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ANTARCTICA; A TALE OF TWO SUPERCONTINENTS?

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INTRODUCTION

Dog Sleds to Satellites

On March 29, 1912, Captain Robert Falcon Scott and his companions, Dr. Edward A. Wilson and Lieutenant H. R. Bowers died in their tent during a blizzard on the Ross Ice Shelf in Antarctica from cold, exhaustion, and lack of nourishment. They were a mere 18 km from a supply depot they had cached months earlier, before their journey to the South Pole. They died disappointed men, having learned on their arrival at the pole that Roald Amundsen and his Norwegian party had beaten them to the long-sought goal by one month. During their return journey, despite full awareness of the seriousness of their situation, Scott and his men had taken time to "geologize" in the Transantarctic Mountains (Scott 1913). They man-hauled 16 kg of rock samples collected there towards civilization until they succumbed. The specimens were retrieved by the party that found their frozen remains the next summer.

The accurate geologic positioning of Antarctica as the "keystone" of a southern supercontinent by Alex Du Toit in his reconstruction of 1937, following the early concepts of Taylor (1910) and Wegener (1912), would not have been on firm ground without the collections made on Scott's expeditions, and on the expedition of Ernest H. Shackleton that pioneered the route through the Transantarctic Mountains to the Polar Plateau in 1908 (Shackleton 1909). Specimens of the *Glossopteris* flora firmly linked Antarctica to the other southern continents, though full acceptance of the hypothesis of a Gondwana supercontinent by the scientific community

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had to await acquisition of marine geophysical data from the southern oceans and its interpretation in terms of seafloor spreading (Norton & Sclater 1979). Satellite altimetry data acquired in the late 1980s now clearly show fracture zones representing the "flow lines" along which the other southern continents and India moved away from the Antarctic keystone during fragmentation of the Gondwana supercontinent (Royer et al 1990, see Figure 1), spectacular confirmation of Wegener's concept of a continental "Polflucht" (flight from the poles) and of Du Toit's geologic correlations.

The scientists on the first expeditions to the continental interior also collected rocks that link Antarctica to a supercontinent that may have predated Gondwana. The global marine transgression and accompanying explosion of life that marked the dawn of the Phanerozoic Eon (c. 550 Ma) are widely believed to have followed fragmentation of a Neoproterozoic[1] supercontinent, with Cambrian marine transgressive sequences on several continents being deposited on subsiding continental margins (Bond et al 1984). The effects of early Paleozoic compression and magmatism, and the present-day ice cap, have combined to obscure the possible late Precambrian–earliest Cambrian rift history in Antarctica. However, Frank Wild collected isolated archaeocyathans—Cambrian reef organisms—on Shackleton's 1908–9 expedition (Taylor 1914), and Scott's journal records Edward Wilson's discovery of "a specimen of limestone with archeocyathus" on February 8, 1912 as his party studied a moraine near Mount Buckley in the Transantarctic Mountains on their return from the pole (Scott 1913). Archeocyathan-bearing Lower Cambrian limestones have now been found to occur along the Transantarctic Mountains from the Weddell Sea to the Ross Sea (Rowell & Rees 1989, 1991). Recently it has been proposed that these deposits reflect marine transgression which followed the separation of Antarctica from North America during supercontinental fragmentation in the late Precambrian, and hence the birth of the Pacific Ocean basin (Moores 1991, Dalziel 1991). The Cambrian limestone collected on Scott's last expedition illustrates that Antarctic geology may be a tale of two supercontinents: Gondwana and a late Precambrian predecessor.

I use a series of global paleogeographic maps to review our understanding of the development of the Antarctic continent and plate in a framework of both the established Gondwana supercontinent and the hypothetical older supercontinent.

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[1] The International Union of Geological Sciences has formally approved division of the Proterozoic Eon into the Paleo-, Meso-, and Neoproterozoic eras at 1.6 and 1.0 Ga (Plumb, K. A., *Episodes*, v. 14, No. 2, pp. 139–40, June 1991).

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Antarctica Today

Antarctica is divided physiographically and geologically by the Transantarctic Mountains which extend for 4500 km from the Ross Sea to the Weddell Sea (Figure 1). The crust of East (or Greater) Antarctica was amalgamated from Archean nuclei during the Mesoproterozoic (1.6–1.0 Ga) and formed a major segment of the Precambrian craton of the Gondwana supercontinent from its amalgamation in latest Precambrian ($\sim$600 Ma) until the birth of the southern oceans in the late Mesozoic ($\sim$150 Ma). West (or Lesser) Antarctica is part of the circum-Pacific mobile belt.

The earliest tectonism clearly associated with the Transantarctic (i.e. proto-Pacific) margin of the East Antarctic craton was rifting during the Neoproterozoic. Marine transgression of the margin took place in the Early Cambrian. By the Middle to Late Cambrian (c. 520–500 Ma) it was undergoing compression, along-strike displacements, and calc-alkaline magmatism in an event known as the Ross orogeny. This event, called the Delamerian orogeny in eastern Australia, involved subduction beneath the craton. Mid-Paleozoic tectonism (c. 500–350 Ma) involved further compression, strike-slip displacements, accretion of terranes, and continental margin arc magmatism. In the late Paleozoic and early Mesozoic (c. 350–200 Ma) the convergent margin moved oceanward as a result of accretion. The sedimentary strata of that age now exposed in the Transantarctic Mountains—the classic Gondwana sequence that covers the craton and lower-middle Paleozoic orogens, thereby uniting the southern continents stratigraphically—represent intracratonic basinal strata.

West Antarctica consists of four geologically distinct terranes (Dalziel & Elliot 1982) separated by subglacial depressions (Jankowski & Drewry 1981, Figure 1). The Ellsworth-Whitmore Mountains block (EWM) is a displaced segment of the craton margin (Schopf 1969). The Antarctic Peninsula (AP), Thurston Island (TI), and Marie Byrd Land (MBL) blocks, together with the New Zealand microcontinent are all Paleozoic to Mesozoic fore-arc and magmatic-arc terranes developed along the sector of the Pacific margin of the Gondwana craton extending between southern South America and eastern Australia. They were displaced after the Gondwanian orogeny in the early Mesozoic when the sedimentary cover of the Gondwana craton was folded and thrust cratonward along the Pacific margin. Uplift and widespread bimodal magmatism also preceded the final fragmentation of Gondwana which started with separation of East and West Gondwana by seafloor spreading in the Somali and Mozambique basins. The timing of breakaway of the major continents from Antarctica is well documented by marine data (Lawver et al 1991, Figure 1), and the

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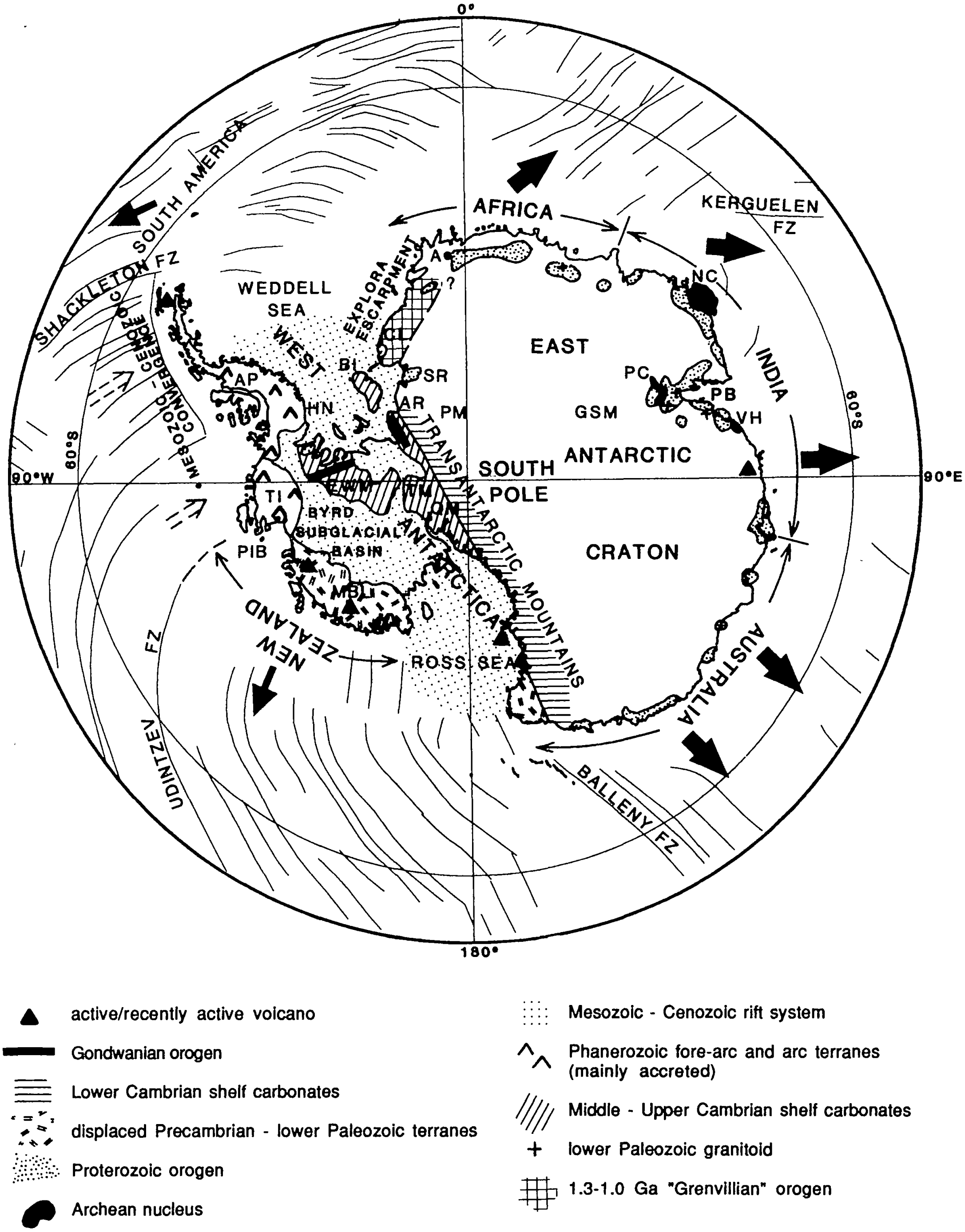

Figure 1 Simplified tectonic map of the Antarctic continent and surrounding ocean basins (from Dalziel 1991, Tingey 1991, Royer et al 1990). Bold arrows show directions taken by the major fragments of the Gondwana supercontinent during fragmentation. A—Annandagstoppane; AP—Antarctic Peninsula; AR—Argentine Range; BI—Berkner Island; CL—Coats Land nunataks (Bertrab, Littlewood, and Moltke); EWM—Ellsworth-Whitmore Mountains block; GSM—Gamburtzev Subglacial Mountains; H—Heimefrontfjella; HN—Haag Nunataks; MBL—Marie Byrd Land; NC—Napier Complex; NVL—North Victoria Land; PB—Prydz Bay; PC—Prince Charles Mountains; PIB—Pine Island Bay; PM—Pensacola Mountains; QM—Queen Maud Mountains; SR—Shackleton Range; TI—Thurston Island; TM—Thiel Mountains; VH—Vestfold Hills.

