions outside the Archaean area of the East Antarctic craton. Similarly the fractures which determined coastlines of Antarctica lie within late Precambrian or early Palaeozoic belts showing that the young oceans around Antarctica followed Kennedy's rule – Mesozoic and Tertiary oceans open along Pan-African or slightly older structures.

Karroo volcanicity and deformation

The Karroo igneous activity was more restricted than that associated with the Pan-African movement and was predominantly basaltic. Both events, however, were alike in that they affected regions of continental crust and mantle many thousands of kilometres across. If not global in scale they were at least intercontinental. The recognition of Karroo igneous rocks along the Transantarctic Mountains (Barrett, Grindley & Webb 1972) and in parts of Antarctica once close to present-day South Africa and Tasmania brings out the remarkable distribution of igneous activity. Karroo volcanic rocks in Africa extend as far north as Malawi (Cox 1970), but are more restricted than Karroo sediments which are widely developed in fault-controlled basins as far north as Madagascar and East Africa. Karroo volcanics are known in Africa from the Cape to Malawi and are largely, but not wholly, concentrated in the eastern half of southern and central Africa from where they extend across Antarctica to approach the Pacific in Victoria Land and Tasmania. They are thus the product of some phenomenon affecting mantle below a selected portion of Gondwanaland extending to the Pacific margin. The question arises as to why this section of the supercontinent was affected in this manner. One might expect some connection between this igneous activity and any contemporary volcanicity on the Pacific floor. Some lines of evidence suggest that a spreading axis possibly making a high angle to the coastline lay off western Antarctica in Triassic times. There appears to be no record of marine Triassic deposits laid down upon continental crust between New Zealand and a point at latitude 38° S in South America (Katz 1973). This suggests that the margin of Gondwanaland was not submerged in this sector during Triassic times unlike the situation of northern Australia or in more northerly parts of South America.

One way in which a continental margin could be elevated above sea level would be through the presence of a spreading axis which intersected the coastline. It is known that such an axis had developed by 80 Ma B.P. when the New Zealand continental block and western Antarctica began to separate (Molnar, Atwater, Mammerickx & Smith 1975). The Tasmanian intrusions dated at 170 Ma are of particular interest in this connection for though they predate any known disruption of Australasia and Antarctica they indicate that by Karroo times basaltic magma was being introduced into the crust although movements were not yet strong enough to disrupt overlying continents. They prompt the question as to whether the Antarctic Karroo volcanics were connected to a contemporary spreading axis off the Tasmanian coast. Cox (1970, p. 230) has discussed the possible steps which may have preceded the continental break-up that followed the Karroo igneous activity in Africa, and has suggested that a centre of uprising convection may have coincided roughly with southern Africa and Antarctica (Cox 1970, p. 232). It seems possible that such a centre could have been connected to an active spreading centre within the Pacific which approached the margin of Gondwanaland near Tasmania and Victoria Land.

Although Karroo volcanicity was predominantly basaltic a number of alkaline complexes were formed as is well known, and in some regions acid rocks played an important rôle, as for example along the Lebombo Monocline in southeast Africa. Though there were many differences between the Karroo and the Pan-African igneous episodes both involved the transfer from mantle to crust of large volumes of igneous rock over substantial portions of Gondwanaland without extensive fragmentation of the supercontinent. Both episodes led to basic, acid and alkaline activity though in very different proportion, granitic rocks predominating in the Pan African events. The scale of the igneous activity in each instance was substantial and was probably connected with extensive changes within underlying mantle which one might expect to have been linked with movements elsewhere. Cox (1970) has estimated that 2000000 km^2 of Africa was either covered by Karroo lavas or cut by dykes or sills. The Pan African events had earlier affected at least one-third of that continent. Antarctica provides clues as to the possible relations of intracontinental igneous activity on such scales with some developments near the margins of the Pacific. Just as the Pan-African activity 500–400 Ma ago coincided with the Ross orogeny and deformation of the crust along the borders of the Pacific and Gondwanaland, so the Karroo faulting and igneous activity overlaps with at least some plutonism in western Antarctica. Granites, granite gneisses or episodes of regional metamorphism dating from between 200 and 180 million years ago have been recorded for instance from the South Orkney (Harrington, Barker & Griffiths 1972), Marguerite Bay (Halpern 1972), the Jones Mountains (Rutford, Craddock, White & Armstrong 1972), western Antarctica and from the New Zealand continental block on Bounty Island (Wasserburg *et al.* 1963). The African Karroo basaltic activity extended from about 190 to 150 million years ago, a time span that appears to cover the Antarctic rocks though these may be somewhat younger than the earliest African Karroo basalts.

