

## THE LITHOSPHERIC SETTING OF THE WEST ANTARCTIC ICE SHEET

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Antarctica consists of two geologically distinct provinces, a Precambrian craton in the eastern hemisphere, and a younger series of mobile belts south of the Pacific Ocean. Unlike its land-based counterpart covering the East Antarctic craton, the base of the West Antarctic ice sheet (WAIS) is largely below sea level in the Ross and Weddell embayments. The East Antarctic craton separated from the other southern continents during the Mesozoic fragmentation of the Gondwanaland supercontinent. Since separation, East Antarctica has been near the South Pole and during the immediate past ~40 million year history of Cenozoic continental glaciation, Antarctica has remained close to its present position. During the breakup of Gondwanaland, the four major crustal units that comprise the exposed rocks of West Antarctica—the Antarctic Peninsula, Thurston Island, the Ellsworth-Whitmore mountains, and Marie Byrd Land—rotated outward from the convergent Pacific margin of the East Antarctic craton as rigid blocks. The driving forces for this relative motion appear to have been a major mantle plume in the case of the Antarctic Peninsula, Ellsworth-Whitmore mountains, and Thurston Island blocks, and ridge-crest subduction in the case of Marie Byrd Land. Both processes resulted in the generation of unusually large areas of extended continental crust, modified by underplating and the intrusion of mafic material between the rigid crustal blocks and the craton margin. This extended and modified crust forms the floors of the Weddell and Ross embayments at elevations permitting the very existence of the WAIS. Cenozoic impingement of a mantle plume beneath Marie Byrd Land and the Ross embayment further altered this crust, initiating formation of the West Antarctic rift system. Ongoing fracturing, volcanic activity, and bordering uplift associated with the development of the rift system combine to modify the predominantly sub-sea level, lithospheric “cradle” of the unique marine-based WAIS, possibly influencing its present and future behavior.

### INTRODUCTION

Antarctica's name is derived from its present location, in the south polar region antipodal to that beneath the northern Constellation Arctus, the Bear. Of the two geologically distinct parts that make up the Antarctic continent, the larger portion is located in the eastern

hemisphere, the smaller portion is to the south of the Pacific Ocean in the western hemisphere. Sometimes referred to as Greater and Lesser Antarctica, they are known more commonly as East and West Antarctica. East Antarctica was a substantial portion of Gondwanaland, the southern part of Pangea, and itself a long-lived supercontinent amalgamated from preexisting continental entities during global plate reorganization at the end of Precambrian times, ~550 Ma. Six of the seven present major lithospheric plates comprising the cold upper thermal boundary layer of the planet, including the Antarctic plate, contain embedded remnants of Pangea. Pangea fragmented after the Triassic Period that ended at

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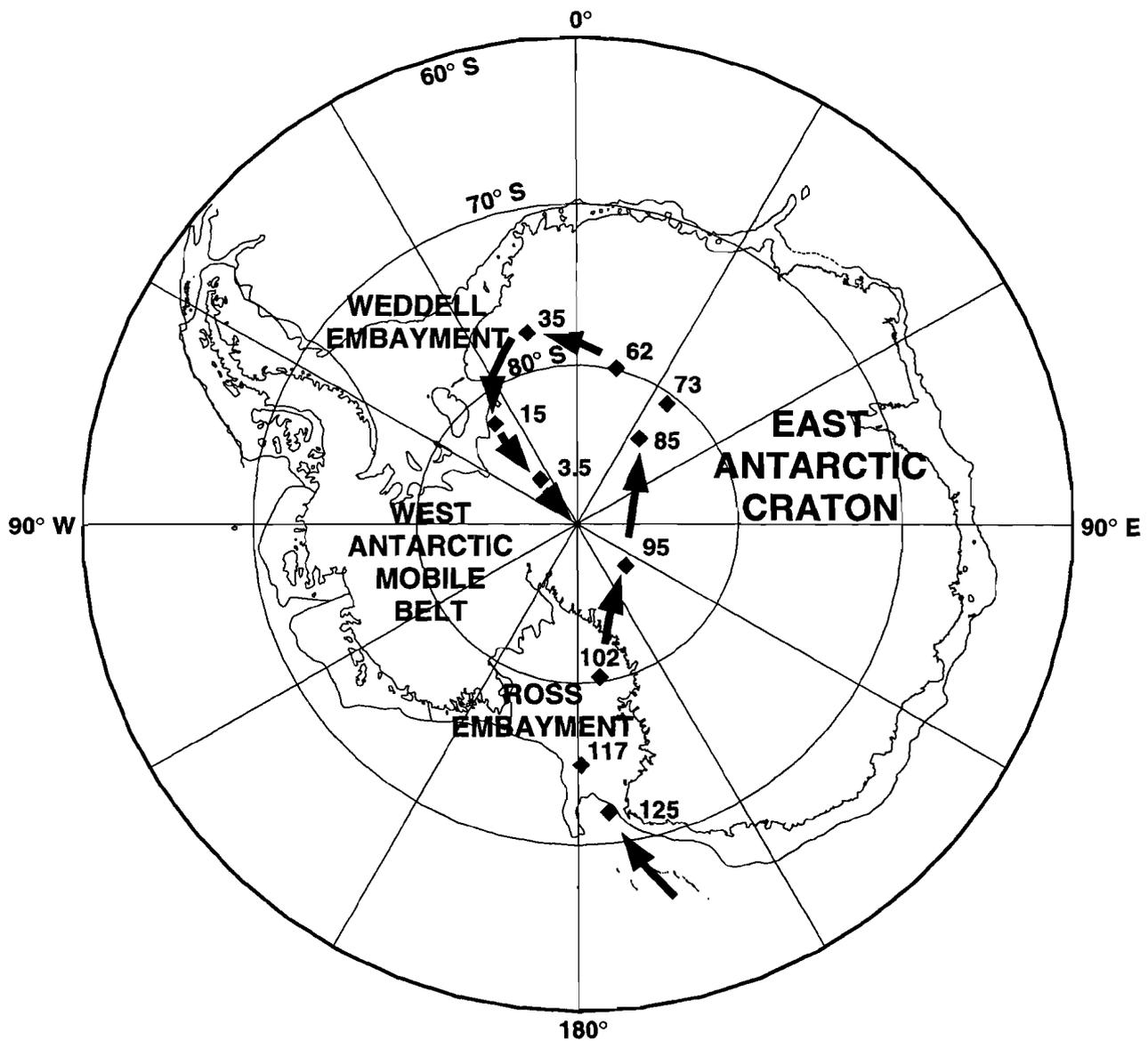


Fig. 1. Antarctic continent with a synthetic apparent polar wander path (Arrows, APWP, derived in part from rotation of data from other continents) for 125 Ma to Present [Di Venere, 1994]. Diamond symbols represent the position along the APWP of the South Pole relative to the continent at the time indicated.

~200 Ma. During the next 100 m.y. period, the Antarctic continent moved from high temperate latitudes to its nearly polar position (Figure 1). Between 185 and 95 Ma, four continents broke away from the present East Antarctic margin during Gondwana fragmentation, as illustrated by the geologically based reconstruction drawn by South African geologist Alex du Toit during the 1930's [DuToit, 1937, Figure 2]. Antarctica is classically known, therefore, as the "keystone" of Gondwanaland and for the past 100 m.y. it has been located over the South Pole.