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motions of the West Antarctic terranes relative to each other and to the East Antarctic craton are constrained by paleomagnetic data (Grunow et al 1991).

The Cenozoic history of the Antarctic continent has been dominated by extension and alkaline volcanism in the Ross embayment and along the Pacific margin of West Antarctica (Le Masurier & Thomson 1990), by block uplift of the Transantarctic Mountains (Fitzgerald 1989), and by the development and fluctuation of the ice cap (Barrett 1989).

A LATE PRECAMBRIAN SUPERCONTINENT?

The East Antarctic craton is almost entirely covered by ice; bedrock is only exposed (<1%) along the coastal fringe and in the Transantarctic Mountains. Nonetheless four Archean nuclei are known (Figure 1). They are separated by Proterozoic metamorphic belts, the youngest of these reflecting crustal growth and suturing of the older continental nuclei during the late Mesoproterozoic (1.3–1.0 Ga) (Tingey 1991, Figure 1).

Reconstruction

Neoproterozoic rifting along the Pacific margins of both East Antarctica and the Australian craton is marked by thick craton-derived turbiditic sequences with associated bimodal igneous rocks. These sequences were deformed in the latest Precambrian to earliest Cambrian and are unconformably overlain by Cambrian marine strata (e.g. Schmidt et al 1965, Rowell et al 1992). This history is remarkably similar to that of other major continental margins interpreted as late Precambrian-Early Cambrian rifts (Bond et al 1984). It suggests that East Antarctica–Australia, restored to their configuration prior to the Mesozoic-Cenozoic development of the southern oceans, separated from some other Neoproterozoic continent along what is now the Transantarctic Mountains front and its continuation into the region of the Flinders Ranges of South Australia. If correct, this concept adds ~25% to the length of latest Precambrian to Early Cambrian rifted margins globally, thus making the general case for a Neoproterozoic supercontinent more compelling.

Moores (1991) has recently put forward evidence that the cratons of North America and East Antarctica–Australia were joined during the late Precambrian. Dalziel (1991) has presented a computer reconstruction showing not only that this is geometrically possible, but also that the boundary separating the 1.3–1.0 Ga Grenville province from the older radiometric provinces of the Laurentian cratonic nucleus may have continued into East Antarctica along the eastern margin of the Weddell Sea

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(Figure 2). Although the paleomagnetic data from uppermost Precambrian and Cambrian rocks are still confusing, this reconstruction is quite compatible with widely accepted poles for the Gondwana supercontinent and North America from the Late Cambrian onward (Van der Voo et al 1984, Dalziel 1991; Figures 3 and 4). Thus, the similarities of the North America and East Antarctica–Australia cratons, the piercing points provided by the boundaries of the Grenville-age (1.3–1.0 Ga) belts, and the similar rifting and transgression histories (Moores 1991, Dalziel 1991) make the former juxtaposition of these 4500 km long margins an attractive possibility. Furthermore, there are no obvious alternative conjugates for either of them.

Dalziel (1991) and Hoffman (1991) have broadened the hypothesis of Moores (1991), reviving the suggestion that the eastern margin of Laurentia may have rifted from western South America (Bond et al 1984, Hartnady 1986). According to this scheme North America broke out of a Neoproterozoic supercontinent (Figure 2) to form the Pacific and Iapetus ocean basins while the Gondwana supercontinent was still amalgamating (Figure 3). The juxtaposition of eastern North America and western South America was originally suggested on the basis of minimum required displacement between breakup of a supercontinent at the end of the Precambrian and established early to middle Paleozoic reconstructions (Bond et al 1984). It is supported by near-simultaneous initiation of thermal subsidence in the mid-Atlantic region of North America and in northwestern Argentina, as well as by the presence in South America of the Cambrian Olenellid trilobite fauna characteristic of North America, and by Late Cambrian paleomagnetic data (Figure 3). The exact tectonic setting of the Cambrian strata in South America is unclear due to a complex history of late Precambrian rifting, late Precambrian and early Paleozoic terrane collision (Ramos 1988), and the superimposed Andean orogenesis. However, the Upper Proterozoic to Lower Cambrian Puncoviscana Formation of northwestern Argentina is a turbidite sequence derived from the craton which is interpreted as a passive margin fan (Aceñolaza et al 1988). It is very similar to the Patuxent Formation of the Transantarctic Mountains (Jezek et al 1985), so that North America is bordered in the reconstruction by continental margins with Neoproterozoic rift-related sequences and Cambrian transgressive sequences comparable to those along its Appalachian, Cordilleran, and Gulf of Mexico margins (Figure 2). The faunal similarities between the Appalachian and Andean margins, as well as the southwestern margins of North America and Africa, imply shoreline colonization routes and/or tectonic displacement of terranes along a mutual boundary prior to complete separation during the early to mid-Paleozoic (Hartnady 1986, Figure 4).

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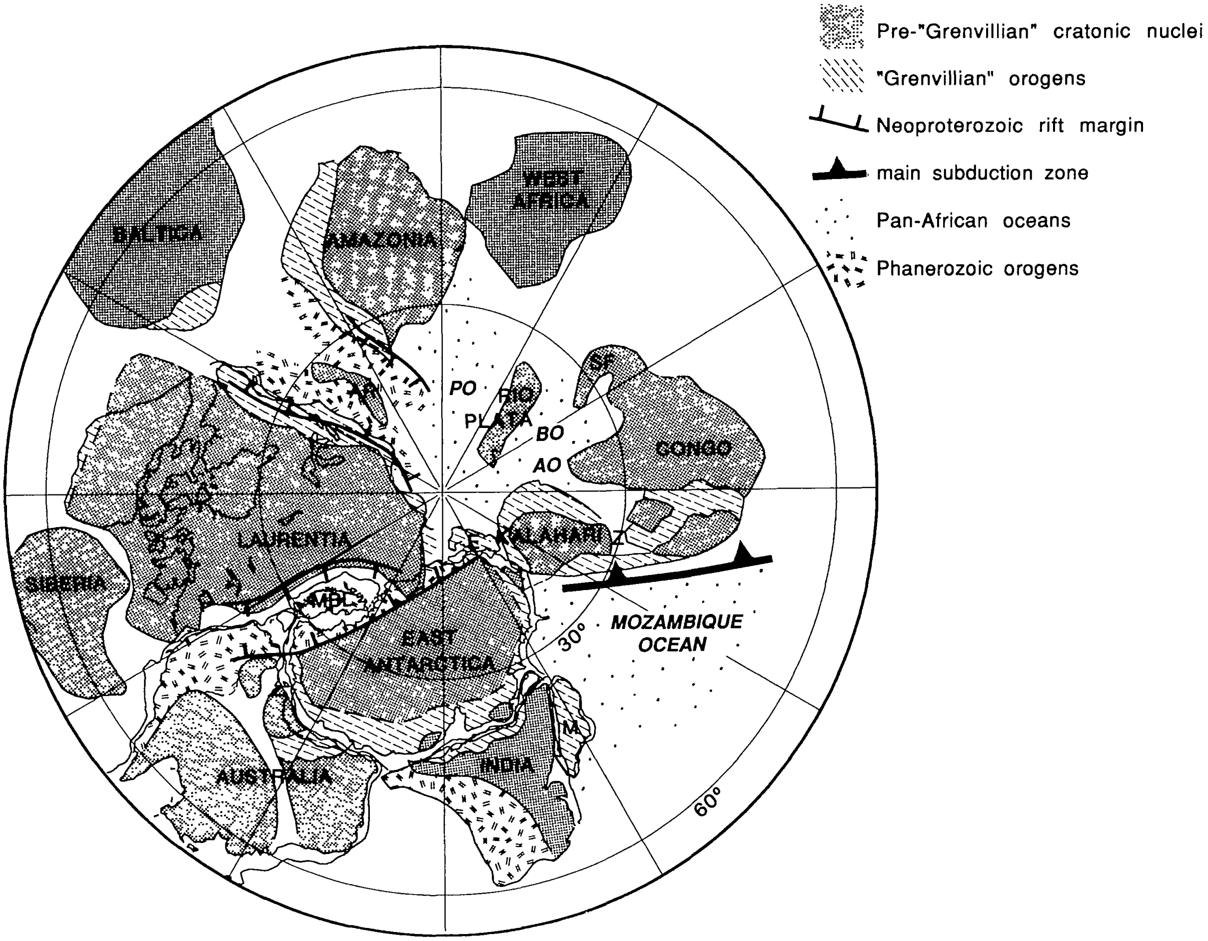

Figure 2 Hypothetical reconstruction of a late Precambrian supercontinent (c. 750 Ma) based on the North America–East Antarctica/Australia relationship suggested by Moores (1991) and amplified by Dalziel (1991). The pole approximates a generalized Euler pole for the fragmentation of the supercontinent and the amalgamation of Gondwana (Figure 3). The small circles about the pole at 30° and 60° are for scale only. Terranes of western North America and West Antarctica have been removed with the exception of Marie Byrd Land and the Ellsworth-Whitmore Mountains block which are shown in restored positions relative to the East Antarctic craton. The relationship of eastern North America and western South America is that of Dalziel (1991) and Hoffman (1991), and was first suggested by Bond et al (1984). Accreted terranes of the Patagonian region have been removed. Positioning of Baltica and Siberia follows Hoffman (1991). Position of the Kalahari craton adjoining East Antarctica is after Groenwald et al (1991), and relationship of the Sao Francisco–Congo and Kalahari cratons is after Hartnady et al (1985) and Hanson et al (1988). Location of ocean basins follows Hartnady et al (1985), Ramos (1988), Porada (1989), Dalziel (1991), and Hoffman (1991). AO—Adomaster Ocean; AR—Arequipa massif; BO—"Brazilide Ocean"; E—Ellsworth-Whitmore Mountains block; K—Kalahari craton; M—Madagascar; MBL—Marie Byrd Land; PO—"Pampean Ocean"; SF—Sao Francisco craton; Z—Zambesi belt.

