THE WEST ANTARCTIC RIFT SYSTEM—A PROPAGATING RIFT "CAPTURED" BY A MANTLE PLUME?

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Abstract: The West Antarctic rift system, marked by a 3–5-kilometer high shoulder from northern Victoria Land to the Ellsworth Mountains, extends through the Ross Embayment and the Byrd Subglacial Basin. Geophysical data suggest that the ice covered area beneath the rift zone is underlain by Cenozoic volcanic rocks (flood basalts?), and extended crust about 20 km thick. Exposed bimodal alkaline volcanic rocks (mostly basalts, indistinguishable from ocean island basalts that have been interpreted to be mantle plume derived) range in age from Oligocene to the present. We propose a plume (approximately ellipsoidal and coincident with the West Antarctic rift system) defined by the distribution of K/Ba ratios of basalts, the elevated tectonomagmatic dome of coastal Marie Byrd Land, the high topography marking the rift shoulder and the inferred flood basalts(?) beneath the ice covered Byrd Subglacial Basin. Although most extension in West Antarctica apparently occurred in the late Mesozoic with Gondwana rifting, all exposed rift related volcanic rocks are post early Oligocene; the time lag is possibly explained by the proposed mantle plume. As spreading centers surrounding the stationary Antarctic plate in the Cenozoic migrated away from Antarctica, continued rifting in West Antarctica to the present was focused by the mantle plume. The plume possibly caused reorganization of the existing ridge system through a ridge jump to the hot, extended, weakened lithosphere present in the Ross Embayment-Byrd Subglacial basin area at the end of the Cretaceous. The propagating rift may have been captured by the thermal plume.

Key words: Antarctica, plume, rifting, volcanism, Cenozoic

Introduction

The West Antarctic rift system is largely ice covered and spans an approximate 3000 × 750 km area from the Ross Sea to the base of the Antarctic Peninsula (Figs. 1 and 2), comparable in area to the Basin and Range in North America or the East African rift systems. Rift activity has been associated with West Antarctic crustal extension episodically, from the late Mesozoic when most of the extension took place syntectonic with rifting of New Zealand and the Campbell plateau from Antarctica, to the present (Behrendt *et al.*, 1991b). The great bulk of exposed West Antarctic rift related volcanic rocks were extruded in the late Cenozoic (LeMasurier, 1990) and not at the time of separation of New Zealand and the Campbell Plateau about 72–85 Ma (Bradshaw, 1989; Lawver *et al.*, 1991) as might have been expected. The main objective of this paper is to explore the reason for this unexplained fact. We present, as a suggested interpretation, rift capture by a mantle plume beneath West Antarctica.

A spectacular rift-shoulder scarp along which peaks reach 4–5 km maximum elevation extends from northern Victoria Land-Queen Maud Mountains to the Ellsworth-Whitmore-Horlick Mountains. The shoulder has maximum present relief of 5 km in the Ross Embayment and 7 km in the Ellsworth Mountains-Byrd Subglacial basin area (Fig. 2). Behrendt and Cooper (1991) proposed episodic uplift for the rift shoulder to have reached about 1 km/m.y., most recently since Pliocene time. Behrendt *et al.* (1991b) suggest that the lack of detection of earthquakes in the active West Antarctic rift system probably results primarily from sparse seismograph coverage, but also from suppression of earthquakes by the ice sheet (e.g. Johnston, 1987) and from the occurrence of high seismicity shortly after deglaciation in the Ross Embayment followed by abnormally low seismicity at present (e.g. Muir Wood, 1989).