Earth has undergone at least six major glaciations since the birth of the Solar System at ~4.55 Ga. Planetary "ice house" conditions, to use Fischer's term [1984], have extended over the planet for comparatively short time intervals of a few million to a few tens of million years during the Paleoproterozoic at ~2.1 Ga, during the Neoproterozoic at ~700 Ma and again at ~600 Ma, during the Paleozoic at ~460 and ~250 Ma, and most recently during the past ~40 m.y. of the Cenozoic Era. In all probability, the two existing remnants of more extensive Cenozoic glaciation, which cover Greenland in

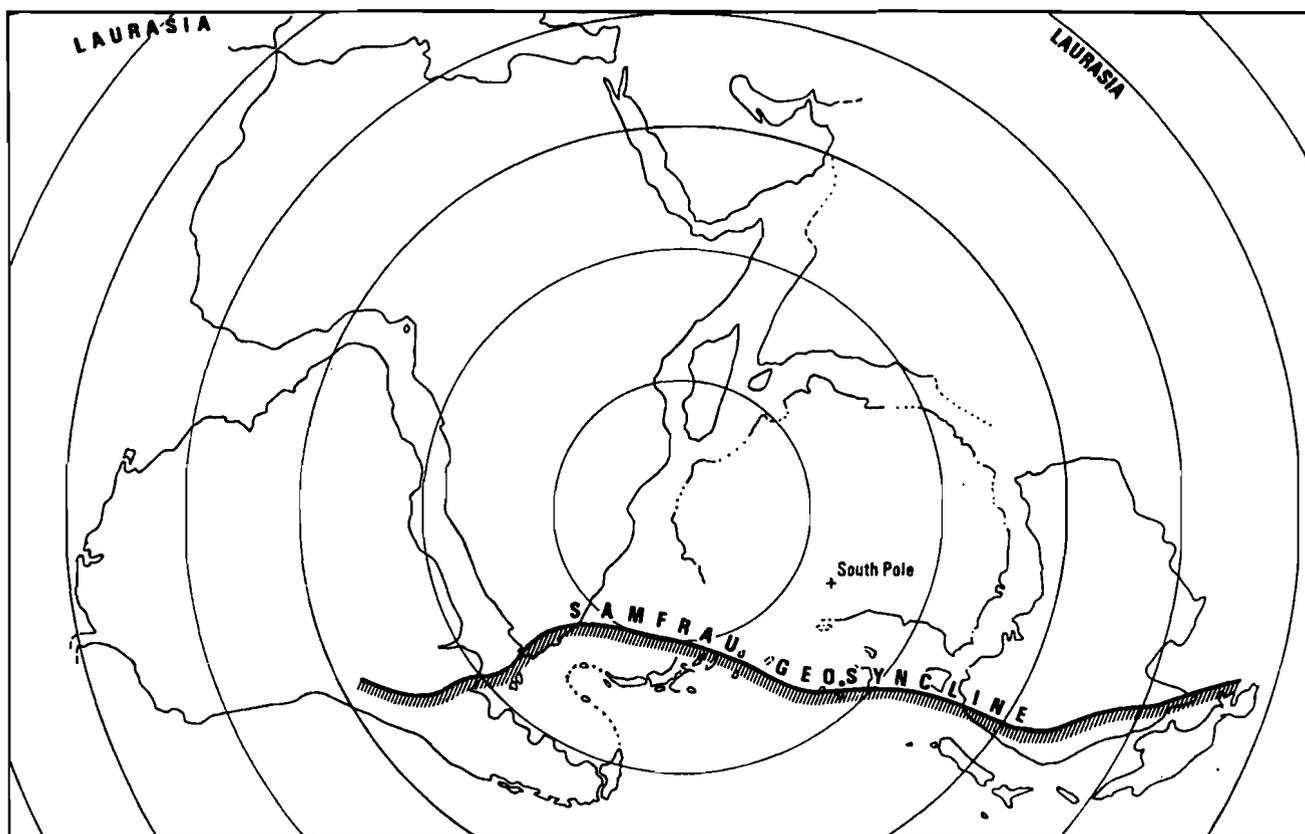


Fig. 2. Simplified version of Du Toit's geologically-based reconstruction of Gondwanaland [Du Toit, 1937].

the north and the Antarctic continent in the south, are ephemeral features of the Earth's surface. Even though the Weddell Sea margin of Antarctica lay very close to the South Pole at the onset of the Cenozoic glaciation, a paleoseaway had yet to open between the Antarctic Peninsula and South America (Figure 3). Thus the present Antarctic ice sheet may have begun to form prior to the establishment of a vigorous circum-polar current, though there was probably marine circulation through West Antarctica at the time of initial ice build-up [Lawver *et al.*, 1992; 1998].

#### THE WEST ANTARCTIC ICE SHEET IN TIME AND SPACE

East Antarctica was part of the tectonically stable Precambrian craton of the Gondwanaland supercontinent from 550 Ma to 200 Ma. It has apparently been a relatively stable area of Precambrian crust since the supercontinent began to break up at that time, though the presence of the small Gaussberg volcano on the coast, the Gamburtzev Subglacial Mountains, and depressions beneath the Lambert-Amery glacier and Lake Vostok have led to speculation concerning widespread recent volcan-

ism and rifting. In contrast, West Antarctica has been part of the tectonically active mobile belt generally known as the circum-Pacific "ring of fire," the zone of plate convergence along ancient continental margins fringing the Earth's largest ocean basin, throughout the Phanerozoic. These margins were formed during the Neoproterozoic (~800 Ma) during the breakup of the Rodinia supercontinent that gave birth to the Pacific Ocean basin. The boundary between East and West Antarctica, now marked by the Pacific side of the Transantarctic Mountains, originated during that event (see Dalziel, 1997, for review). Stable East Antarctica has remained predominantly above sea level and has a land based ice sheet. The West Antarctic Ice Sheet (WAIS) is largely marine-based. Understanding of the history of the WAIS, and consideration of its present and future behavior, must start with an appreciation of the lithospheric setting that permits its existence.

Reconstruction of Gondwana using the seafloor spreading data obtained from marine geophysical surveys confirmed Du Toit's reconstruction, but resulted in a geologically unacceptable overlap between an in-place Antarctic Peninsula and the Falkland Plateau [Norton and Sclater, 1979, Figure 4]. Together with the earlier