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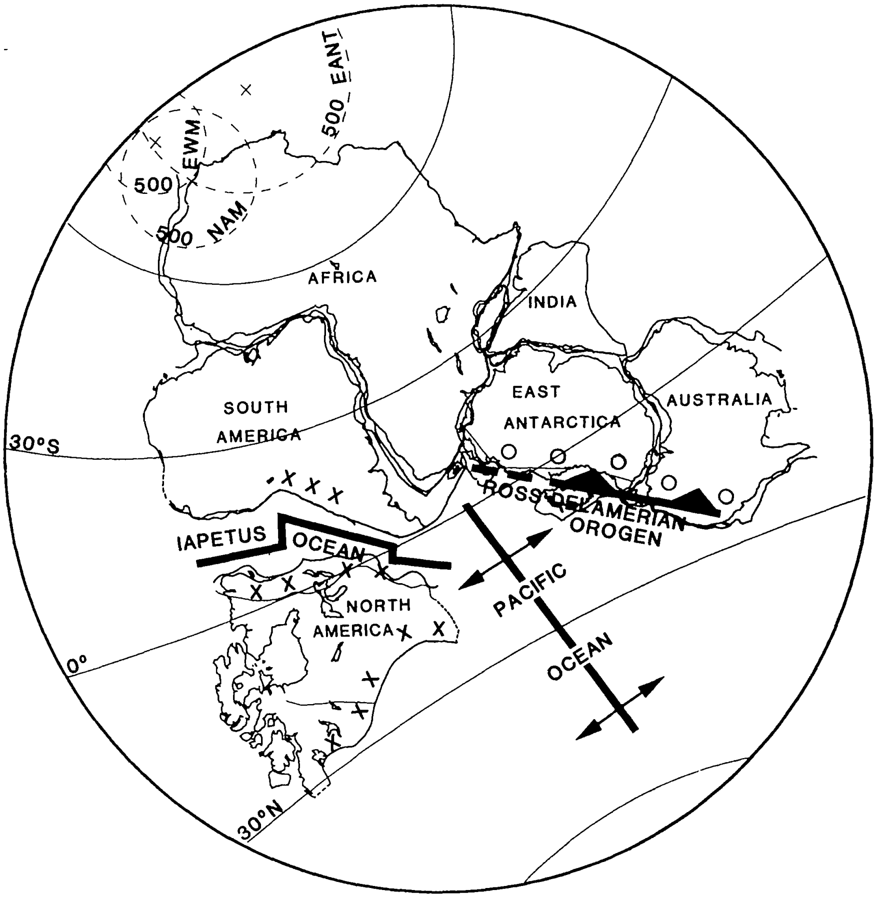

Figure 3 Paleomagnetically controlled reconstruction of the Pacific and southern (i.e. South America–North America) Iaptus oceans on final amalgamation of the Gondwana supercontinent at the end of the Cambrian (c. 500 Ma). The paleomagnetic poles and circles of confidence (alpha 95) are as described in Dalziel (1991, Figure 2). Crosses and circles respectively denote the North American and East Antarctic/Australian trilobite faunal realms of Jell (1974).

Eastern Gondwana (East Antarctica–Australia–India) was assembled by the end of the "Grenvillian" orogenesis at 1.0 Ga. The Kalahari craton of southern Africa was attached to the Archean rocks of the Annandagstoppane in East Antarctica (Groenwald et al 1991), and the Zambezi belt between the eastern extremities of the Kalahari and Congo–Sao Francisco cratons were sutured by ~0.8 Ga (Hanson et al 1988). Therefore, if the juxtapositions of East Antarctica–Australia with western North America and eastern North America with western South America are accepted, a major supercontinent existed at that time (Figure 2). Western Gondwana (South America–Africa), however, has several late Precambrian sutures (Hartnady et al 1985, Ramos 1988, Porada 1989). It is along the boundaries between the Brazilian–West African, Rio de la Plata, and Sao Francisco–

Congo–Kalahari cratons, and particularly along the Mozambique belt between West Gondwana and East Gondwana (where there are ophiolitic and eclogitic fragments, and blueschists), that ocean basins must have closed during the final amalgamation of the "daughter" Gondwana supercontinent during the break-out of Laurasia from the "parent" Neoproterozoic supercontinent. The computer reconstruction for c. 0.75 Ga that is presented in Figure 2, while hypothetical, permits ocean-continent relations to be studied within an accurate global framework.

Fragmentation

Critical issues for the hypothesis of a late Precambrian supercontinent are: 1. the timing of rift-drift transition along the East Antarctic–Australian, western Laurentian, eastern Laurentian, and western South American margins; 2. the timing of final collision along the sutures within West Gondwana and the Mozambique belt; and 3. the length of the Cambrian Period. The geometry of the model shown in Figure 2 requires consumption of ocean basins with a total width of approximately 8500 km. If the Cambrian is significantly shorter than the 60 million years (570–510 Ma) suggested by Harland et al (1990), and there are indications that this is the case (see discussion by McElhinny 1991), the changes required in the models of Dalziel (1991) and Hoffman (1991) would be difficult to envisage as happening between the Precambrian-Cambrian boundary (the approximate time of rift-drift transition according to the thermal subsidence curves of Bond et al 1984) and the Cambrian-Ordovician boundary (widely accepted as the youngest possible time for final consolidation of Gondwana; Figures 2 and 3). They could require unlikely seafloor spreading and convergence rates. Moreover, although "Pan-African" radiometric ages as young as ~500 Ma are widespread in Gondwana, in many cases they appear to represent a thermal event post-dating final suturing of that supercontinent (see Stern et al 1992).

Hence the Neoproterozoic rift systems shown on Figure 2 are vital. Do they actually reflect the formation of oceanic lithosphere significantly earlier than the Precambrian-Cambrian boundary? If so there would have been more time to amalgamate Gondwana by continental collision along the Western Gondwana and Mozambique sutures by 650–600 Ma as required by the geochronologic data (Hartnady 1991, Dalziel 1992, Stern et al 1992), and to generate the embryonic Pacific and Iapetus ocean basins which were 9000 km and 1700 km wide respectively by the end of the Cambrian as shown in Figure 3.

Along the Transantarctic Mountains, there are igneous rocks associated with the Upper Proterozoic turbidites of the Patuxent Formation and its equivalents, the Goldie, La Gorce, and Duncan formations of the

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Beardmore Group (Stump et al 1986). Geochemical study of mafic pillow lavas interbedded with the Goldie Formation yielded a Sm-Nd mineral isochron of age of 762 ± 24 Ma with a low Sm/Nd ratio and an εNd value of +6.85, suggesting to Borg et al (1990) that the rocks formed in an oceanic rather than a continental setting. Data recently acquired as part of the Joint US-UK West Antarctic Tectonics Project from mafic rocks in the Patuxent Formation demonstrate that these are significantly more evolved and do not fall within the range predicted for mid-ocean-ridge basalts or intra-oceanic arc magmas. While their isotopic compositions are similar to those of hot-spot related volcanics such as those of Bouvet Island, and to primitive subduction-related lavas, they could also have been derived from enriched mantle of the sub-continental lithosphere (Storey et al 1991). Their geologic setting, provenance, and association with felsic volcanic rocks supports an intracontinental rift setting. Hence the rocks of the Beardmore Group appear to represent tectonic environments ranging from an intracontinental rift to at least a narrow ocean basin. They were all deformed in the latest Precambrian or Early Cambrian prior to deposition of Middle Cambrian marine strata (Rowell et al 1992). The rocks of the Patuxent Formation, for example, are folded by two sets of tight, upright folds with sub-horizontal hinge lines, and also by late-stage, steep and variably plunging folds.

The Neoproterozoic Beardmore Group along the Pacific margin of East Antarctica–Australia and its counterparts in North America, the Belt-Purcell and Windermere sequences, cut across the fabric of the older cratonic crystalline basement. At the very least, therefore, these rocks appear to represent rifts that weakened the continental crust of a Neoproterozoic supercontinent and controlled the final breakup. Some workers believe the Windermere rocks represent a passive continental margin sequence (Ross 1991). The equivalent rocks in eastern North America and western South America (the Chilhowee-Catoctin and Puncoviscana sequences respectively) also controlled final rifting, but differ in that they themselves follow a Mesoproterozoic "Grenvillian" orogenic belt (Figure 2).

The geochemical data from the central Transantarctic Mountains indicates that some of the Neoproterozoic basins along the East Antarctica–Australia margin were partly floored by oceanic lithosphere. The absence of subduction-related magmatism associated with the Beardmore deformational event, however, suggests that the Beardmore Ocean itself was narrow (Borg et al 1990), perhaps like that between Madagascar and Africa today. The deformation may be of no more significance than the late compression in the Keeweenawan rift (Van Schmus et al 1987), or may reflect significant transpression between two major continents as they

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first started to move apart and may even have involved thrusting of Archean amphibolite over Proterozoic crystalline rocks in the Miller Range (Goodge et al 1991). Motion and deformation of this type, like the late Mesozoic interaction between South America and Africa in the equatorial Atlantic, would be expected if North America and East Antarctica–Australia moved as suggested in Figures 2 and 3 between the latest Precambrian and the end of the Cambrian. Deformation in the Puncoviscana Formation of Argentina (Aceñolaza et al 1988) could likewise reflect transpressional North America–South America relative motion.

At present, therefore, the supercontinental model of Figure 2 seems reasonable for the early to mid-Neoproterozoic ($\sim$0.8–0.7 Ga), with amalgamation of the "daughter" Gondwana supercontinent before the end of the Precambrian. This does, however, require a separate explanation of the thermal subsidence in the latest Precambrian to earliest Cambrian that initiated the Cordilleran miogeocline along the western margin of Laurentia. Reliable paleomagnetic data for the major continents during the latest Precambrian to Middle Cambrian are urgently needed to test these intriguing ideas.

THE GONDWANA SUPERCONTINENT

Early to Mid-Paleozoic

From the Cambrian until the birth of the southern oceans in the Middle Jurassic, Antarctica formed the core of the Gondwana Supercontinent. During that interval of approximately 350 million years, Gondwana appears to have moved significantly with respect to the spin axis of the earth (Figure 4). Although the paleomagnetic data are not unequivocal, they are supported by geologic evidence of two distinct glaciations. North Africa was positioned over the South Pole during the Late Cambrian and Ordovician (c. 500–450 Ma) when the Saharan area underwent glaciation. Motion over the pole may have put southern South America there by the Middle Silurian (c. 425 Ma), the drift then reversing so that central Africa was in a polar position in the Late Devonian (375 Ma). The drift direction apparently reversed again in the late Paleozoic, the supercontinent moving across the pole so that present day southern South America, southern Africa, India, East Antarctica, and Australia were affected by the Permo-Carboniferous glaciation (300–250 Ma). By the beginning of the Mesozoic (245 Ma) the South Pole was in the Pacific Ocean basin off West Antarctica.