The West Antarctic rift system is characterized by bimodal alkaline volcanic rocks ranging in age from Early Oligocene to the present. These are exposed (Fig. 2) asymmetrically along the rift shoulder and coastal Marie Byrd Land to the south end of the Antarctic Peninsula. The trend of the Jurassic tholeiites (Ferrar dolerites, Kirkpatrick basalts) marking the Jurassic Transantarctic Rift (Schmidt and Rowley, 1986) is coincident with the exposures of the Cenozoic volcanic rocks along the section of the Transantarctic Mountains from northern Victoria Land to the Horlick Mountains (Fig. 2). The Cenozoic rift shoulder diverges at the Horlick Mountains from the Jurassic Ferrar tholeiite trend (Fig. 2) and the tholeiites are exposed continuously (including the Dufek intrusion) along the lower-elevation (1–2 km) section of Transantarctic Mountains to the Weddell Sea (Behrendt and Cooper, 1991).

The basis for inferring a mantle plume source for the Late Cenozoic volcanic rocks includes both their geochemical characteristics and their relationship to tectonic doming. La/Nb ratios, and Sr and Nd isotopic data from the Cenozoic alkaline volcanic rocks indicate that basalts throughout West Antarctica (including the rift system and the Antarctic Peninsula) were derived from a depleted mantle source at least 100 km deep within the asthenosphere (Futa and LeMasurier, 1983; LeMasurier, 1990; Hole and LeMasurier,

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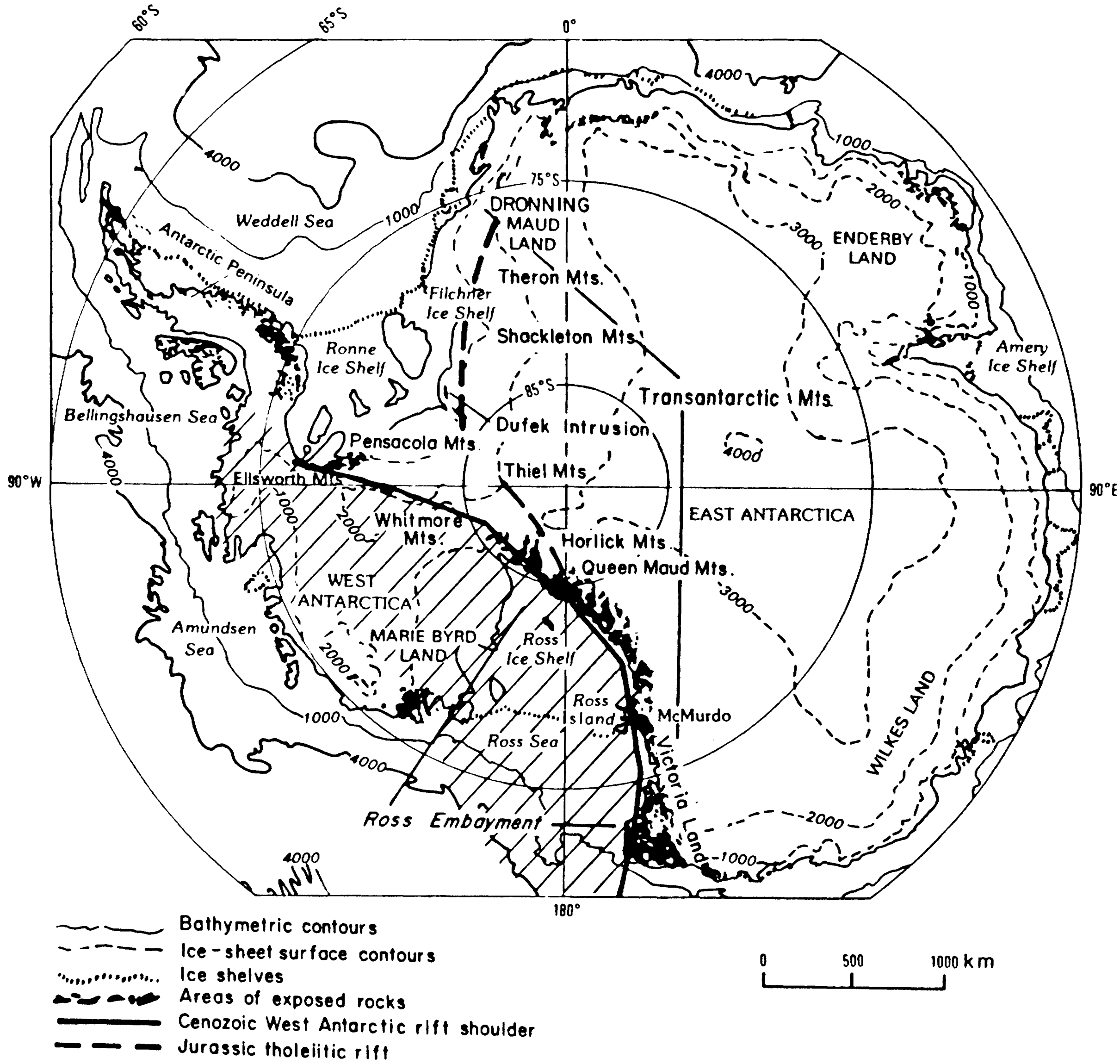