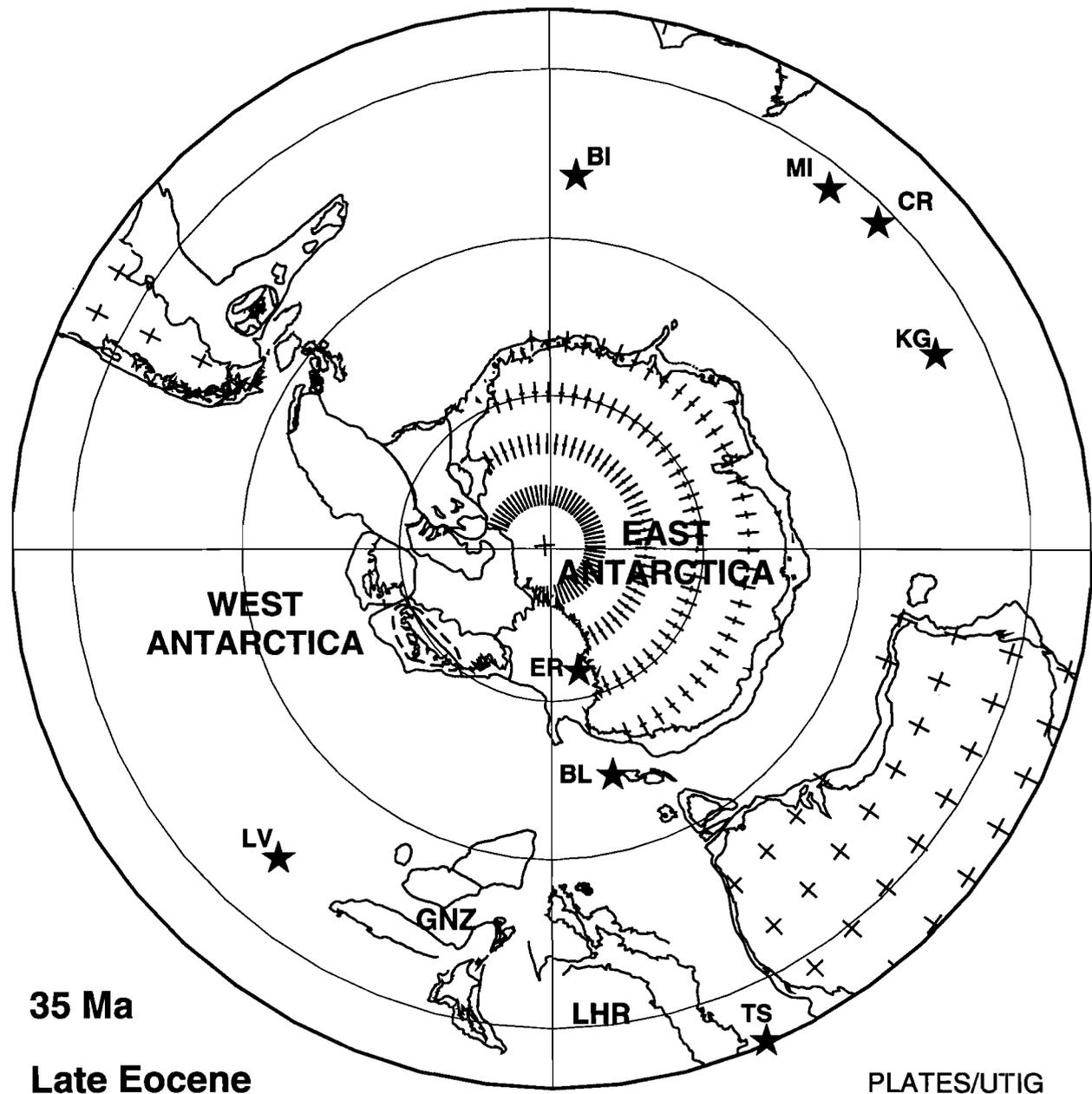


Fig. 3. Southern hemisphere at ~35 Ma based on seafloor spreading data. Cross - present South Pole; Stars - selected present-day hot spot; BI - Bouvet Island; BL - Balleny Islands; CR - Crozet Island; ER - Mount Erebus; GNZ - New Zealand microcontinent; KG Kerguelen; LHR - Lord Howe Rise; LV - Louisville Island; MI - Marion Island; TS - Tasman seamounts. Dashed line - extent of plume related to dome and volcanism [LeMasurier and Landis, 1996]. (PLATES project, Institute for Geophysics, University of Texas at Austin)

recognition that the Ellsworth Mountains of West Antarctica, the highest on the continent, were geologically part of the margin of the East Antarctic craton [Schopf, 1969], this led to the suggestion that West Antarctica consists of at least four major crustal blocks that have moved relative to each other, and also

relative to the East Antarctic craton during the Mesozoic and Cenozoic fragmentation of Gondwanaland [Dalziel and Elliot, 1982, Figure 5]. Geological and paleomagnetic studies over the past decade and a half have confirmed this hypothesis, and resulted in a generally consistent model for the tectonic evolution of the

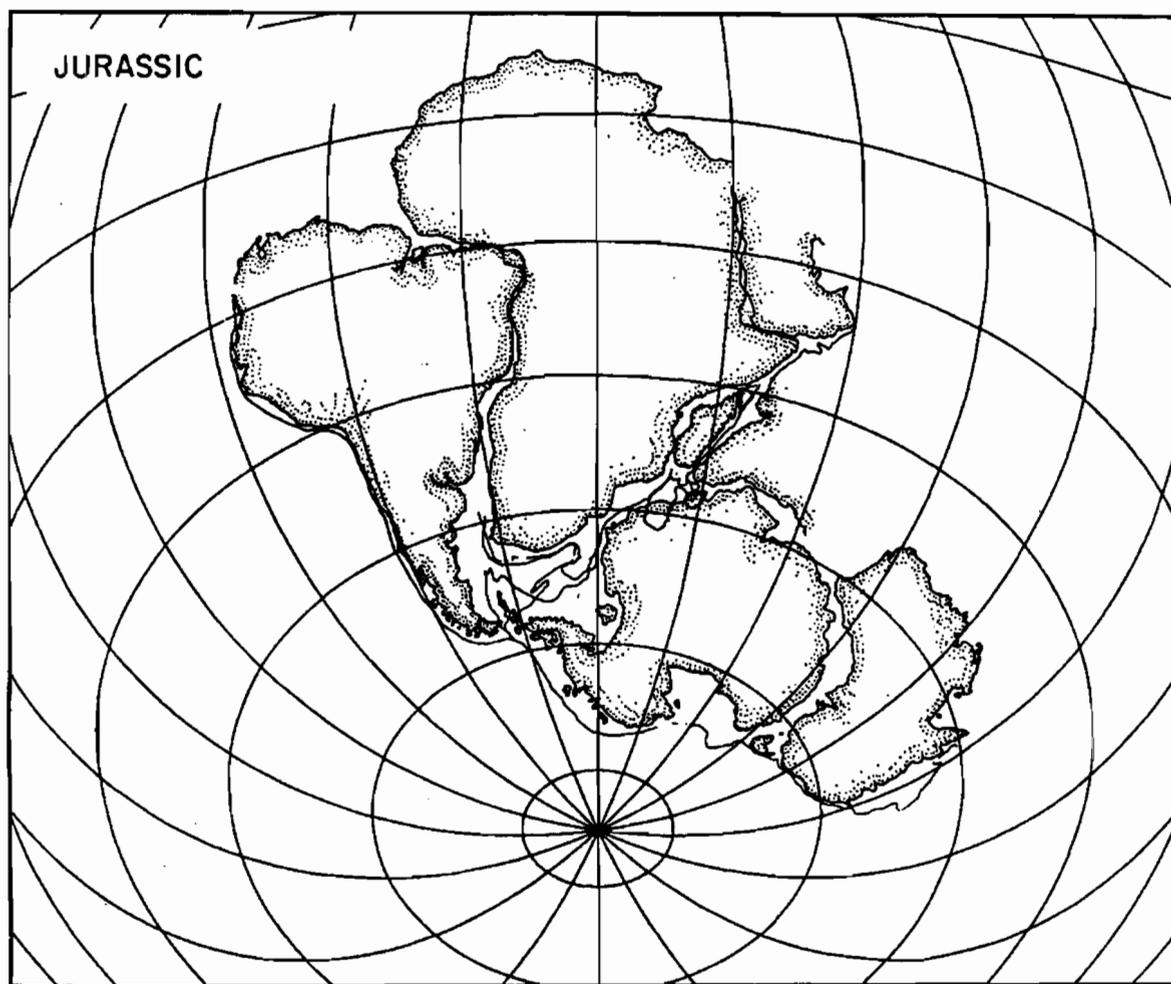


Fig. 4. Norton and Sclater's reconstruction of Gondwanaland using present-day geography of the Falkland Plateau and West Antarctica and seafloor spreading data [Norton and Sclater, 1979]. Note overlap of the Falkland Plateau and Antarctic Peninsula.

Antarctic continent since it separated from the other southern continents [for review, see Dalziel, 1992]. Hence, the WAIS is located on crust developed in association with microplate movement during the Mesozoic fragmentation of the Gondwanaland supercontinent.

If the crustal blocks of West Antarctica delineated in Figure 5 had rotated strictly as rigid continental microplates as a result of seafloor spreading, however, they would now be separated by Mesozoic ocean basins with depths of perhaps 3–4000 m or more. As in the Arctic, there would be multi-year sea ice, or possibly an ice shelf between isolated islands fringing the Pacific margin of the ice covered East Antarctic craton, but there would be no grounded WAIS. We believe that it is in new consideration of the processes that resulted in the movement of the West Antarctic crustal blocks presented in this contribution, that understanding of the lithospheric setting of

the WAIS emerges. An unusual combination of tectonic processes generated the crustal environment in which a marine based ice sheet extending across an entire continent was able to develop. In contrast, the marine-based ice sheets of Hudson Bay and the Gulf of Bothnia formed in embayments of the North American and Eurasian continents and had single restricted outflows to the world ocean.

#### ORIGIN OF THE WEDDELL SEA EMBAYMENT

The Weddell Sea embayment developed at the junction of three continents, Antarctica (ANT), Africa (AFR), and South America (SAM) in a late Precambrian embayment of the Gondwanaland margin [Dalziel, 1982; Dalziel, 1997]. The growth of oceanic lithosphere between these three major continents during the