The motion of a continent relative to the spin axis of the earth as derived from paleomagnetic data alone does not yield information regarding relative plate motions along its boundaries. However, major episodes of compression, subduction-related magmatism, and tectonic accretion along the

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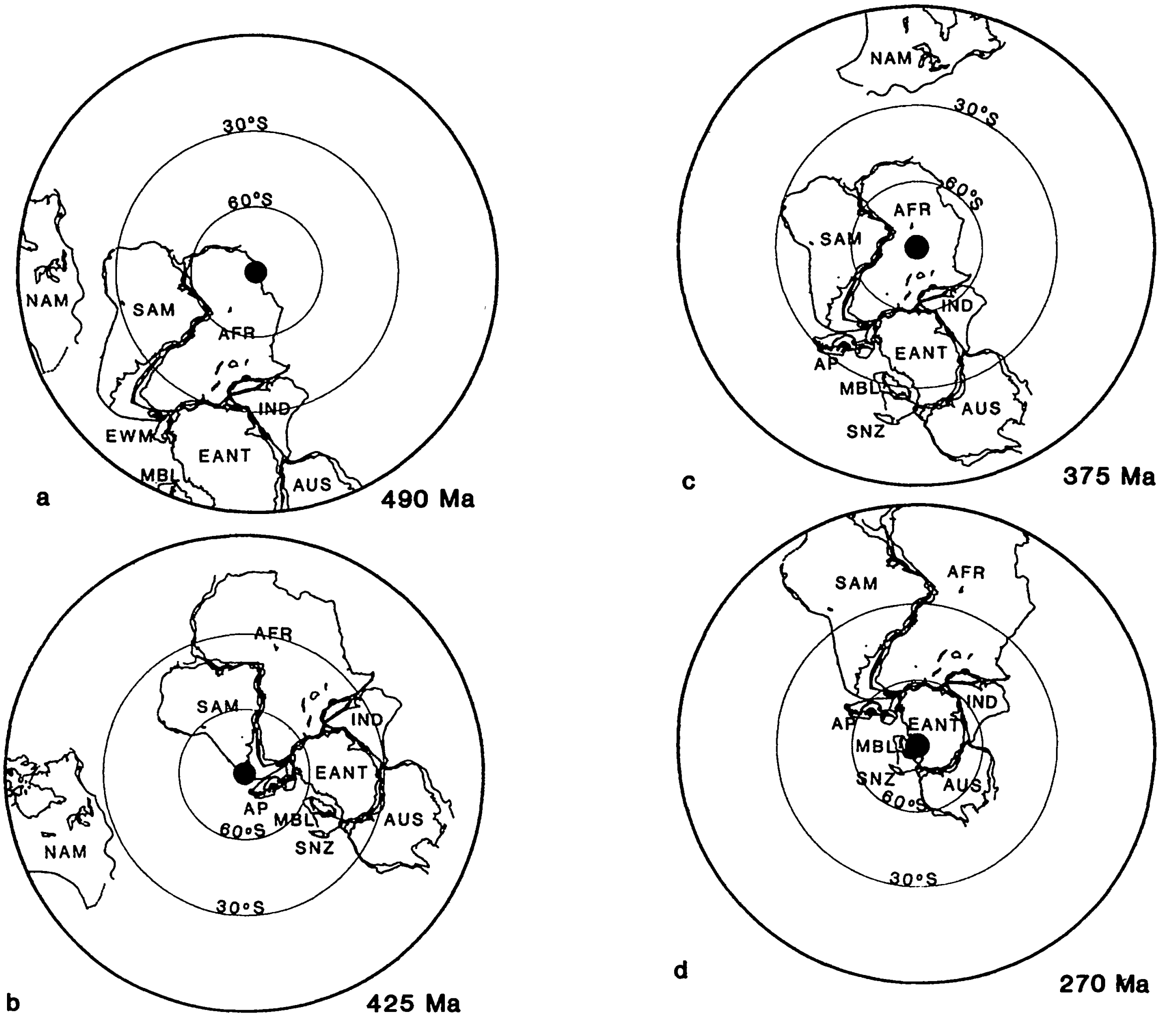

Figure 4 Drift of the Gondwana supercontinent and Laurentia relative to the south geographic pole (*filled circle*) from the Ordovician until the Permian, based on paleomagnetic data described in Dalziel (1991, Figure 2).

Pacific margin of North America and South America during the late Mesozoic and Cenozoic (150 Ma to present), when motions are also constrained by marine geophysical data, coincide with periods when those continents were converging with the floor of the Pacific Ocean (e.g. Dalziel 1986). A general correlation between the drift history of Gondwana between the Cambrian and the Middle Jurassic (500–150 Ma) and the tectonic development of its Pacific margin may reflect the same type of process (Coney 1990, Coney et al 1990).

The earliest period of tectonism along the Pacific margin of East Antarctica–Australia following the Neoproterozoic rifting and deformation recorded by the Beardmore Group, is the Cambrian-Ordovician Ross-Delamerian event (c. 500 Ma). The exact nature and timing of the

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Ross-Delamerian event are uncertain because of inadequate data and the difficulty of relating stratigraphic and geochronometric data in the Cambrian. The event appears to have involved both strike-slip and compressional deformation as well as subduction-related magmatism above a cratonward-dipping slab (Rowell & Rees 1989, Borg et al 1990). Strike-slip deformation may have started as early as the Middle Cambrian (Rowell et al 1992).

The differences between the Antarctica-Australia and North America trilobite faunas in the Cambrian indicate that there was a substantial oceanic barrier between the two margins by the Middle Cambrian (Jell 1974). This is in keeping with the reconstruction shown in Figure 3 which suggests the Pacific Ocean was ~9000 km wide by the end of the Cambrian, making transformation of the rifted East Antarctica–Australia margin into a zone of convergence by that time quite plausible. On the other hand, the southern Iapetus between eastern North America and western South America remained narrow (~1700 km). Destruction of the East Antarctica–Australia late Precambrian–Early Cambrian rifted margin by the end of the Cambrian explains the limited development of the early Paleozoic shelf sequence. Outer parts of the East Antarctica–Australia margin (Figure 1) may have been displaced laterally (Rowell & Rees 1989, Rowell et al 1992).

Portions of the displaced margins such as the Pensacola and Queen Maud mountains form a narrow exterior zone of the craton along the Transantarctic Mountains (Figure 1). Others may have been accreted in North Victoria Land and southeastern Australia where the geology is extremely complex (Bradshaw et al 1985). Although opinions on details differ widely, there is general agreement that a collage of mixed continental, oceanic island arc, Andean-type magmatic arc, and deep marine sedimentary rocks was tectonically emplaced against the Ross orogen of North Victoria Land by the latest Devonian to Permian (c. 375–250 Ma; see Borg & De Paolo 1991). Subduction beneath this composite terrane prior to docking appears to have been opposed to that of the Ross orogen, as the chemistry of the Devonian Admiralty intrusives has the opposite polarity to that of the Cambro-Ordovician intrusives along the craton margin (Borg et al 1987, 1990).

Late Paleozoic to Early Mesozoic

Convergence dominated the history of the entire Pacific margin of Gondwana during the Paleozoic (Coney 1990), and the basement of the southern Andes and Antarctic Peninsula exposes subduction-related magmatic arc rocks of mid- to late Paleozoic age (Pankhurst 1990, Milne & Millar 1991). There was massive fore-arc accretion along these margins during the late

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Paleozoic to early Mesozoic, including accretion of exotic seamounts with caps of fusulinid limestone (Dalziel 1982, Figure 5). Ramos (1986) has suggested that these rocks were accreted to the margin of the Gondwana supercontinent as a single entity—the Patagonia terrane, the collision generating the early Mesozoic Gondwanide fold belt of the Sierra de la Ventana in Argentina, the Cape fold belt in southern Africa, and the Ellsworth and Pensacola Mountains of Antarctica (Figure 5). There are no reliable paleomagnetic data directly indicating that the Patagonia terrane is allochthonous. However, deformation within the African craton, and the rotation of the Falkland Islands (FI) and EWM terranes followed Gondwanide folding and occurred prior to the appearance of seafloor within the Gondwana craton (Daly et al 1991, Dalziel & Grunow 1991). This intraplate deformation and the localized Gondwanide folding may have resulted from a collisional event. Offset of the subduction zones along the Antarctic Peninsula and NZ margins in the Triassic reconstruction of Grunow et al (1991) (Figure 5) could reflect closure of a marginal basin floored by stretched continental crust, there being no convincing evidence of a suture.

During the Devonian to Early Jurassic, the Gondwana craton-cover strata were deposited in the interior of the Gondwana supercontinent. The Beacon Supergroup of the Transantarctic Mountains represents this sequence in Antarctica. The Beacon was deposited in a series of basins behind the convergent Pacific margin, and records both the movement of the supercontinent relative to the South Pole (Figure 4), and events along the Pacific margin. Most prominent are the deposits resulting from Permo-Carboniferous glaciation when Antarctica was located over the South Pole, and the development of a foredeep basin in the Pensacola and Ellsworth Mountains region during the Permian in response to loading of the continental margin during the Gondwanide orogeny (Collinson 1991, Barrett 1991; Figure 5). It is the Permian strata that carry the *Glossopteris* flora found by the first geologists to visit the continent.

THE ANTARCTIC CONTINENT AND PLATE

Initial Fragmentation of Gondwana

In reviewing our understanding of the development of the present-day Antarctic continent and plate from the breakup of the Gondwana supercontinent to the present day, I use a series of maps (Figure 5–10) recently developed by Grunow et al (1991). These use data from the oceanic basins to constrain the major continents, and paleomagnetic data together with geologic information to position microcontinents and other displaced terranes. Displacement of the FI and EWM blocks following the Gondwanide folding was the first tectonism associated with the fragmentation of the

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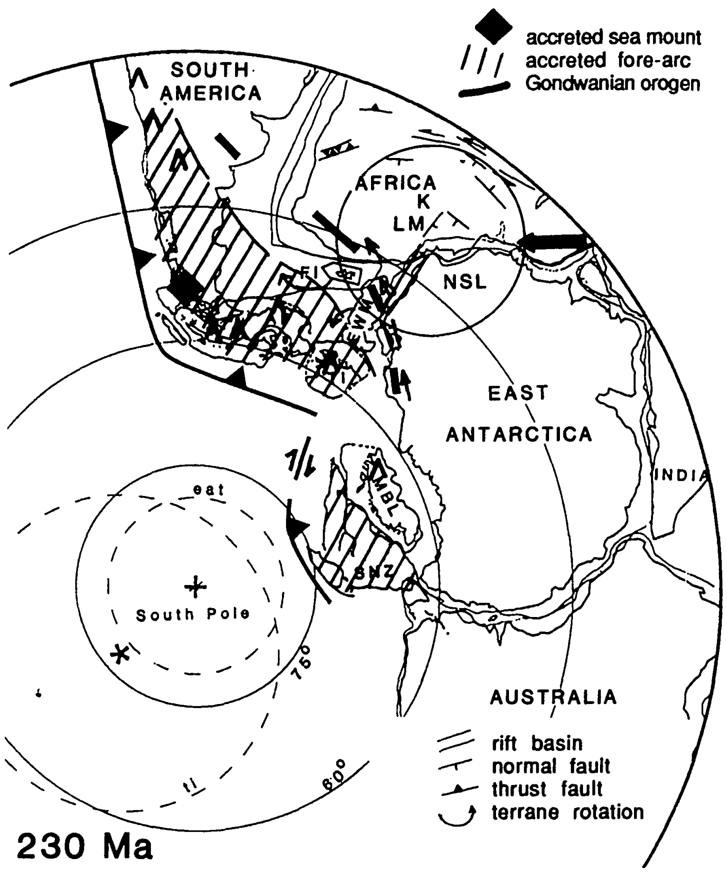