Neither the Pan-African nor the Karroo events led directly to ocean floor development, though the Pan-African belts were to become the locus of much subsequent igneous activity and to determine the position of the lines along which much of Gondwanaland broke up. In parts of Gondwanaland Karroo igneous activity of Jurassic age seems to have led into Cretaceous activity in nearby regions where sea floor spreading was about to start. Kent (1974) has drawn attention to Cretaceous volcanics in and near Madagascar which would have been close to the newly opening Cretaceous Indian Ocean, and not far distant from Karroo volcanics erupted earlier in eastern Africa. A suggestion of unusual conditions in the mantle below eastern Africa is indicated outside volcanic areas. Kent (1974) in a discussion of vertical movements near the continental margins of East Africa, a region marked by Karroo deposition without volcanic activity, points out that the largest faults, up to 10 km in throw, were contemporary with Karroo Early Jurassic deposition. Later Post-Cretaceous and Tertiary stresses were, Kent indicates, relieved by smaller faults closer to the edge of the continental shelf (Kent 1974, p. 320). In other words the Karroo events may have affected the mantle not only where igneous rocks reached the crust but over a wider area around the volcanic region which extended from Tasmania to Central Africa.

The distortion of the Gondwanaland seaboard of the Pacific

During the break-up of Gondwanaland complicated movements occurred in western Antarctica and other regions along the Pacific coast of the supercontinent. In a review such as this no attempt is made to provide detailed descriptions of individual regions or to trace the history of disruption. The purpose of this section is to consider some distinctive phenomena, picked out as illustrations of the general case.

Relations of New Zealand and Antarctica

Several authorities (e.g. Molnar *et al.* 1975) have proposed a reconstruction of the South Pacific which places the block including New Zealand, the Campbell Plateau and the Chatham Rise, in the vicinity of the present-day Ross Sea in continuity with Marie Byrd Land. If the submarine Campbell Plateau and the Chatham Rise are continental as seems to be the case (see Fleming 1970; Molnar *et al.* 1975) the structures which Fleming has proposed extend from the New Zealand fold belts into the Campbell Plateau and Chatham Rise may continue through Byrd Land and the continental shelf off western Antarctica to the Antarctic Peninsula and the Scotia arc. If one accepts such reconstructions, interesting consequences arise as Katz (1973), has pointed out. Mesozoic sediments in the Antarctic Peninsula laid down in numerous fault-bounded terrestrial or shallow water Jurassic and Cretaceous basins resting on older continental crust contrast with contemporary deposits in southernmost South America which Katz categorizes as a mio-eugeosynclinal couple. Katz suggests that the contrasts which he sets out in detail indicate that the two regions have not been connected segments of an originally continuous and straight mountain belt along the Pacific margin as has been suggested. The Antarctic Peninsula can also be contrasted with the Pacific margin exhibited in and near New Zealand. There in the Phanerozoic a succession of belts developed, which are exposed in South Island. Fleming (1970) has summarized the Mesozoic history of the New Zealand geosyncline developed off a foreland or geanticlinal region built of Precambrian and Lower Palaeozoic rocks exposed in western South Island. Oceanwards from the foreland a succession of Phanerozoic belts were formed apparently on oceanic crust. Shelley (1975) has provided a recent interpretation where he views the Phanerozoic development of New Zealand in terms of four eastward migrating cycles related to a succession of Benioff zones. In each cycle deposition on oceanic crust east of a continental land mass and subsequent orogeny progressively extends the land mass into the ocean. It is possible that some such structures might exist on the continental shelf off western Antarctica, but on land within that part of the Antarctic land mass, the surviving younger circum-Pacific structures appear to have formed on top of older ones in a way which did not necessarily entail the extension of land into the ocean. Further north in South America, as Katz has emphasized, the nature of the circum-Pacific structures changes yet again.

Until more is known about the ocean floor immediately west of western Antarctica this section of the Pacific margin is likely to remain unclear. Katz has suggested that rocks as old as Jurassic might be present on the floor of the Bellingshausen Sea (1973, p. 356), a conclusion, he points out, consistent with the magnetic anomalies reported by Hayes (1971).

Katz emphasizes the Atlantic type margin of the Antarctic Peninsula and the lack of evidence of subduction since the Cretaceous (Katz 1973, p. 356). The question arises as to whether this situation which is in contrast with much of the Pacific margin off South America and Australasia has its origin in some earlier structural arrangement.

In the absence of knowledge of the ocean floor one can turn to evidence of sedimentary facies on land. Early Mesozoic rocks are scarce on the Antarctic Peninsula, suggesting that the folded Permo-Carboniferous rocks there may at that time have formed an uplifted region undergoing erosion. The earliest deposits lying on eroded crystalline rocks of the Permo-Carboniferous appear to be Bajocian-Kimeridgian in age. The question arises as to where any deposits formed by erosion during this interval are now to be found. In New Zealand the third of four orogenic cycles, the Rangitata orogeny, developed in a succession extending from the Permian to the Jurassic laid down at least in part on ocean floor (see for example Figure 4, Shelley 1975, p. 671). Was a similar succession laid down west of the Antarctic Peninsula and if so is it still in place?