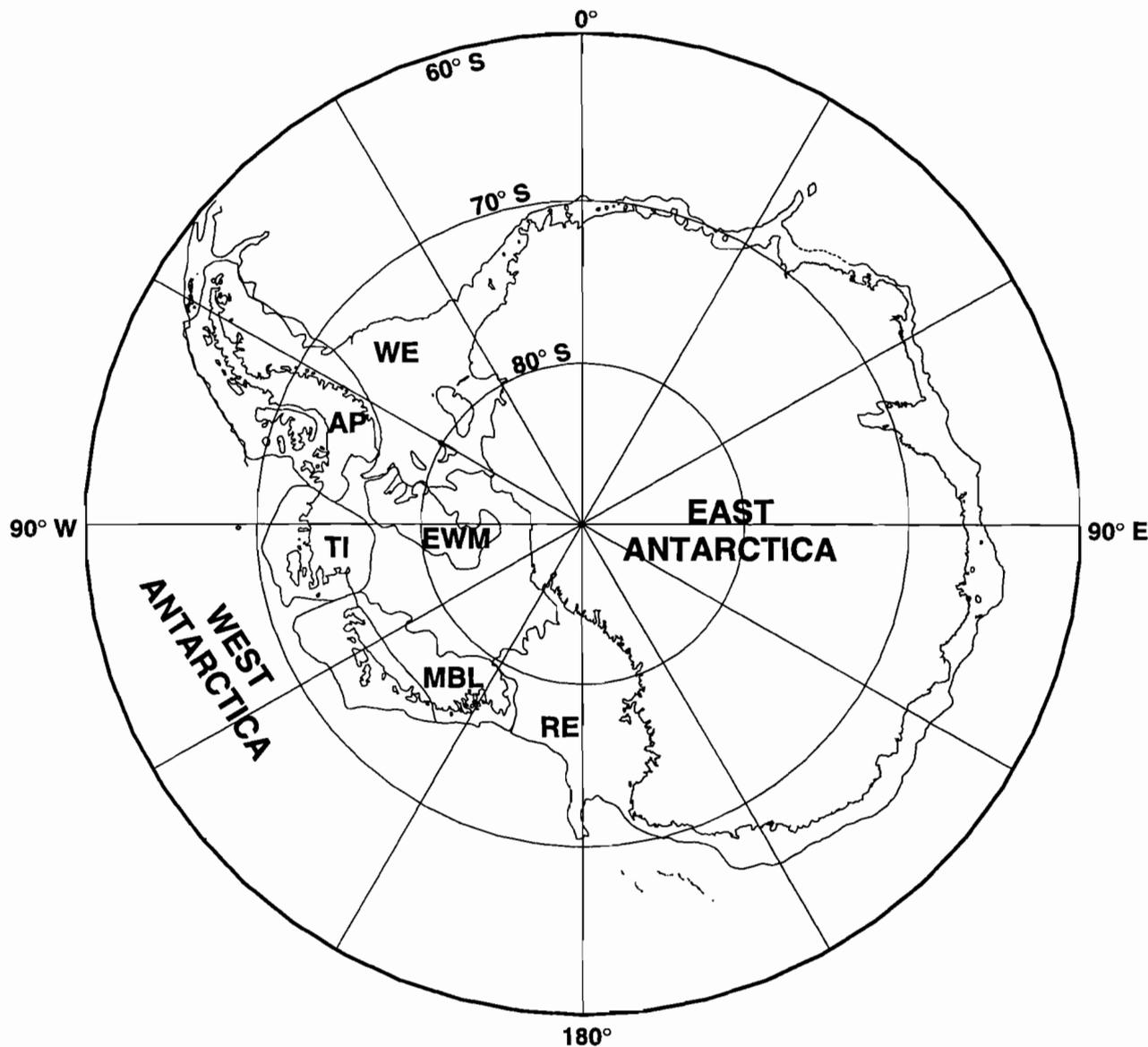


Fig. 5. Antarctica showing East Antarctic craton and displaced rigid crustal blocks of West Antarctica [after Dalziel and Elliot, 1982]. AP - Antarctic Peninsula crustal block; EWM - Ellsworth-Whitmore mountains crustal block; RE - Ross embayment; MBL; Marie Byrd Land crustal block (line across the block represents boundary of "west" and "east" Marie Byrd Land [Di Venere, 1995, see Fig. 8]; TI - Thurston Island crustal block; WE - Weddell embayment.

fragmentation of Gondwanaland has established their relative motion over the past 165 m.y. (AFR-ANT) or 130 m.y. (SAM-AFR) [Lawver *et al.*, 1985; Lawver and Scotese, 1987; Norton and Sclater, 1979]. Geologic and paleomagnetic evidence from the Falkland Islands and the Ellsworth Mountains and adjacent nunataks, however, indicate that independent motion of smaller rigid fragments of continental lithosphere relative to the three major continents commenced prior to the development of the present major ocean basins.

Adie [1952] first pointed out on geologic grounds that the Falkland Islands appear to have originated as the missing southeastern corner of the Karoo basin off the Natal margin. Based solely on seafloor spreading data from the South Atlantic, the Falkland Islands would have been located only off the Agulhas Plateau of southern Africa in a Mesozoic reconstruction, over 1000 km from their geologically probable original position off the corner of the Karoo basin. Adie [1952] pointed out that restoration of the structures in the rocks of the islands to

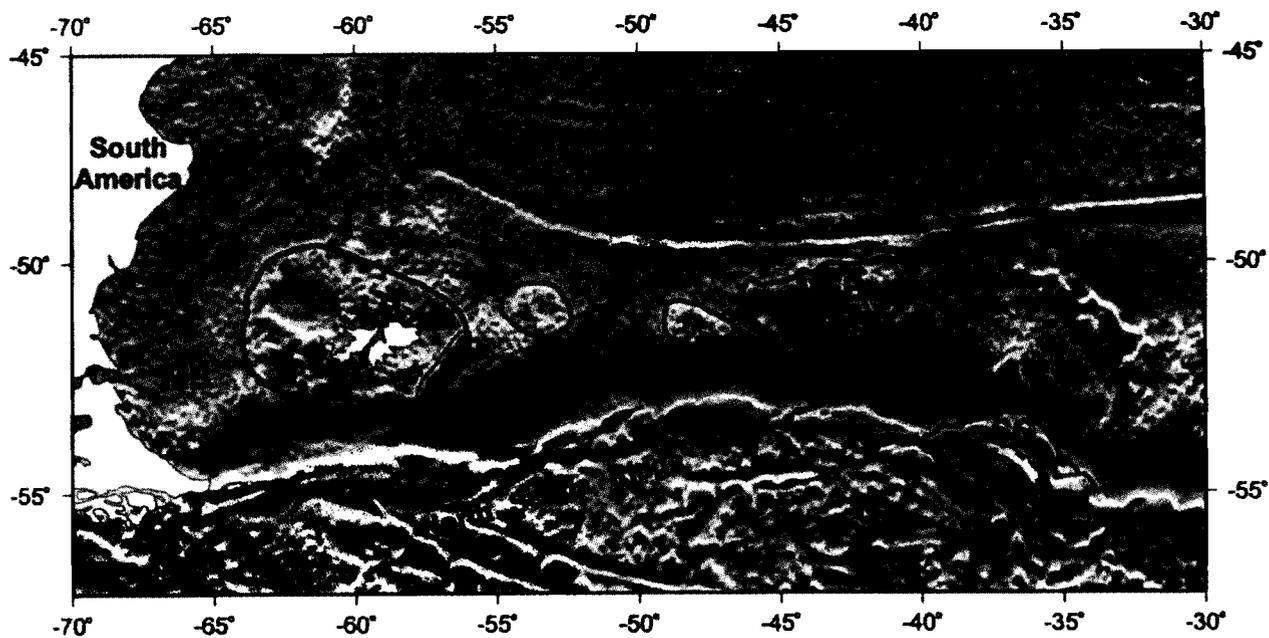


Fig. 6. Tectonic elements of the Falkland Plateau (GTOPO topography and predicted bathymetry is gray-scale version of *Smith and Sandwell, 1997*). LB - Lafonian (Falkland Island) crustal block; FPB - central Falkland Plateau basin; MB - south Malvinas basin; MEB - Maurice Ewing Bank crustal block; SG - South Georgia microcontinent.

their original orientation required  $\sim 180^\circ$  of rotation relative to Africa. Rotation of the Falkland Plateau relative to Africa by closing the South Atlantic Ocean basin accounts for only  $\sim 30^\circ$  of that rotation. Moreover, rotation of Antarctica relative to Africa by closure of the southwest Indian Ocean basin accounts for none of the rotation that Schopf [1969] realized is required to restore the structures in the rocks of the Ellsworth Mountains to a geologically reasonable position aligned with the contemporaneous Gondwanide fold belt in the Cape Mountains of southern Africa and the Pensacola Mountains on the margin of the East Antarctic craton. Paleomagnetic data support the geologic arguments of both Adie [1952] and Schopf [1969]. As noted in a review of the evidence by Dalziel and Grunow [1992], the temporal intervals in which both the clockwise motion of the Falkland Islands and the anticlockwise motion of the Ellsworth Mountains occurred are the same. Rotation could only have taken place between the cessation of the Gondwanide folding that affects rocks as young as Permian and rift-drift transition in the South Atlantic Ocean (Early Cretaceous) and Southwest Indian Ocean (Middle Jurassic).