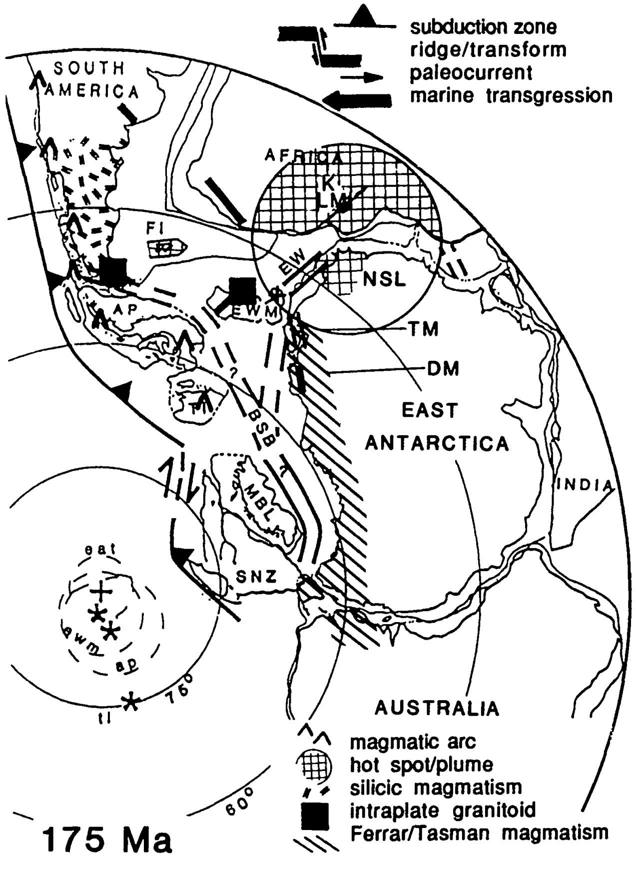

Figure 5 (*Left*) Gondwana during the Late Triassic (230 Ma) after the Gondwanide orogeny; based on the reconstruction of Grunow et al (1991), intraplate deformation in Africa after Daly et al (1991), and reconstruction of the Gondwanide orogen after Dalziel & Grunow (1991). Arc magmatism from Pankhurst (1990). The positioning of the incipient Karoo/Bouvet plume (*circle*) follows that of White & McKenzie (1989). AP—Antarctic Peninsula block; EWM—Ellsworth-Whitmore Mountains block; FI—Falkland Islands terrane (shape schematic); K—Karoo basin; LM—Lebombo monocline; MBL—Marie Byrd Land; NSL—Neuschwabenland; SNZ—south New Zealand (South Island, Campbell Plateau, and Chatham Rise); TI—Thurston Island block. Dashed circles are confidence circles about paleomagnetic poles (*asterisks* and *crosses*) of Grunow et al (1991) and are identified by letters as above. The reconstructions in Figures 5 through 10 are all polar stereographic projections centered on the paleomagnetic south pole (*cross*) determined for East Antarctica (*eat*).

Figure 6 (*Right*) Gondwana in the Middle Jurassic (175 Ma) after the rotation of the Falkland Island and Ellsworth-Whitmore Mountains blocks; based on the reconstruction of Grunow et al (1991). The location of the magmatic provinces follows Cox (1978), Dalziel et al (1987), White & McKenzie (1989), and Storey & Alabaster (1991). Additional abbreviations: BSB—Byrd Subglacial Basin (including Bentley Subglacial Trough); DM—Dufek Massif; EW—Explora wedge; TM—Theron Mountains.

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Gondwana supercontinent. Initial counterclockwise rotation of the EWM block accompanied opening of a northeast-trending rift flanked by inward-dipping reflectors along the eastern side of the Weddell Sea (Kristoffersen & Hinz 1991). The northern end of this rift appears to have been the Explora wedge of seaward-dipping reflectors on the Antarctic side, and the Lebombo monocline on the African side (Figures 5 and 6, see Martin & Hartnady 1986). The latter is an east-facing flexure in the Karoo plateau lavas, and the former is interpreted to be a thick volcanic sequence (Hinz & Krause 1982). Karoo volcanism had two main peaks, at 193 ± 5 and 178 ± 5 Ma (Cox 1988), and the Explora wedge is interpreted to be Middle Jurassic based on data from ODP Leg 113 (Doyle et al 1991). The layered mafic Dufek massif at the southern end of the failed rift in Antarctica is part of the Ferrar mafic igneous province which has been dated at 179 ± 7 Ma (Kyle et al 1981), and intraplate granites cutting the folded Paleozoic strata of the EWM block average 173 ± 3 Ma (Millar & Pankhurst 1987). White & McKenzie (1989) have postulated that the Karoo magmatism, and that of the Weddell Sea margin, resulted from the initial expression of a mantle plume now represented by the Bouvet Island hot-spot, and Brewer (1989) has identified Jurassic dikes in the Theron Mountains as representing the limit of magmatism related to the suggested Karoo-Bouvet plume along the Transantarctic margin (Figure 6). However, the persistence of the Ferrar diabases and related silicic volcanic rocks along this entire margin into Tasmania and South Australia (Elliot 1991), and the kinematics of related faulting (Wilson 1991), demonstrate Middle Jurassic rifting within Gondwana far beyond the immediate influence of the proposed plume. This extension could have been controlled by stresses generated above the Pacific margin subduction zone (Cox 1978, Dalziel et al 1987).

Initial seafloor spreading between the Somali and Mozambique basins during the Late Jurassic (c. 165 Ma) truncated the Explora-Lebombo rift by right-lateral shearing between Africa and East Antarctica (Lawver et al 1991, Figure 7). This separation was accompanied by widespread extension and silicic magmatism in southern South America, leading to the development of the ophiolitic floor of the Rocas Verdes basin along the Andean margin (Dalziel 1981). Again the influence of a Pacific margin extensional stress regime is apparent. The Larsen Harbour Complex on South Georgia has been dated using U-Pb/zircon geochronometry at 150 Ma (Mukasa et al 1988). Storey & Alabaster (1991) have recently reviewed the geochemistry of the widespread magmatism associated in time and space with the initial fragmentation of Gondwana. They argue that during the initial stages of breakup, the Pacific margin magmas of the Antarctic Peninsula and southernmost South America (magmatic arc of Figures 6 and 7), and the contemporaneous Ferrar-Tasman suite, were both derived from a lithospheric mantle source enriched by the long-lived Paleozoic to early Mesozoic subduction of sediments. Lower to Middle Jurassic continental magnesian andesites comparable to those of Baja California and the Setouchi volcanic belt in Japan occur along the Pacific margin of the Antarctic Peninsula and on South Georgia, and they suggest that the high geothermal gradient indicated by the composition of these rocks was generated by subduction of an active spreading ridge. However, propagation of the main spreading ridge separating East and West Gondwana, through the embryonic Weddell Sea, into an extensional regime beyond the Antarctic Peninsula/Andean arc as shown by Grunow et al (1991, Figure 7) would also provide a thermal regime for magma generation of this type. Separation of the Antarctic Peninsula from southern South America at this time was very slow, and small relative motions between the EWM, TI, and AP blocks resulted in localized deformation such as the Late Jurassic to Early Cretaceous folding event at the base of the AP known as the Palmer Land orogeny (Grunow et al 1991).

Isolation of Antarctica

During the Early Cretaceous the South Atlantic started to open, turning the two plate East Antarctica–Africa system into the three plate South America–East Antarctica–Africa system (Lawver et al 1991), and in the model of Grunow et al (1991) the EWM block joined the Antarctic Peninsula and TI blocks to move essentially as one entity (Weddellia) during the opening of the Weddell Sea. Weddellia appears to have rotated clockwise along a transform fault between Berkner Island and the EWM block (Figure 8). The precise timing of the opening of the Weddell Sea remains to be resolved, but the ~30° clockwise rotation of Weddellia required by the paleomagnetic data from the TI block appears to have occurred between ~125 and ~110 Ma, and to have been transferred to relative motion across the magmatically active Pacific margin subduction zone along the boundary between the TI and MBL/New Zealand blocks—present-day Pine Island Bay (Grunow et al 1991). This almost exactly reversed the motion that generated the Gondwanide fold belt (compare Figures 5 and 8).

With the rapid opening of the South Atlantic Ocean basin during the Cretaceous normal interval, opening of the Weddell Sea was completed, and with the probable exception of some East Antarctica–MBL motion, the present-day shape of Antarctica was completed (Figure 9). Mid-Cretaceous increase in the convergence rate along the Andean margin and westward motion of the South American plate in a mantle reference frame (Dalziel 1986) resulted in collapse and inversion of the Rocas Verdes basin

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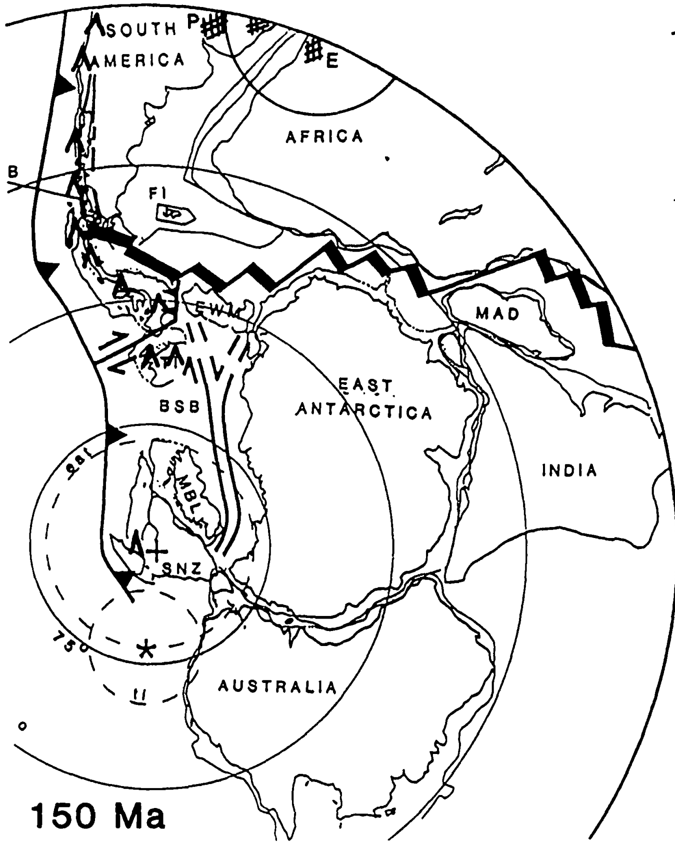

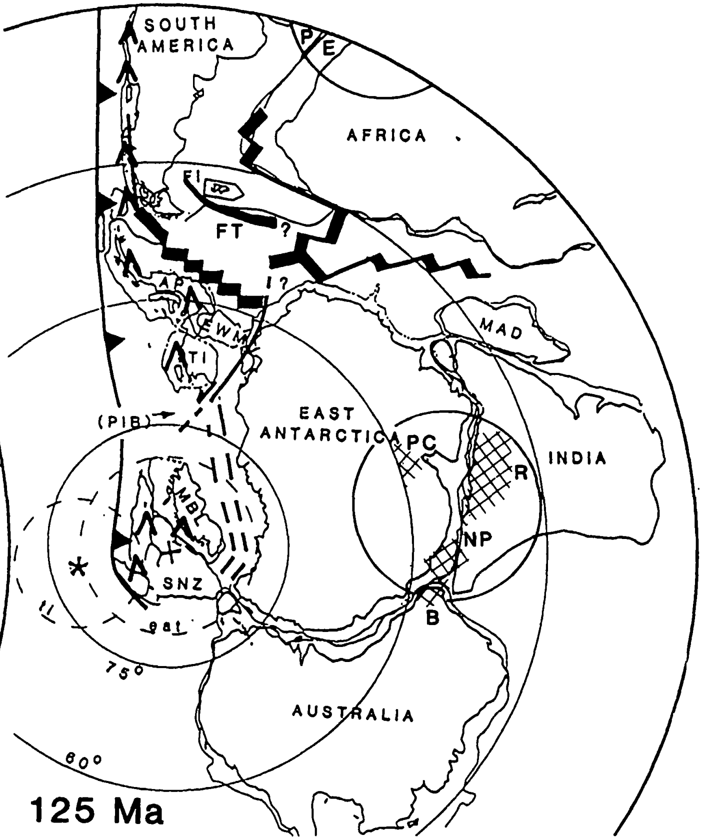

Figure 7 (*Left*) Gondwana in the latest Jurassic (150 Ma) after the initial separation of East and West Gondwana; based on the reconstruction of Grunow et al (1991). Opening of the Rocas Verdes basin is based on Mukasa et al (1988), and the location of the incipient Parana/Tristan da Cunha plume follows White & McKenzie (1989). Legend as in Figures 5 and 6. Additional abbreviations: E—Etendeka volcanics; P—Parana volcanics; RVB—Rocas Verdes basin.