Fig. 1. Index map of Antarctica showing some of the features discussed in the text. The Transantarctic Mountains extend across the continent from Victoria Land near the Ross Sea to the Theron Mountains near the Weddell Sea and comprise the ranges shown by the heavy dashed line as well as those bordering the Ross Embayment. Diagonal lines show approximate location of West Antarctic rift system. Heavy line is approximate rift shoulder. To conform with convention and other publications, maps of Figs. 1, 2 and 3 (covering all or large regions of Antarctica) have grid north (parallel to 0° Meridian) at top; the larger scale map (Fig. 4) has normal convention. All maps use polar stereographic projection.

1990). The most effective geochemical discriminator between rift related basalts and post-subduction basalts from the Antarctic Peninsula seems to be K/Ba ratios (Hole and LeMasurier, 1990). The rift-related basalts from along the rift shoulder bordering the Ross Embayment, coastal Marie Byrd Land and western Ellsworth Land (Fig. 2) all have K/Ba ratios <50, and are indistinguishable from those of ocean island basalts frequently cited as examples of plume or plume tail volcanism (e.g. Kerguelen). Antarctic Peninsula basalts which lie north of the rift system, have K/Ba ratios >50, and a post-subduction "slab window" origin has been proposed to account for their geochemical signature (Hole, 1988).

The Marie Byrd Land volcanic province is characterized by a broad structural dome defined by uplift of a very flat Late Cretaceous erosion surface to a maximum elevation of ~2700 m at the dome crest. Basalts resting on this surface become systematically older with increasing elevation of the surface, suggesting that the dome grew contemporaneously with volcanism at a rate of ~100 m/m.y. during the past 25 m.y. (LeMasurier and Rex, 1989). Since ~18 Ma, the loci of felsic volcanism have migrated centrifugally away from the center of dome uplift along rectilinear paths, suggesting tectonically induced propagation of relict fractures coupled with the systematic release of magma stored in crustal magma chambers (LeMasurier and Rex, 1989). This tectonomagmatic dome lies in the center of the ellipsoidal area defined by K/Ba ratios <50. It is the composite of geochemical, structural and volcanological phenomena that have been interpreted as a manifestation of mantle plume