The stumbling block in the acceptance of these geologically and paleomagnetically reasonable movements has been the absence of an obvious mechanism. There is limited space for rotation of the Ellsworth-Whitmore crustal block between the East Antarctic craton and the Antarctic Peninsula in geometrically precise paleotectonic reconstructions (Figure 5). Crust at the head of the

Weddell Sea has been regarded as comprising an additional continental block, the Ronne, Filchner, or Weddell Sea embayment block [Dalziel and Elliot, 1982; de Wit *et al.*, 1988]. Seismic reflection data obtained from both the Falkland Plateau and the Weddell Sea and Weddell embayment show no sign of disturbance of the reflectors that could be attributed to such lithospheric rotations [Jokat *et al.*, 1997; Richards *et al.*, 1996].

The Falkland Plateau is a marginal plateau of the South American continent (Figure 6). It consists of two main "nodes" of Precambrian continental crust, one of which is exposed in the Falkland Islands while the other was recovered by drilling Maurice Ewing Bank at the eastern tip of the plateau [Barker *et al.*, 1977]. The limit of rigid continental crust is marked by edge anomalies in the satellite altimetry-derived gravity field (reflected in the "predicted bathymetry" for the plateau [Smith and Sandwell, 1997]). The islands occupy the central area of the larger continental Lafonian block or microplate. These proven continental nodes, and other possible smaller ones, are separated by rift-bounded Mesozoic sedimentary basins, the largest of which, the central Falkland Plateau basin, may be floored by oceanic crust [Barker, 1999; Lorenzo and Mutter, 1988, Figure 6]. Despite extensive seismic reflection profiling of the basins, no notable evidence of shortening has been found, even in the south Malvinas basin which separates the Lafonian block from South America (see Dalziel, 1997, Figure 10B). Thus the rotation of the Lafonian block indicated by the geologic and paleomagnetic data, took

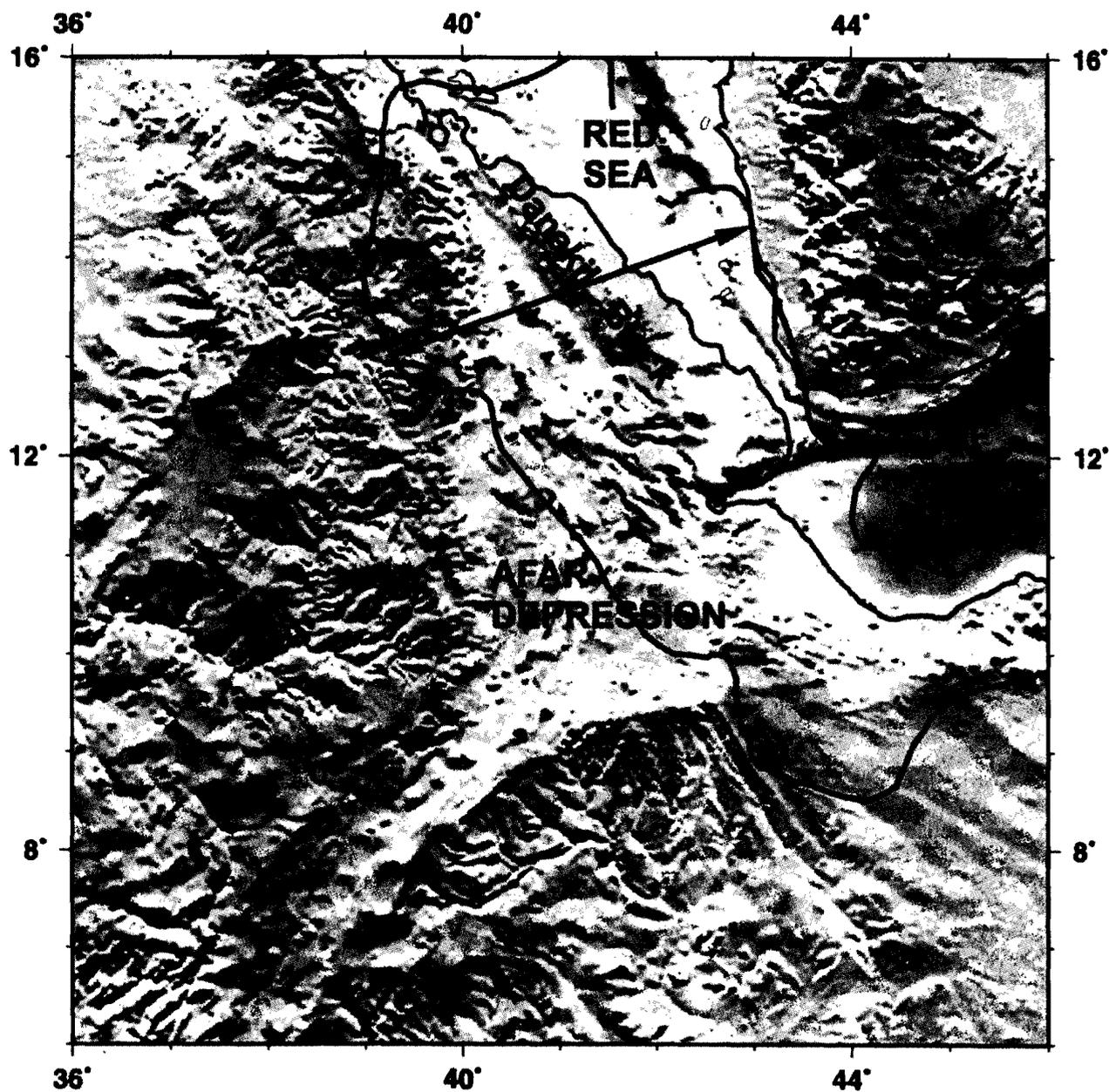


Fig. 7. Topography of the Afar triangle and surrounding regions of the northeast Africa, the Red Sea, Gulf of Aden, and Arabian Peninsula (GTOPO topography and predicted bathymetry is gray-scale version of *Smith and Sandwell, 1997*). Black line shows the extent of the Ellsworth-Whitmore mountains crustal block of Antarctica on the same scale for comparison (see Fig. 5), the line with double arrows showing the position and length of the Ellsworth Mountains within that block.

place purely by extension of continental crust, possibly involving development of an incipient ocean basin beneath the central Falkland Plateau basin, and involving intrusion and extrusion of mafic igneous material. A large percentage of the area of the Falkland Plateau may have been generated by extension in the Mesozoic. We suggest that the crust beneath the head of the Weddell

Sea and the Filchner-Ronne Ice Shelf is likewise an areal addition to the extent of the Antarctic continent generated by contemporaneous extension and magmatism associated with the rotation of the Ellsworth-Whitmore mountains crustal block or continental node.

The non-rigid rheologic behavior of the crust of Gondwanaland in the area of the developing Weddell Sea