Figure 8 (*Right*) Gondwana in the Early Cretaceous (125 Ma) immediately after initial opening of the South Atlantic Ocean basin; based on the reconstruction of Grunow et al (1991). Location of the incipient Kerguelen/Broken Ridge plume follows Royer & Coffin (1992). Additional abbreviations: B—Bunbury basalts; K—Kerguelen/Broken Ridge plume; FT—Falkland Trough; NP—Naturaliste Plateau; PC—Prince Charles Mountains; R—Rajmahal traps.

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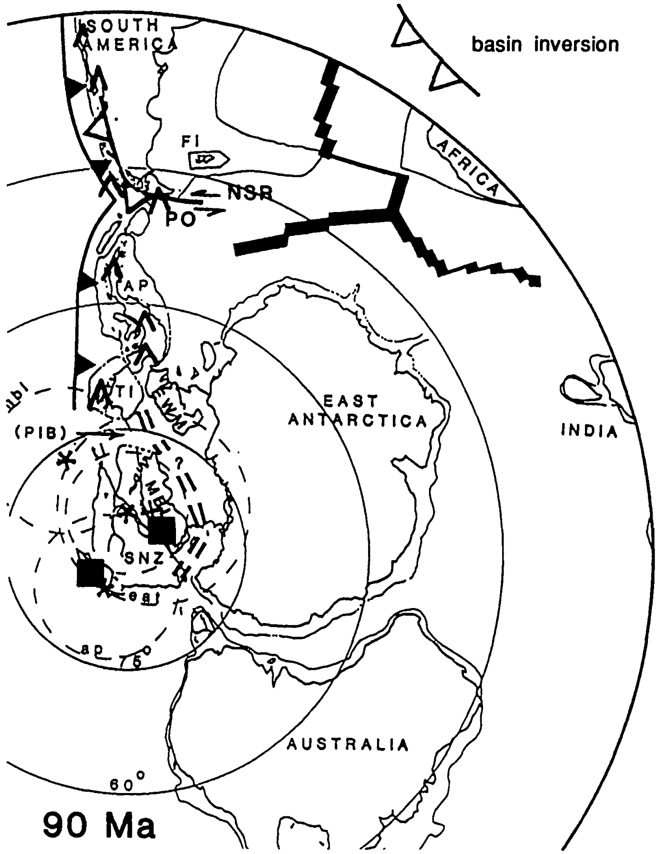

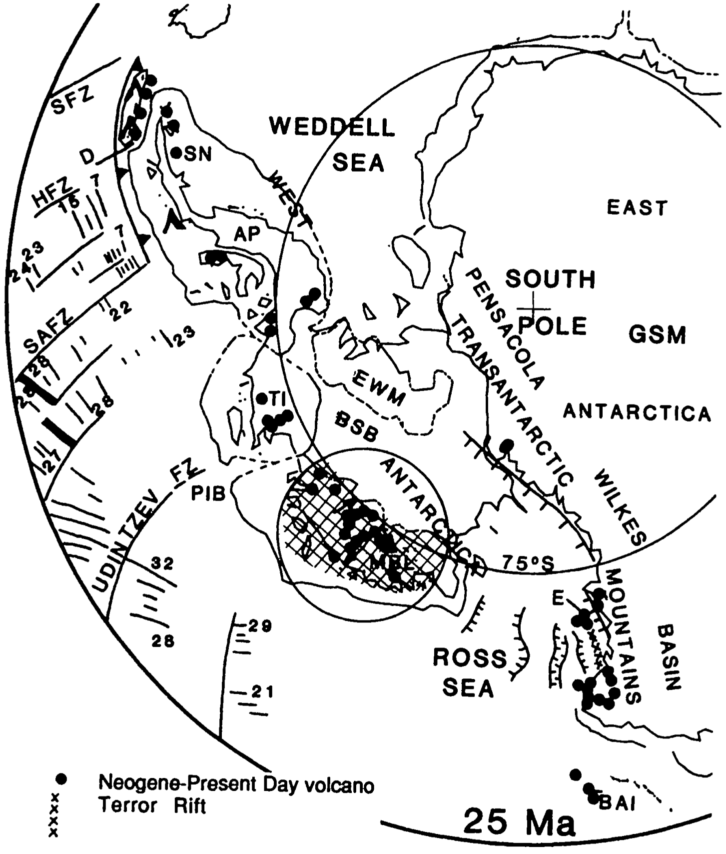

Figure 9 (*Left*) The Gondwana continents bordering the Pacific in the mid-Cretaceous (90 Ma) during formation of the Patagonian orocline and initial separation of South America and the Antarctic Peninsula; based on the reconstruction of Grunow et al (1991). The inversion of the Rocas Verdes basin to initiate Andean orogenesis follows Dalziel (1981), and the MBL/SNZ granitoids are based on Tulloch & Kimbrough (1989), Weaver et al (1991), Kimbrough (1991), and Richard et al (1991). Legend as in Figure 5. Additional abbreviations: NSR—North Scotia Ridge; PIB—Pine Island Bay; PO—Patagonian orocline.

Figure 10 (*Right*) Antarctica during the latest Paleogene (25 Ma) immediately following the opening of Drake Passage. Magnetic anomaly identification in the southern Pacific Ocean basin follows Mayes et al (1990). Location of Cenozoic volcanics (including Neogene and Present-Day deposits) is from LeMasurier & Thomson (1990), uplift of the Transantarctic Mountains from Fitzgerald et al (1989), and subsidence of the Pensacola-Wilkes basin from Stern & ten Brink (1989). Additional abbreviations: B—Balleny Islands; D—Deception Island; E—Mount Erebus; HFZ—Hero Fracture Zone; JRI—James Ross Island; SAFZ—South Anvers Fracture Zone; SFZ—Shackleton Fracture Zone; SN—Seal Nunataks.

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and the development of the Patagonian orocline by counterclockwise rotation of the Andean magmatic arc in Tierra del Fuego (Cunningham et al 1991). This accompanied the initiation of left-lateral motion of South America relative to the completed Antarctic plate along the site of the present-day North Scotia Ridge, and isolated West Antarctica tectonically from South America at the same time that East Antarctica and Australia finally separated.

The Cretaceous was a time of extensive arc magmatism along the Andean margin of South America and the Antarctic Peninsula and TI blocks of Antarctica (Pankhurst 1990). In MBL, however, the Byrd Coast granites of that age, although calc-alkaline and epizonal, are mostly peraluminous, and some of them have trace element compositions characteristic of A-type anorogenic granitoids (Weaver et al 1991). Thus it appears that although a late Mesozoic magmatic arc extended along the entire Pacific margin of West Antarctica/New Zealand, some of the Cretaceous granitoids of MBL reflect a different tectonic setting. Recent work in the Fosdick Mountains area of MBL has yielded mid-Cretaceous U-Pb zircon ages on Byrd Coast granites (e.g. 103 ± 3 Ma, see Kimbrough 1991), while older work yielded Rb-Sr mineral dates of 102–92 Ma reflecting Late Cretaceous uplift of deep-seated migmatitic rocks (Richard et al 1991). These ages are similar to those determined from high-grade metamorphic rocks from the South Island of New Zealand which were interpreted as a tectonically denuded core complex (Tulloch & Kimbrough 1989), and suggest mid–Late Cretaceous extension and uplift in MBL and New Zealand immediately preceding separation of the latter from West Antarctica along the fracture zones revealed by the satellite altimetry data (Figure 1).

ICE, TECTONISM, AND THE FUTURE

Ice now covers the Antarctic continent. Marine seismic and side-scan data, supported by drilling results, show that the ice cap formerly extended to the edge of the continental shelf. Reports in the 1960s that mid-Tertiary volcanics rest on a glaciated surface were greeted with extreme skepticism. Drilling in Prydz Bay (Figure 1) has now shown that the history of glaciation extends back through the entire Oligocene, and there are indications of Eocene glaciation even on the northern fringes of West Antarctica. There is therefore a possibility that glaciation in East Antarctica extends back even into the Cretaceous, and that the growth and decline of ice sheets has been much more rapid and frequent than formerly believed (Webb 1990).

Development and fluctuation of the Antarctic ice sheet accompanied

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major tectonic changes even after the basic geography of the continent was established in the mid-Cretaceous. Immediately following rifting of New Zealand from MBL at about 90 Ma (Figure 9), subduction ceased sequentially eastward along the margin of West Antarctica from Pine Island Bay to the Hero Fracture Zone (Mayes et al 1990, Figure 10). Uplift of the Transantarctic Mountains along the western side of the Ross Sea embayment, initiated in the Mesozoic (Fitzgerald & Stump 1991), was renewed at about 60 Ma (Fitzgerald 1989). A bimodal alkaline volcanic province developed by the Oligocene, and spread from the Transantarctic Mountains to the tip of the Antarctic Peninsula (LeMasurier & Thomson 1990, Figure 10). Uplift of the Transantarctic Mountains, and related flexural development of the Pensacolas-Wilkes Subglacial Basin, has recently been modeled as the result of heating of the free craton edge (Stern & ten Brink 1989)—which originated in the Neoproterozoic—during extension in the Ross Sea embayment, notably the volcanically active Terror Rift (Behrendt & Cooper 1991, Figure 10). This extension may be related to final movement of MBL with respect to East Antarctica. Faulting associated with uplift of the Transantarctic Mountains indicates a component of right-lateral displacement (Wilson 1991).

The cause of the extension and volcanicity is still unclear. Antarctica has become almost stationary with respect to the South Pole since the Late Cretaceous (Figure 9), and it is therefore tempting to suggest that it is related to a mantle plume as Kyle et al (1991) have recently done for Marie Byrd Land (Figure 10). From Pine Island Bay to the tip of the Antarctic Peninsula, however, the volcanicity appears to be related to a continental margin extensional regime which developed after the cessation of subduction, and the small isolated Gaussberg alkaline volcano at ~90°E on the margin of the East Antarctic craton (LeMasurier & Thomson 1990) occurs at the end of the Kerguelen Plateau. The Cenozoic volcanic and extensional regime does not, therefore, appear to have one simple tectonic explanation.