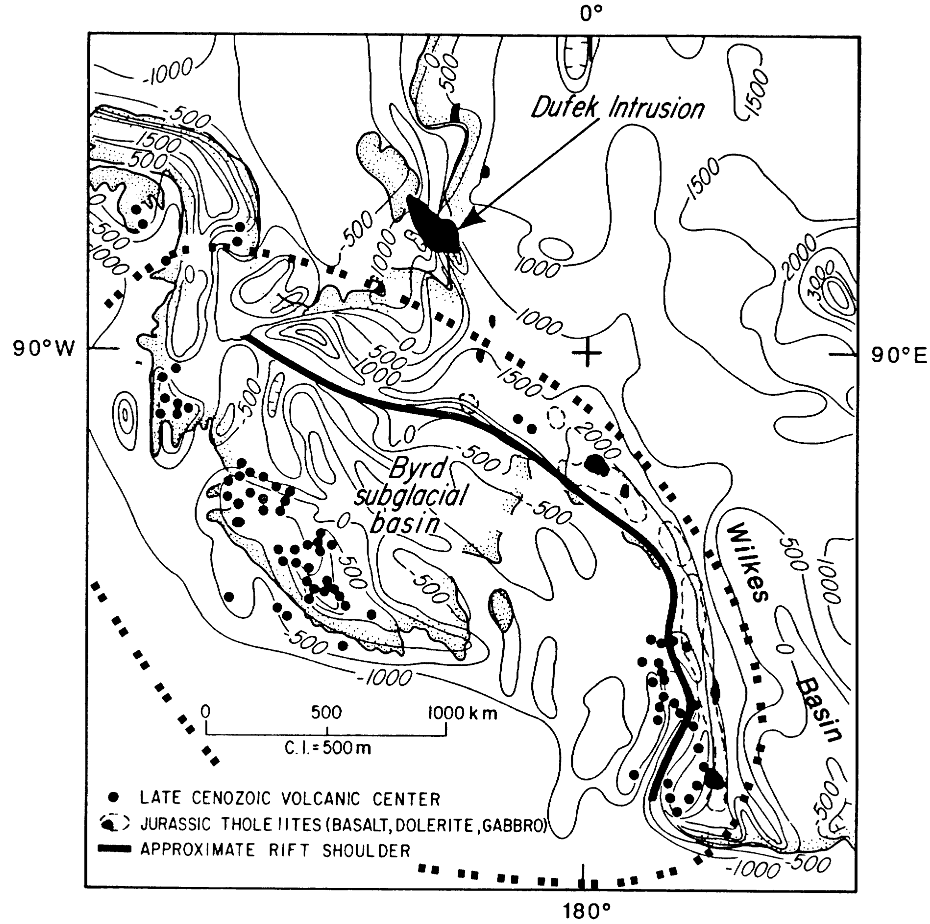

Fig. 2. Generalized isostatically adjusted bedrock elevation map after ice removal. Contour interval 500 m (modified from Drewry, 1983). Location of Late Cenozoic volcanic centers from Gonzales-Ferran (1982) and LeMasurier and Thomson (1990). Locations of Jurassic tholeiites (basalt, dolerite, and gabbroic Dufek intrusion) from Craddock *et al.* (1969). The area beneath the rift zone (elevations below sea level) is probably underlain by extended crust about 20 km thick (Behrendt *et al.*, 1991b, c) based on interpretation of seismic and gravity data. Dashed line indicates suggested area of mantle plume.

activity. We have not overlooked the possibility that these phenomena could simply be the characteristics of an intracontinental rift system undergoing extension and asthenospheric upwarping resulting in decompression melting. However, the mechanisms for initiating and propagating a rift system in West Antarctica are limited by its location within a plate that has been virtually stationary since the Late Cretaceous as we discuss below.

High temperatures at shallow depth (Berg *et al.*, 1989; White, 1989) beneath the Ross Sea continental shelf and adjacent Transantarctic Mountains and heat flow measurements (Blackman *et al.*, 1987; Della Vedova, 1992) are supportive of thermal uplift of the mountains associated with lateral heat conduction from the rift (Stern and ten Brink, 1989), and can possibly also explain the volcanism, rifting and high elevation of the entire rift shoulder to the Ellsworth-Horlick-Whitmore Mountains. High heat flow values of 71.2 mWm^{-2} at 80°S, 120°W and 79.6 mWm^{-2} at 82°53′ S, 136°40′ W (Alley and Bentley, 1988) from ice-covered areas of the rift are supportive of active rifting there. The high heat flow could be additional evidence of a mantle plume beneath the West Antarctic rift.