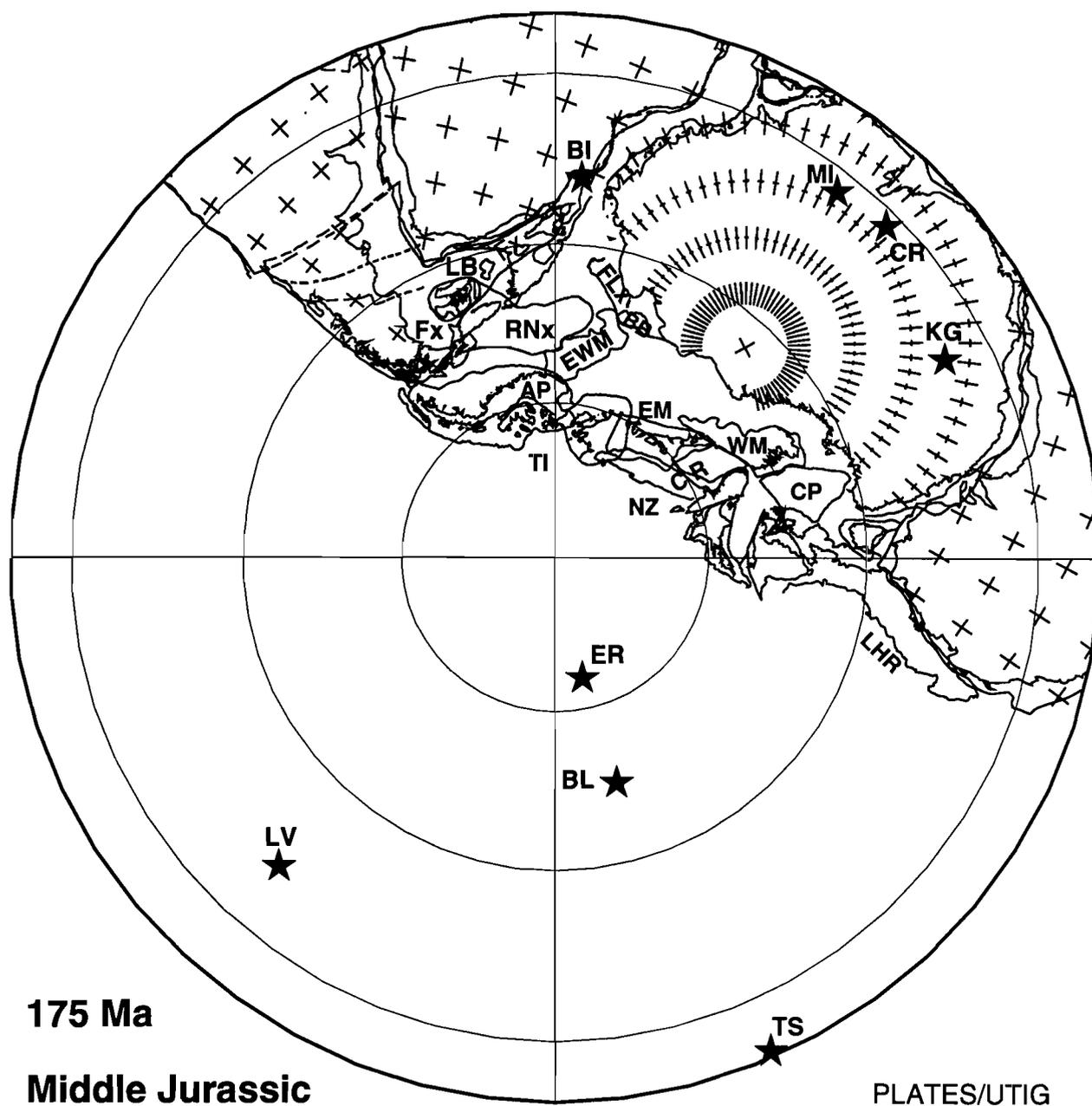


Fig. 8. Reconstruction of the region of Gondwanaland surrounding the incipient Weddell embayment at 175 Ma. Hot spots (stars) and abbreviations as in previous figures with additions: BB - Berkner Island block; CP - Campbell Plateau; CR - Chatham Rise; EM - East Marie Byrd Land block; FLx - Filchner extended lithosphere; Fx - Falkland Plateau extended lithosphere; RNx - Ronne extended lithosphere; WM - West Marie Byrd Land block. (PLATES)

during Jurassic times is associated with the rapid emplacement of the dominantly mafic Karoo-Ferrar large igneous province (LIP) that extended from southern Africa over 4000 km to southern Australia and New Zealand and has been widely attributed to the impinge-

ment on the base of the lithosphere of the "head" of a large hot mantle plume [Dalziel, 1992; Storey, 1995; White and McKenzie, 1989; Dalziel et al., 2000]. High precision U-Pb dating of minerals from the Karoo and Ferrar rocks suggests very rapid emplacement at ~182

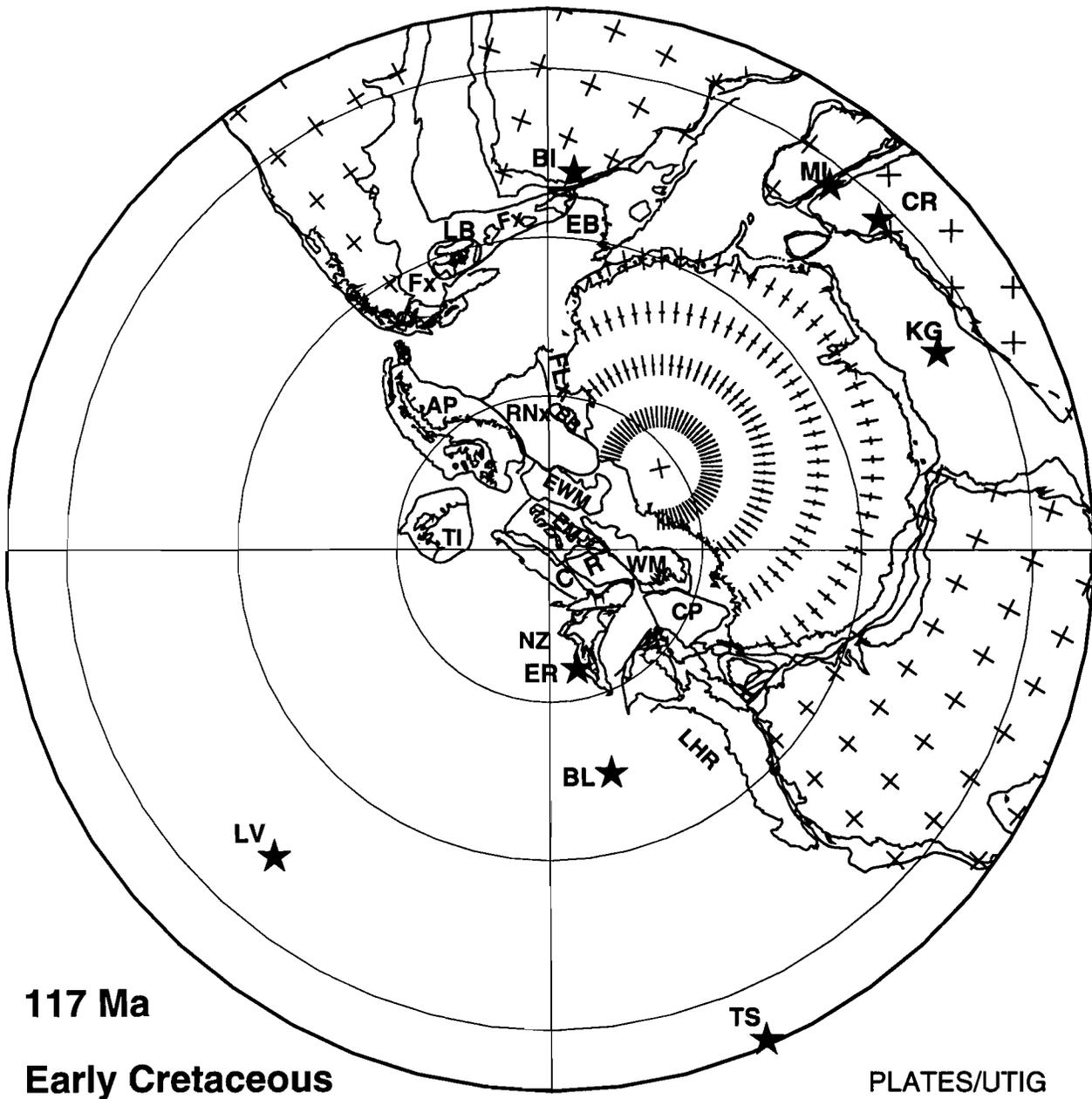


Fig. 9. West Antarctica within Gondwanaland at 117 Ma. Hot spots (stars) and abbreviations as in previous figures with addition: NZ - New Zealand blocks. (PLATES)

Ma [Encarnación *et al.*, 1996]. We envisage the process of formation of the new continental crust of South America and the Weddell Sea embayment as having been very rapid. Paleomagnetic data from granitic rocks associated with the Karoo-Ferrar LIP intruded into the Ellsworth-Whitmore continental block indicate significant rotation involving a paleolatitudinal shift had occurred by ~175 Ma [Grunow *et al.*, 1987a]. The enlargement of the area of the Falkland Plateau of South

America and the Weddell embayment of Antarctica occurred by stretching of continental lithosphere and opening of rifts partly floored by oceanic crust [Barker, 1999] and infilled with sedimentary detritus in a rising and emergent dome above the impinging plume head. Development of the consequent drainage system on the dome has been documented by Cox [1989]. It is noteworthy that the area of non-rigid behavior and augmentation of the area of crust within Gondwanaland

corresponds to a part of the supercontinent formed in Mesoproterozoic times rather than the Archean-Paleoproterozoic Kalahari nucleus.