A relationship between environmental changes and tectonism has been recognized for many years. Opening of gateways allowing deep ocean circulation around the entire Antarctic continent and uplift of the Transantarctic Mountains both occurred during the Cenozoic and have been linked to climatic deterioration and development of the Antarctic ice cap by several authors. The Prydz Bay drilling results indicate, however, that significant glaciation preceded development of a complete deep water pathway for the circum-polar current. Recently Behrendt & Cooper (1991) have suggested that the start of the latest cold period which changed Antarctic glaciation from temperate to polar (2.5 Ma) was related to rapid (~1 km/m.y.) uplift of the Transantarctic Mountains.

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This important topic leads to the issue of future studies of the Antarctic continent. Although major advances have been made in the study of both tectonic and environmental changes through time, too little is known of their relationship. The continental interior may hold significant clues. The thickest part of the West Antarctic ice sheet is grounded in the Byrd Subglacial Basin (Figure 1) which reaches near-oceanic depths, yet the age and tectonic nature of this basin is unknown. It formed part of a seaway between the Indo-Atlantic and Pacific Oceans until glaciation, and may have had an important influence on oceanic circulation. The East Antarctic ice sheet covers the Gamburtzev Subglacial Mountains which have a relief of 3–4 km and come close to the surface, yet they are totally unknown geologically. The drainage basins of this ice sheet date back to the Permian, possibly to the Proterozoic. Debris in moraines along the Transantarctic Mountains indicate that they contain Neogene marine strata and suggest rapid and frequent fluctuations in the extent of the ice cover which are not obvious in sediment cores from the deep ocean basins (Webb 1990). The tantalizing indications of tectonic control of climatic change from the fringes of the Antarctic continent demand that we put more effort into studies of the rocks beneath the ice and submerged around the continent in this unique and critical global laboratory.

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Many colleagues around the world who provided me with preprints of articles in press have helped make this review as up-to-date as possible. I apologize that space severely limits the number of citations. Constructive comments from Kevin Burke, Mike Coffin, Dickson Cunningham, Olav Eldholm, Anne Grunow, Richard Hanson, Larry Lawver, and Terry Wilson greatly improved the manuscript.

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1992AREPS..20..501D

Literature Cited

Aceñolaza, F. G., Miller, H., Toselli, A. J. 1988. The Puncoviscana Formation (Late Precambrian-Early Cambrian)—Sedimentology, tectonometamorphic history and age of the oldest rocks of NW Argentina. In *Lecture Notes in Earth Sciences 17*, ed. H. Balhlburg, Ch. Breitkreuz, P. Giese, pp. 25–37. Heidelberg: Springer-Verlag

Barrett, P. J., ed. 1989. Antarctic Cenozoic history from the CIROS-1 drillhole, McMurdo Sound. *DSIR Bull.* 245: 5–6. Wellington: DSIR

Barrett, P. J. 1991. The Devonian to Triassic Beacon Supergroup of the Transantarctic Mountains and correlatives in other parts of Antarctica. See Tingey 1991

Behrendt, J. C., Cooper, A. 1991. Evidence of rapid Cenozoic uplift of the shoulder escarpment of the West Antarctic rift system and a speculation on possible climate forcing. *Geology* 19: 315–19

Bond, G. C., Kominz, M., Devlin, W. 1991. Rapid global-scale events during the Precambrian-Cambrian transition: consequence of rapid dispersal of a late Proterozoic supercontinent? *Geol. Soc. Am. Abstr. with Programs* 23: A112 (Abstr.)

Bond, G. C., Nickeson, P. A., Kominz, M. A. 1984. Breakup of a supercontinent between 625 Ma and 555 Ma: New evidence and implications for continental histories. *Earth Planet. Sci. Lett.* 70: 325–45

Borg, S. G., DePaolo, D. J. 1991. A tectonic model of the Antarctic Gondwana margin with implications for southeastern Australia: Isotopic and geochemical evidence. *Tectonophysics* 196: 339–58

Borg, S. G., DePaolo, D. J., Smith, B. M. 1990. Isotopic structure and tectonics of the Central Transantarctic Mountains. *J. Geophys. Res.* 95: 6647–67

Borg, S. G., Stump, E., Chappel, B. W., McCulloch, M. T., Wyborn, D., et al. 1987. Granitoids of northern Victoria Land, Antarctica: Implications of chemical and isotopic variations to regional crustal structure and tectonics. *Am. J. Sci.* 287: 127–69

Bradshaw, J. D., Weaver, S. D., Laird, M. G. 1985. Suspect terranes and Cambrian tectonics in northern Victoria Land, Antarctica. In *Tectonostratigraphic Terranes of the Circum-Pacific Region*, ed. D. G. Howell, pp. 467–79. Houston: Earth Sci. Ser. No. 1

Brewer, T. S. 1989. Mesozoic dolerites from Whichaway Nunataks. *Antarct. Sci.* 1: 151–55

Collinson, J. W. 1991. The palaeo-Pacific margin as seen from East Antarctica. See Thompson et al 1991, pp. 199–204

Coney, P. J. 1990. Terranes, tectonics and the Pacific Rim. *Aust. Inst. Mining Metall., Pacific Rim* 90: 19–30

Coney, P. J., Edwards, A., Hine, R., Morrison, F., Windrim, D. 1990. The regional tectonics of the Tasman orogenic system, eastern Australia. *J. Struct. Geol.* 12: 514–44

Cox, K. G. 1978. Flood basalts, subduction and the break-up of Gondwanaland. *Nature* 274: 47–49

Cox, K. G. 1988. The Karoo Province. In *Continental Flood Basalts*, ed. J. D. Macdougall, pp. 239–72. Dordrecht: Kluwer

Cunningham, W. D., Klepeis, K. A., Gose, W. A., Dalziel, I. W. D. 1991. The Patagonian orocline: New paleomagnetic data from the Andean magmatic arc in Tierra del Fuego. *J. Geophys. Res.* 96: 16,061–68

Daly, M. C., Lawrence, S. R., Kimun'a, D., Binga, M. 1991. Late Palaeozoic deformation in central Africa: a result of distant collision? *Nature* 350: 605–7

Dalziel, I. W. D. 1981. Back-arc extension in the southern Andes, a review and critical reappraisal. *Philos. Trans. R. Soc. London Ser. A* 300: 319–35

Dalziel, I. W. D. 1982. Pre-Jurassic history of the Scotia Arc region. In *Antarctic Geoscience*, ed. C. Craddock, pp. 111–26. Madison: Univ. Wis. Press

Dalziel, I. W. D. 1986. Collision and cordilleran orogenesis, an Andean perspective. In *Collision Tectonics*, ed. M. P. Coward, A. C. Ries, Geol. Soc. London Spec. Publ. No. 19, pp. 389–404

Dalziel, I. W. D. 1991. Pacific margin of Larentia and East Antarctica/Australia as a conjugate rift pair: Evidence and implications for an Eocambrian supercontinent. *Geology* 19: 598–601

Dalziel, I. W. D. 1992. Reply to comment on "Pacific margins of Laurentia and East Antarctica-Australia as a conjugate rift pair: Evidence and implications for an Eocambrian supercontinent" by Ian W. D. Dalziel (Geology, V. 19, pp. 598–601), by Robert J. Stern, Mohamed Sultan and Mohamed Gamal-Salam. *Geology*. In press

Dalziel, I. W. D., Elliot, D. H. 1982. West Antarctica: Problem child of Gondwanaland. *Tectonics* 1: 3–19

Dalziel, I. W. D., Grunow, A. M. 1992. Late Gondwanide tectonic rotations within Gondwanaland: Causes and consequences. *Tectonics*. In press

© Annual Reviews Inc. • Provided by the NASA Astrophysics Data System

1992AREPS..20..501D

Dalziel, I. W. D., Storey, B. C., Garrett, S. W., Grunow, A. M., Herrod, L. D. B., et al. 1987. Extensional tectonics and the fragmentation of Gondwanaland. In *Continental Extensional Tectonics*, ed. J. F. Dewey, M. P. Coward, P. Hancock, Geol. Soc. London Spec. Publ. 28, pp. 433–41

Doyle, P., Crame, J. A., Thomson, M. R. A. 1991. Late Jurassic-Early Cretaceous macrofossils from Leg 113, Hole 692B, eastern Weddell Sea. In *Proc. ODP, Sci. Results, 113*, ed. P. F. Barker, J. P. Kennett et al, pp. 443–48

Du Toit, A. L. 1937. *Our Wandering Continents*. Edinburgh: Oliver & Boyd. 366 pp.

Elliot, D. H. 1991. Triassic-Early Cretaceous evolution of Antarctica. In *Geological Evolution of Antarctica*, ed. M. R. A. Thomson, J. A. Crame, J. W. Thomson, pp. 541–48. Cambridge: Cambridge Univ. Press

Fitzgerald, P. G. 1989. Uplift and formation of the Transantarctic Mountains application of apatite fission trace analysis to tectonic problems. *28th Int'l. Geo. Congress*, Washington, DC. Abstr. p. 491

Fitzgerald, P. G., Stump, E. 1991. Late Cretaceous and Cenozoic uplift of the Transantarctic mountains: Implications for regional tectonics. *Geol. Soc. Am. Abstr. with Programs* 23: A305 (Abstr.)

Goodge, J. W., Borg, S. G., Smith, B. K., Bennett, V. C. 1991. Tectonic significance of Proterozoic ductile shortening and translation along the Antarctic margin of Gondwana. *Earth Planet. Sci. Lett.* 102: 58–70

Groenwald, P. B., Grantham, G. H., Watkeys, M. K. 1991. Geological evidence for a Proterozoic to Mesozoic link between southeastern Africa and Dronning Maud Land, Antarctica. *J. Geol. Soc. London*. 148: 1115–24

Grunow, A. M., Kent, D. V., Dalziel, I. W. D. 1991. New paleomagnetic data from Thurston Island: implications for the tectonics of West Antarctica and the Weddell Sea. *J. Geophys. Res.* 96: 17,935–54

Hanson, R. E., Wilson, T. J., Brueckner, H. K., Onstott, T. C., Wardlaw, M. S., et al. 1988. Reconnaissance geochronology, tectonothermal evolution, and regional significance of the middle Proterozoic Choma-Kalomo block, southern Zambia. *Precambrian Res.* 42: 39–61

Harland, W. B., Armstrong, R. L., Cox, A. V., Craig, L. E., Smith, A. G., Smith, D. G. 1990. *A Geologic Time Scale 1989*. Cambridge: Cambridge Univ. Press. 263 pp.