The apparent lack of marine Triassic rocks on continental crust between New Zealand and the 38th parallel which Katz reports as marking the most southerly Triassic marine facies in South America, has been referred to earlier. It is probably premature to attach too much importance to this; it might mean that this section of the Pacific margin has lost an outermost rim containing marine Trias which might have lain west of western Antarctica or alternatively that during Triassic times movement of the Pacific floor continued to maintain the adjoining continental crust above sea level as had been the case during the Upper Palaeozoic mountain building in western Antarctica.

Fragmentation and transcurrent movements near the Gondwana–Pacific boundary

The succession of basins filled with sediments and volcanics and the fold belts which followed mark out a zone up to 1000 km wide along the Pacific borders of Gondwanaland. Collectively they have imposed a pronounced grain on the continental margin marked out both by variations in thickness and pronounced physical properties and by an anisotropy produced by deformation within the crust and probably also in the underlying mantle. Steeply dipping mylonite zones, belts of relatively fine grained rock developed in regions of high strain provide obvious examples of major weaknesses likely to influence the reaction of the crust to subsequent stress. Western Antarctica represents such a region, heterogeneous in many respects, and typical of the margin of Gondwanaland as a whole.

Three types of movement have been particularly well developed at various times during the Phanerozoic within this outermost part of the supercontinent close to the adjoining ocean. One is the migration of basins and fold belts through the width of this zone. In general migration is outwards with time as in eastern Australia where the late Precambrian structures near Adelaide have given place in the course of time to the present-day active trenches in the nearby Pacific. Where successive belts develop to a greater degree on top of their predecessors rather than to one side, as for example in western Antarctica during much of the Phanerozoic, one may suspect anomalous behaviour in the adjoining ocean and the presence of some structure other than a trench and zone of subduction close to the continental margin. Katz (1973) and others have emphasized the Atlantic character of part of the western Antarctic Pacific coast and the suggestion has been made earlier in this paper that a spreading axis might have lain close to Antarctica at least as far back as Triassic times.

Two other and quite different types of deformation have been recognized within Gondwanaland close to the Pacific. One is the opening of small oceans isolating blocks of the continent from the main mass. These are well documented and need not be discussed. The separation of New Zealand as the Tasman Sea developed off Australia is a surviving example and instances where seas have opened and then been largely closed have been cited from the pre-Tertiary history of eastern Australia and from the southernmost South America and the Antarctic Peninsula.

The remaining kind of structural development is the development of major transcurrent displacements of parts of the periphery of a supercontinent in contact with the Pacific. The displacement of continental crust on the Pacific side of the San Andreas fault system is probably the best known example of a still active transcurrent displacement linked to movement of the Pacific floor. The separation of the micro-continent of which New Zealand forms a part, from western Antarctica (Molnar *et al.* 1975) and the displacement of those two comparatively small blocks relative to eastern Antarctica and Australia provides another well documented example.

In that instance a spreading axis penetrated a comparatively short distance into Gondwanaland and for some 40 million years brought about the continued separation of the West Antarctic and New Zealand block, although the main mass of Antarctica and Australia west of Tasmania remained united (Molnar *et al.* 1975). Although the structures are not known in detail the break separating East and West Antarctica along which transcurrent movement took place lies within an earlier Phanerozoic fold belt. It will be interesting to learn the extent to which the earlier structure governed the location of the transcurrent zone. Such examples illustrate a more general proposition which can be expressed thus. The outer parts of Gondwanaland (and also of Laurasia) are marked by heterogeneities developed since the late Precambrian which provide lines of weakness along which blocks of continent can be detached from the main continental mass. Attached to plates composed mainly of oceanic crust such fragments may travel for distances of 10^2–10^3 km along the supercontinent margin. When past movement can be recognized they may provide evidence of the presence of extinct spreading axes of which no direct evidence remains in ocean floor structures. Jones, Irwin & Ovenshine (1972) and Schweickert (1976) have suggested that parts of western North America were transported northwards along the coastline in this fashion. Beck (1975) has employed palaeomagnetic measurements to demonstrate rotation of a number of small blocks in western U.S.A. in a manner which would be consistent with such movements. In Antarctica several authorities have suggested major transcurrent movements such as those involved in the displacement of South Georgia from South America suggesting that these occurred during the movements which led to the evolution of the Scotia Arc. Taken with studies of metamorphic changes and of igneous activity on land close to the margin of the Pacific an understanding of the structural history of western Antarctica and of other parts of the periphery of Gondwanaland may be expected to unravel something of the enigma of the pre-Cretaceous history of the Pacific and of its relations to the supercontinents along its margin.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

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