A present-day analogue for the formation and rotation of the rigid blocks of the Falkland Plateau and the Weddell Sea embayment is the Afar region of northeast Africa. There the Danakil block that is approximately the same length as the Ellsworth Mountains within the EWM block, has rotated counterclockwise by  $\sim 10^\circ$  as a result of extension and the propagation of rifts in the Afar triangle during only the last few million years [Souriot and Brun, 1992, Figure 7]. This process has effectively generated "continental" lithosphere. Even if it includes sediment filled, small, failed, ocean basins presently below sea level, the Afar depression has been added to the area of Africa [Mohr, 1989]. The rotation of the Danakil horst is occurring seemingly independent of true seafloor spreading. Thus the rotated, rigid Lafonian and Ellsworth-Whitmore mountains crustal blocks, are part of the South American and Antarctic continents together with the oceanic central basin of the Falkland Plateau and the extended continental lithosphere beneath the Ronne and Filchner ice shelves at the head of the Weddell Sea (Figures 8 and 9).

The subsequent tectonic history of the Weddell Sea basin was one of seafloor spreading with "Weddellia" (the Antarctic Peninsula and Thurston Island blocks of West Antarctica—the Pacific margin magmatic arc, together with the Ellsworth-Whitmore continental node and the stretched crust of the Weddell Sea embayment) rotating counterclockwise as the oceanic lithosphere beneath the Weddell Sea formed between 165 and 130 Ma [Grunow *et al.*, 1987a, 1987b, 1991]. Weddellia may also include part of eastern and coastal Marie Byrd Land [DiVenere *et al.*, 1995, 1996; Mukasa and Dalziel, 2000].

#### ORIGIN OF THE ROSS EMBAYMENT

The sparsely exposed basement rocks of western and interior Marie Byrd Land are similar to those of the margin of the East Antarctic craton on the Transantarctic Mountains side of the Ross Sea [Bradshaw *et al.*, 1997]. Paleomagnetic data from volcanic and plutonic complexes in Marie Byrd Land, moreover, indicate that the Ross Sea embayment had not formed by the mid-Cretaceous [DiVenere *et al.*, 1994]. Sea floor spreading data on the other hand, clearly show that the continental margin of the Ross embayment had essentially its present geography by the time the Campbell Plateau of the New Zealand microcontinent separated from the West Antarctic margin at  $\sim 85$  Ma [Lawver and Gahagan, 1994, Figure 10]. Separation of the rigid block of western Marie Byrd Land from the East Antarctic craton and development of the crust of the Ross embayment accompanied a marked change in the magmatism along the Pacific margin. Prior to  $\sim 100$  Ma this margin was an active subduction zone with calc-alkaline arc activity. At

that time it changed abruptly to bimodal rift-related magmatism [Weaver *et al.*, 1994; Mukasa and Dalziel, 2000].

The change in magmatism along the Marie Byrd Land margin has been ascribed to the Cretaceous impingement of a plume head on the lithosphere [Storey *et al.*, 1999; Weaver *et al.*, 1994]. As discussed in Mukasa and Dalziel [2000] however, there is little evidence for such an event, indeed, impingement of a plume in the region of a subduction zone more likely results in uplift and the cessation of continental margin magmatism [Murphy *et al.*, 1998; Dalziel *et al.*, 2000] rather than an immediate switch to rift related magmatism as happened in Marie Byrd Land in the mid-Cretaceous. On the contrary, an active spreading ridge, the Pacific-Phoenix ridge, was subducted beneath the New Zealand margin of Gondwanaland at that time, [Lawver and Gahagan, 1994]. In our view, this is the most likely cause of both the extension in the Ross Sea embayment and the separation of the New Zealand microcontinent (Plate 1).

Cenozoic alkaline volcanism in Marie Byrd Land, which started at  $\sim 35$  Ma (Figure 3), included several active volcanoes [LeMasurier, 1990] and was preceded by uplift of the peneplained surface of the Marie Byrd Land block [LeMasurier, 1990; LeMasurier and Landis, 1996; Figure 3]. Geochemical data indicate that these are plume-related volcanics, hence the uplift of the Marie Byrd Land block may be largely or wholly the result of doming above a plume [Hole and LeMasurier, 1994]. The rest of the Ross embayment and most of the New Zealand microcontinent appear to represent the same sort of stretched continental crust. Indeed, the islands of New Zealand exist solely as a result of tectonism and volcanism along the Australian-Pacific plate boundary that traverses the microcontinent.

#### DEVELOPMENT OF THE WEST ANTARCTIC RIFT SYSTEM

There may be active volcanoes beneath the WAIS itself [Blankenship *et al.*, 1993]. Active volcanoes along the western side of the Ross embayment and in Marie Byrd Land indicate possible present-day rifting of the Antarctic continent. The young escarpment of the Transantarctic Mountains and the uplifted marine peneplain in Marie Byrd Land are taken to bound what is known as the West Antarctic rift system—'WARS' [Behrendt and Cooper, 1991; Behrendt *et al.*, 1994; 1996, Figure 10]. The geochemistry of the bimodal volcanic rocks indicates impingement of a mantle plume beneath the nearly stationary Antarctic continental lithosphere as the likely cause of both uplift and volcanism [Behrendt *et al.*, 1992; Hole and LeMasurier, 1994]. The WARS is believed to extend from North Victoria Land to the base of the Antarctic Peninsula [Behrendt and Cooper, 1991, Plate 1] with volcanicity that dates back to  $\sim 35$  Ma. Uplift of the Transantarctic Mountains, widely believed to be related to the inception of WARS, dates from the early Cenozoic [Fitzgerald, 1992].