Geophysical Results

Behrendt *et al.* (1991b, c) discuss the results of their new geophysical investigations combined with a review of earlier studies; these results are briefly summarized here.

Based on widely spaced aeromagnetic profiles in West Antarctica (Behrendt, 1964; Jankowski *et al.*, 1983), Behrendt *et al.* (1991b) interpret that Cenozoic volcanic rocks are mostly absent in the ice-covered part of the Whitmore-Ellsworth-Mountain block. In contrast, they suggest the widespread occurrence of Cenozoic(?) volcanic rocks beneath the western part of the ice sheet overlying the Byrd Subglacial Basin. Behrendt *et al.* (1991b) also infer that these hypothesized volcanic rocks are most likely basalts. It will be important to know, possibly from interpretations of new aeromagnetic surveys in progress (Blankenship *et al.*, 1991), whether flood basalts are actually present beneath the ice cover of the Byrd Subglacial Basin. An aeromagnetic survey over the western Ross Sea continental shelf shows linear anomaly patterns indicative of rift fabric (Behrendt *et al.*, 1991b) and discrete circular anomalies along NNW-trending zones suggestive of numerous submarine volcanoes (Behrendt *et al.*, 1991a).

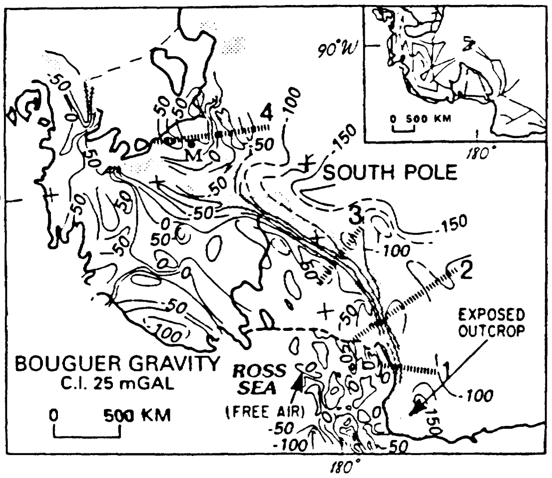

Fig. 3. Bouguer anomaly contour map (Behrendt, 1991b) for West Antarctica compiled from data collected at seismic reflection stations (about 30–40 km spaced) where ice thickness measurements were made by oversnow traverse parties and other surveys. Ross Ice Shelf from the map of Robertson *et al.* (1982). The free air anomaly map over the Ross Sea Shelf is from Davey and Cooper (1987). The numbered bands indicate areas where data density allowed reasonably accurate calculation of gradients: 1) Duerbaum *et al.* (1989); 2) Robinson (1964); Smithson (1972); Robinson and Splettstoesser (1984); 3) Robinson (1964); Robinson and Splettstoesser (1984); 4) Behrendt *et al.* (1974).