Hartnady, C. J. H. 1986. Was North America ("Laurentia") part of south-western Gondwanaland during the late Proterozoic era? *Suid-Afr. Tydskr. Wet.* 82: 251–54

Hartnady, C. J. H. 1991. About turn for supercontinents. *Nature* 352: 476–78

Hinz, K., Krause, W. 1982. The continental margin of Queen Maud Land, Antarctica: Seismic sequences, structural elements, and geological development. *Geol. Jahrb.* E23: 17–41

Hoffman, P. F. 1991. Did the breakout of Laurentia turn Gondwanaland inside out? *Science* 252: 1409–12

Jankowski, E. J., Drewry, D. J. 1981. The structure of West Antarctica from geophysical studies. *Nature* 291: 17–21

Jell, P. A. 1974. Faunal provinces and possible planetary reconstruction of the middle Cambrian. *J. Geol.* 82: 319–50

Jezek, P., Willner, A. P., Aceñolaza, F. G., Miller, H. 1985. The Puncoviscana trough—a large basin of Late Precambrian to Early Cambrian age on the Pacific edge of the Brazilian shield. *Geol. Rundsch.* 74/3: 573–84

Kimbrough, D. L., Richard, S. M. 1991. *Geochronology of basement rocks in the Fosdick Mountain region of West Antarctica and correlation with Cretaceous extensional terrains of southern New Zealand. 6th Int. Symp. Antarc. Earth Sci., Ranzan, Japan*, pp. 313–16 (Abstr.)

Kristoffersen, Y., Hinz, K. 1991. Evolution of the Gondwana plate boundary in the Weddell Sea area. See Thomson et al 1991, pp. 225–30

Kyle, P. R., Elliot, D. H., Sutter, J. F. 1981. Jurassic Ferrar Supergroup tholeiites from the Transantarctic Mountains, Antarctica, and their relationship to the initial fragmentation of Gondwana. In *Gondwana Five*, ed. M. M. Cresswell, P. Vella, pp. 283–87. Rotterdam: A. A. Balkema

Kyle, P. R., McIntosh, W. C., Panter, K., Smellie, J. 1991. *Is volcanism in Marie Byrd Land related to a mantle plume? Gondwana 8*, Hobart, Australia (Abstr.)

Lawver, L. A., Royer, J.-Y., Sandwell, D. T., Scotese, C. R. 1991. Evolution of the Antarctic continental margins. See Thomson et al 1991, pp. 533–40

LeMasurier, W., Thomson, J. W., eds. 1990. Volcanoes of the Antarctic plate and Southern Ocean. *Antarctic Research Series, 48*. Washington, DC: Am. Geophys. Union

Martin, A. K., Hartnady, C. J. H. 1986. Plate tectonic development of the Southwest Indian Ocean: A revised reconstruction of East Antarctica and Africa. *J. Geophys. Res.* 91: 4767–86

Mayes, C., Sandwell, D. T., Lawver, L. A. 1990. Tectonic history and new isochron

© Annual Reviews Inc. • Provided by the NASA Astrophysics Data System

1992AREPS..20..501D

chart of the South Pacific. *J. Geophys. Res.* 95: 8543–67

McElhinny, M. 1991. A review of "A geologic time scale 1989" by Harland, W. B., et al eds., 1990. Cambridge University Press. 263 pp. *Nature* 349: 26

Millar, I. L., Pankhurst, R. J. 1987. Rb-Sr Geochronology of the region between the Antarctic Peninsula and the Transantarctic Mountains: Haag nunataks and Mesozoic granitoids. In *Gondwana Six: Structure, Tectonics, and Geophysics*, ed. G. D. McKenzie, pp. 151–60. Washington, DC: Am. Geophys. Union

Milne, A. J., Millar, I. L. 1991. Mid-Palaeozoic basement in eastern Graham Land and its relation to the Pacific margin of Gondwana. See Thomson et al 1991, pp. 335–40

Minister, J. B., Jordan, T. H. 1978. Present-day plate motions. *J. Geophys. Res.* 83: 5331–54

Moores, E. M. 1991. The Southwest U.S.–East Antarctic (SWEAT) connection: A hypothesis. *Geology* 19: 425–28

Mukasa, S. B., Dalziel, I. W. D., Brueckner, H. K. 1988. Zircon U-Pb Constraints on the Kinematic Evolution of the Northern Scotia Arc. *GSA Annu. Meet. Denver, CO, 1988, Abstr. with Programs*, p. A12

Norton, I. O., Sclater, J. G. 1979. A model for the evolution of the Indian Ocean and the breakup of Gondwanaland. *J. Geophys. Res.* 84: 6803–30

Pankhurst, R. J. 1990. The Paleozoic and Andean magmatic arcs of West Antarctica and southern South America. In *Plutonism from Antarctica to Alaska*, ed. S. M. Kay, C. W. Rapela, pp. 1–7. Geol. Soc. Am. Spec. Pap. 241

Porada, H. 1989. Pan-African rifting and orogenesis in southern to equatorial Africa and eastern Brazil. *Precambrian Res.* 44: 103–36

Ramos, V. A. 1986. Discussion of "Tectonostratigraphy, as applied to analysis of South African Phanerozoic basins," by H. de la R. Winter. *Trans. Geol. Soc. South Afr.* 89: 427–29

Ramos, V. A. 1988. Late Proterozoic-early Paleozoic of South America—a collisional history. *Episodes* 11: 168–74

Rees, M. N., Pratt, B. R., Rowell, A. J. 1989. Early Cambrian reefs, reef complexes, and associated lithofacies of the Shackleton Limestone, Transantarctic Mountains. *Sedimentology* 36: 341–61

Richard, S. M., Smith, C. H., Luyenduyk, B. P., Kimbrough, D. L. 1991. *Geological and geophysical investigations in the Northern Ford ranges, Marie Byrd Land, West Antarctica: implications for a zone of Late Mesozoic, deep crustal migmatization and flow in the Fosdick metamorphic complex. 6th Int. Symp. Ant. Earth Sci., Ranzan, Japan*, pp. 501–2 (Abstr.)

Ross, G. M. 1991. Tectonic setting of the Windermere Supergroup: the continental perspective. *Geology* 19: 1125–28

Rowell, A. J., Rees, M. N. 1989. Early Paleozoic history of the upper Beardmore Glacier area: implications for a major Antarctic structural boundary within the Transantarctic Mountains. *Antarct. Sci.* 1: 249–60

Rowell, A. J., Rees, M. N. 1991. Setting and significance of the Shackleton Limestone, central Transantarctic Mountains. See Thomson et al 1991, pp. 171–76

Rowell, A. J., Rees, M. N., Evans, K. R. 1992. Evidence of major Middle Cambrian deformation in the Ross orogen Antarctica. *Geology*. In press

Royer, J.-Y., Coffin, M. F. 1992. Jurassic to Eocene plate tectonic reconstructions in the Kerguelen Plateau region. *Proc. ODP Sci. Results, 120*. In press

Royer, J.-Y., Gahagan, L. M., Lawver, L. A., Mayes, C. L., Nürnberg, D., et al. 1990. A tectonic chart for the Southern Ocean derived from Geosat Altimetry data. In *Antarctica as an Exploration Frontier—hydrocarbon potential, geology and hazards*, ed. A. Grantz, L. Johnson, J. F. Sweeney. AAPG Studies in Geology 31: 89–100

Schmidt, D. L., Williams, P. L., Nelson, W. J., Ege, J. R. 1965. Upper Precambrian and Palaeozoic stratigraphy and structure of the Neptune Range of Antarctica. *US Geol. Surv. Prof. Pap. 525D*, pp. 112–19

Schopf, J. M. 1969. Ellsworth Mountains: position in West Antarctica due to sea floor spreading. *Science* 164: 63–66

Scott, R. F. 1913. *Scott's Last Expedition*, ed. L. Huxley. New York: Dodd & Mead

Shackleton, E. H. 1909. *The Heart of the Antarctic*. London: Heinemann. 419 pp.

Stern, R. J., Sultan, M., Abdel-Salam, M. G. 1992. Discussion of the paper "Pacific margins of Laurentia and East Antarctica-Australia as a conjugate rift pair: Evidence and implications for an Eocambrian supercontinent," by I. W. D. Dalziel (Geology, v. 19, pp. 598–601). *Geology*. In press

Stern, T. A., ten Brink, U. S. 1989. Flexural uplift of the Transantarctic Mountains. *J. Geophys. Res.* 94: 10,315–30

Storey, B. C., Alabaster, T. 1991. Tectonomagmatic controls on Gondwana breakup models: evidence from the proto-Pacific margin of Antarctica. *Tectonics*. In press

Storey, B. C., Macdonald, D. I. M., Millar, I. L., Pankhurst, R. J., Alabaster, T., et al.

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1992AREPS..20..501D

1991. *Upper Proterozoic rift-related basin and bimodal volcanic sequences in the Pensacola Mountains, Antarctica: precursor to Cambrian supercontinent breakup? Gondwana 8*, Hobart, Australia (Abstr.)

Stump, E., Smit, J. H., Self, S. 1986. Timing of events during the late Proterozoic Beardmore Orogeny, Antarctica: geological evidence from the La Gorce Mountains. *Geol. Soc. Am. Bull.* 97: 953–65

Taylor, F. B. 1910. Bearing of the Tertiary mountain belt on the origin of the Earth's plan. *Bull. Geol. Soc. Am.* 21: 179–226

Taylor, G. G. 1914. Short notes on palaeontology. In *Glaciology, physiography, stratigraphy, and tectonic geology of south Victoria Land*, ed. T. W. E. David, R. E. Priestley, British Antarctic Expedition 1907–9. Reports on the Scientific Investigations. *Geology* 1: 1–319

Thomson, M. R. A., Crame, J. A., Thomson, J. W., eds. 1991. *Geologic Evolution of Antarctica.* Cambridge: Cambridge Univ. Press

Tingey, R. J. 1991. *The Geology of Antarctica.* Oxford: Oxford Univ. Press. In press

Tulloch, A. J., Kimbrough, D. L. 1989. The Paparoa metamorphic core complex, New Zealand: Cretaceous extension associated with fragmentation of the Pacific margin of Gondwana. *Tectonics* 8: 1217–34

Van der Voo, R., McCabe, C., Scotese, C. 1984. Was Laurentia part of an Eocambrian supercontinent? In *Plate reconstructions from Paleozoic paleomagnetism*, ed. R. Van der Voo, C. Scotese, N. Bonhommet, pp. 131–36. Am. Geophys. Union Geodyn. Ser. 2

Van Schmus, W. R., Bickford, M. E., Zietz, I. 1987. Early and middle Proterozoic provinces in the central United States. In *Proterozoic Lithospheric Evolution*, ed. A. Kroner, pp. 43–68. Am. Geophys. Union Geodyn. Ser. 17

Weaver, S. D., Bradshaw, J. D., Adams, C. J. 1991. Granitoids of the Ford Ranges, Marie Byrd Land, Antarctica. See Thomson et al 1991, pp. 345–52

Webb, P. N. 1990. The Cenozoic history of Antarctica and its global impact. *Antarct. Sci.* 1: 3–21

Wegener, A. 1912. Die Entstehung der Kontinente. *Petermanns Mitteilungen*, pp. 185–95, 253–56, 305–9

White, R., McKenzie, D. 1989. Magmatism at rift zones: the generation of volcanic continental margins and flood basalts. *J. Geophys. Res.* 94: 7685–7729

Wilson, T. J. 1991. Mesozoic and Cenozoic structural patterns in the Transantarctic Mountains, southern Victoria Land. *Antarct. J. U.S.* In press