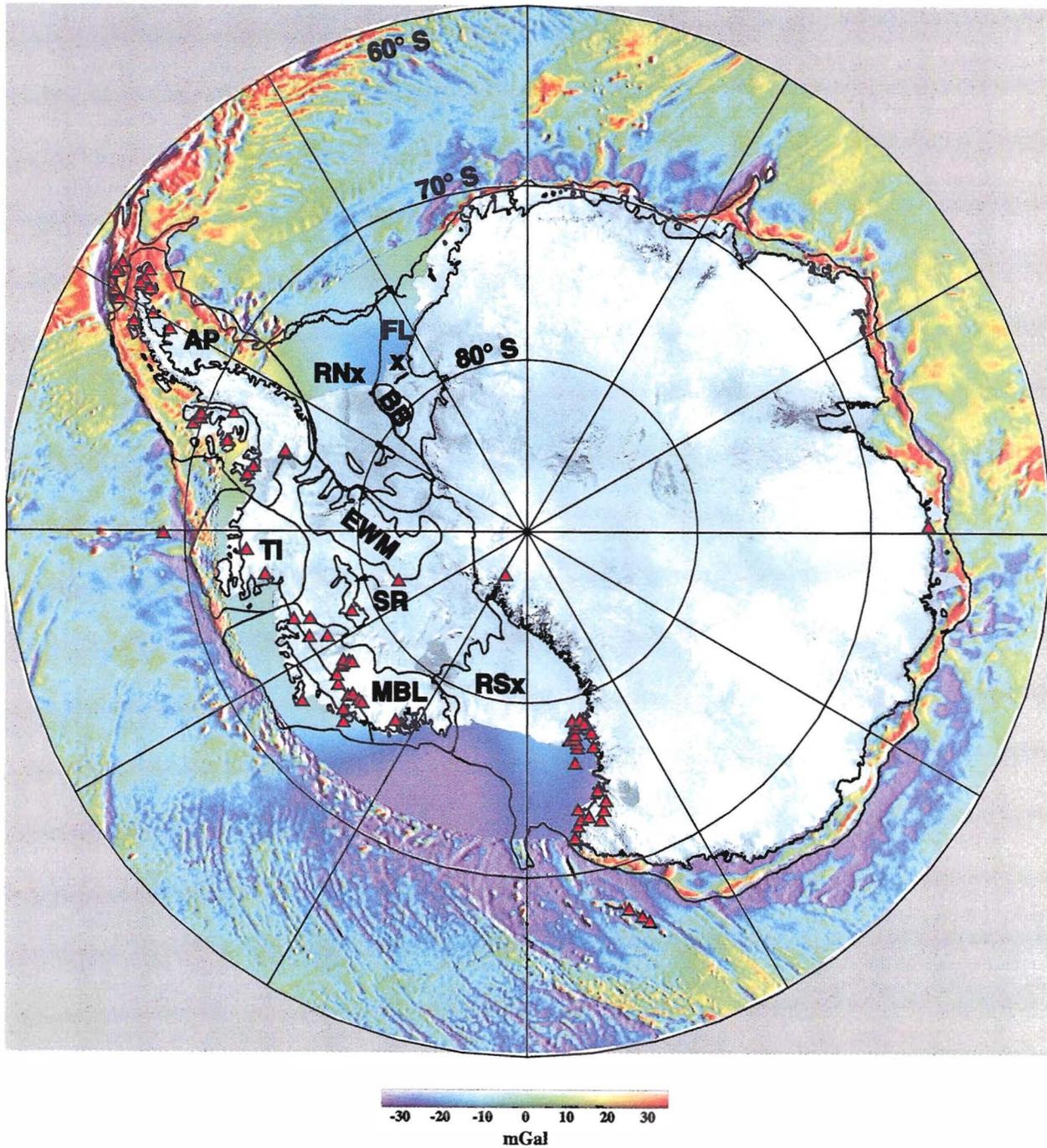


Plate 1. Combined AVHRR-satellite gravity image of present-day Antarctica [Lawver *et al.*, 1993], with active and recently active volcanoes [LeMasurier, 1990; Blankenship *et al.*, 1993; Behrendt *et al.*, 1999], and sub-ice lithospheric provinces of this paper. Abbreviations as in previous figures with addition: SR - Sinuous Ridge (indicated with arrow).

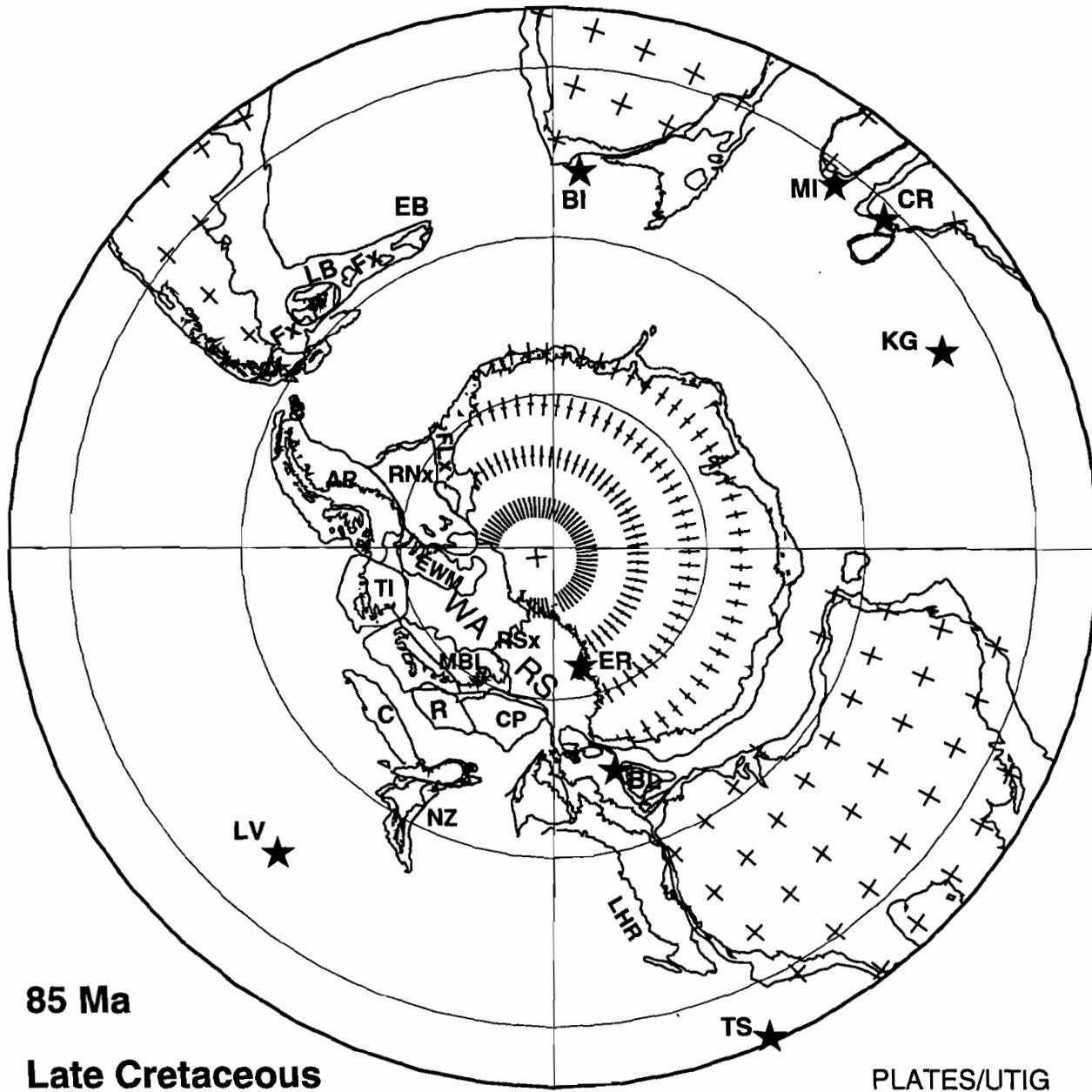


Fig. 10. Reconstruction of the southern continents at 85 Ma showing the setting of the Ross embayment. Hot spots (stars) and abbreviations as in previous figures. (PLATES)

Behrendt and Cooper [1991] suggested that the Cenozoic rift system resulted from the "capture" by a mantle plume of a rift propagating clockwise around the Antarctic continent during the break-up of Gondwanaland (see also Behrendt *et al.*, 1992). As discussed above, we distinguish several phases in this so-called propagation, ascribing them to different causes. Thus, we see the volcanically active West Antarctic rift system

of the present day, including the sinuous ridge that may be volcanically active [Behrendt *et al.*, 1998], as the result of plume-driven uplift, extension and of fracturing along pre-existing lines of weakness. Those were most notably: the Neoproterozoic margin of the East Antarctic craton; continental lithosphere of the Ross Sea embayment between Marie Byrd Land and East Antarctica stretched during mid-Cretaceous separation of

the New Zealand microcontinent from West Antarctica; and continental lithosphere between Marie Byrd Land and the EWM block. The situation appears analogous to that of the 'capture' of the spreading center in the northwest Indian Ocean by the impingement of the Afar plume in the Neogene to form the Gulf of Aden and the Red Sea [Omar and Steckler, 1995, Figure 7].

### CONCLUSIONS: THE LITHOSPHERIC "CRADLE" OF THE WAIS

We suggest that in a coincidence of time and space, several major tectonic events have combined to create the environment in which the unique marine-based WAIS that straddles an entire continent could form and endure for several millions of years. First, a major mantle plume impinged on the base of the lithosphere in the Middle Jurassic and generated the extended and magmatically modified crust of the Weddell Sea embayment. It also resulted in the uplift of the Ellsworth-Whitmore mountains crustal block and in the rotation of this block into a position impeding drainage of ice into the Weddell Sea. Second, subduction of the Pacific-Phoenix ridge in the mid-Cretaceous shut off subduction along the South Pacific margin of the continent and resulted in extension to form the crust of the Ross embayment. Third, impingement of another plume during the Cenozoic resulted in the uplift of Marie Byrd Land and possibly of the Transantarctic Mountains bordering the WAIS, as well as the volcanically active region which most of West Antarctica occupies today. The relatively shallow depth (<1000 m) of the Ross and Weddell embayments allows the formation of ice to the sea floor. The fact that both embayments have open access to the world's oceans allows escape of cold, dense seawater. Otherwise a dense unfrozen brine layer would be trapped beneath floating ice in the West Antarctic region. Hence, without the abnormal area of stretched continental crust in the Weddell and Ross embayments, the uplifted Ellsworth-Whitmore mountains crustal block, and the flanking uplifts of the Transantarctic Mountains and Marie Byrd Land plateau, there probably would not now be a WAIS.

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