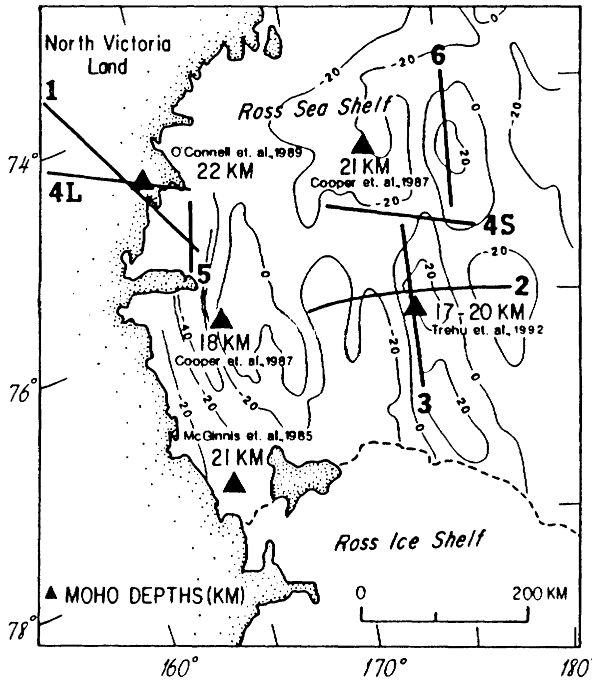

Fig. 4. Locations of large-offset seismic experiments along profiles in Ross Sea Shelf-Victoria Land area. Profiles 1–6 are from the 1988–89 GANOVEX V expedition. Profile 3 is along the strike of the Central Basin. Generalized free air gravity contours at a 20-mgal interval are from Davey and Cooper (1987).

The rift shoulder is marked by a linear approximately 200 (+50 to −150) mgal Bouguer anomaly (Fig. 3) gradient (2–7 mgal/km) from northern Victoria Land possibly to the Ellsworth Mountains (where data are too sparse to determine maximum amplitude and gradient). The steepest gravity gradients (4–7 mgal/km in places) across the rift shoulder require high density (mafic or ultramafic?) rock within the crust (Robinson, 1964; Smithson, 1972; Behrendt *et al.*, 1991b). The gravity data require at least 12 km thinner crust beneath the West Antarctic rift system in contrast to East Antarctica. Sparse land seismic data reported along the rift shoulder with crustal velocities greater than 7 km/s in addition to marine data indicating velocities above 7 km/s beneath the Ross Sea continental shelf support this interpretation (Behrendt *et al.*, 1991b).

Large offset seismic profiles over the Ross Sea continental shelf collected by the German Antarctic North Victoria Land Expedition V (GANOVEX V) (Fig. 4) combined with earlier USGS and other results indicate 17–21 km thickness for the crust in the Ross Sea (Behrendt *et al.*, 1991b; Tréhu *et al.*, 1992). Tréhu *et al.* (1992) show that the mantle is essentially flat beneath line 2 (Fig. 4), including beneath the Central basin. We interpret this as evidence of rift stage continental crust that has been thinned by extension. A regional positive Bouguer gravity anomaly (0–50 mgal), the width of the rift extends (Fig. 3) from the Ross Sea continental shelf throughout the Ross Embayment and Byrd Subglacial Basin area of the West Antarctic rift system. Behrendt *et al.* (1991b) interpret this anomaly, contrasted to the steep negative gradient across the rift shoulder, as indicative that the Moho beneath the extended crust of the Ross Embayment-Byrd Subglacial Basin is probably closer to 20 km depth (probably coincident with the top of the asthenosphere as suggested by the model of Stern and ten Brink, 1990 in the Ross Embayment) than the 30 km reported in earlier interpretations made from gravity data alone (e.g. Bentley *et al.*, 1960; Groushinsky and Sahina, 1982).

Horst and graben structures indicating at least two periods of extension are interpreted beneath the Ross Sea on the basis of marine seismic reflection data (Hinz and Block, 1983; Cooper *et al.*, 1987, 1991). The Victoria Land Basin demonstrates that the latest crustal extension occurred in that area from about Eocene to the present (Cooper *et al.*, 1987, 1991). Rift basins are inferred beneath the Ross Ice Shelf (Cooper *et al.*, 1991), and horst and graben structures, mostly filled with ice, probably extend (Behrendt *et al.*, 1991b) beneath the Byrd Subglacial Basin (Fig. 2). Late Cenozoic horst and graben structures are also reported (LeMasurier, 1990; LeMasurier and Rex, 1989) in the uplifted coastal Marie Byrd Land area (Fig. 2) of the West Antarctic rift system.

Discussion

Behrendt *et al.* (1991b) proposed that the separation of the southern hemisphere continents from Antarctica was the result of a propagating rift which is illustrated in the cartoon in Fig. 5. We suggest that after the separation of New Zealand-Campbell Plateau 85–72 Ma, rifting continued, probably after a lag to the Late Cenozoic, into West Antarctica as indicated. White and McKenzie (1989) suggested the presence of a mantle plume associated with the extensive magmatism syntectonic with the separation of Africa from Antarctica 179–162 Ma. Storey and Alabaster (1991), however, point out that the presence of a plume in this location at about 195 ± 5 Ma was not obviously associated with the opening of a new ocean which appears to have occurred later. At any rate there is no evidence of plume related magmatism associated with the rifting of Australia and New Zealand-Campbell Plateau from Antarctica.

Hole and LeMasurier (1990), Behrendt *et al.* (1991b), Kyle *et al.* (1991) and Storey and Alabaster (1991) suggested that the West Antarctic rift system is underlain by a mantle plume such as that discussed for other areas by White and McKenzie (1989), Hill (1991) and Hill *et al.* (1992). We suggest that the problem of accounting for the volume of late Cenozoic magmatism may be solved by the presence of a mantle plume beneath the thinned, weakened lithosphere in the West Antarctic rift. The hypothesized plume could be nothing more than a geochemical expression of the tensional rifting process, as mentioned previously, as ocean island basalts seem to be the more primary mantle melts in a variety of settings. However, if that were the case, we would expect much greater extension in the Cenozoic, considering the volume of volcanism, than seems to be allowed by continental reconstructions from sea floor spreading interpretations (Lawver *et al.*, 1991). Cooper *et al.* (1982) discuss the complexity of the New Zealand-Campbell Plateau-West Antarctica reconstruction and suggest three quite different models to fit the known geology. These contrasting models indicate the uncertainties in reconstruction and suggest to us that there may be greater uncertainty in the amount of Cenozoic extension in West Antarctica than the Lawver *et al.* (1991) models indicate. Probably, the strongest evidence that the observed ocean island volcanism in the West Antarctic rift is produced by a plume would be the demonstration that great volumes of flood basalts exist beneath the ice cover of the Byrd Subglacial Basin. Thus far the geophysical evidence is supportive but not conclusive.

Hill *et al.* (1992), in a general discussion of plumes, estimate that a given piece of continental crust will be affected by a "plume head event" every 500 to 800 m.y. and suggest that there is apparent episodicity with periods of 100–200 m.y. separated by much longer periods of magmatic quiescence. At present and throughout the Cenozoic the Antarctic plate is generally considered have been stationary (e.g. Okal, 1981), or very slowly moving (e.g. Smith and Drewry, 1984; Smith and Livermore, 1991). Weinstein and Olson (1989) in an examination of global hotspot distributions, showed a "definite negative correlation between plate velocity and hotspot density". Smith and Drewry (1984) and LeMasurier and Rex (1989) discuss evidence of hotspots in various places in the Ross Embayment and Marie Byrd Land. Weinstein and Olson (1989) show hotspots in the Ross Embayment and Marie Byrd Land from various compilations for the entire earth. This hotspot evidence led to the suggestion that the West Antarctic rift system is underlain by an ellipsoidal mantle plume head as we show in Fig. 2.

The approximate location of the hypothesized plume head (Fig. 2) is based on topography and exposures of Cenozoic volcanic rocks having chemistry similar to ocean island basalts and the Hole and LeMasurier (1990) interpretation of a plume based on K/Ba ratios. The tectonomagmatic doming in coastal Marie Byrd Land, discussed in a previous section, is more suggestive of an area within a rift than a rift shoulder. The bathymetric contours of the continental margin bordering the Amundsen Sea (Fig. 1) extend out from the center of the suggested plume (Figs. 1 and 2) and support the hypothesis that the mantle plume is ellipsoidal and extends into this area. Possibly the mafic extrusion, intrusion and underplating that Behrendt *et al.* (1991b, c) interpret throughout the rift from magnetic and gravity data (Fig. 3), and high mid and lower crustal seismic velocities (Behrendt *et al.*, 1991b; Tréhu *et al.*, 1992) result from a thermal plume mechanism.

There may have been a delay of volcanism after arrival of the proposed plume head beneath the West Antarctic rift. Kent (1991) notes that "plume activity beneath a continent is not marked by sudden onset of flood-basalt activity", and refers to the rifting of India from the Amery Ice Shelf area of East Antarctica starting with a "paleoslope" that formed in early Permian time, 150 m.y. before final breakup between 136 and 120 Ma. Kent points out the time lapse between plume arrival and continental volcanism there. Hill (1991) discusses the delay of 20 m.y. or more after commencement of plume uplift before the start of voluminous basaltic magmatism elsewhere such as we suggest possibly exists beneath the ice-covered Byrd Subglacial Basin. Fitzgerald (1989) interprets start of uplift of the Transantarctic Mountains at 60 Ma, whereas extensive rift volcanism did not start until about 30–40 Ma. Stern and ten Brink (1989) calculate that about 70 m.y. is required for an average negative density contrast of 1.5% associated with thermal conduction to penetrate 50 km horizontally beneath the Transantarctic Mountains to provide the necessary thermal uplift. Behrendt and Cooper (1991) proposed major rapid late Cenozoic uplift of the rift shoulder, while acknowledging earlier uplift.

The time lags discussed above are of the same order as that separating rifting of New Zealand and the Campbell Plateau from Antarctica and the onset of extensive volcanism in the West Antarctic rift system. The age of the oldest known Cenozoic volcanism is about early Oligocene in the Ross Embayment and is progressively younger (LeMasurier, 1990) towards the end of the rift near the Antarctic Peninsula, while remaining active at the Ross Sea end (this age progression led to the propagating rift interpretation in Fig. 5). Currently the entire rift is probably active.

Smith and Livermore (1991) speculate that the Cenozoic volcanism along the Transantarctic Mountains in Victoria Land was triggered by thermal anomalies in the asthenosphere which were associated with, and may have been the causes of, continental breakup. However, Hill (1991) argues that deviatoric stresses due to doming over a mantle plume are not likely to be sufficiently large to initiate continental rifting. Rather, Hill proposes that a plume would focus rifting (on the scale of the West Antarctic rift) through reorganization of an existing ridge system through a ridge jump. This process could possibly provide sufficient extra force to drive a weak plate scale system (e.g. a near stationary plate surrounded by spreading centers) such as exists in the Antarctic plate. Hill *et al.* (1992) point out that the extra stresses may result in the transfer of the spreading axis to as

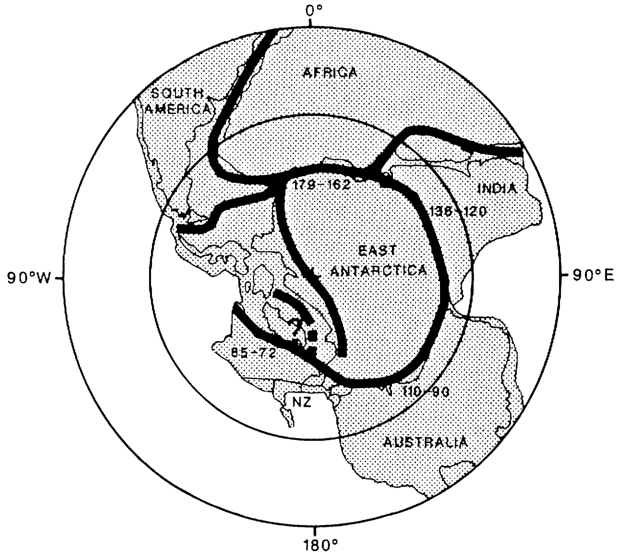

Fig. 5. Cartoon showing suggested progression of rifting of southern hemisphere continents from Antarctica and continuation into the West Antarctic rift superimposed on early Mesozoic reconstruction of Gondwanaland modified from Lawver *et al.* (1991). The heavy line indicates interpreted and suggested locus of initial rifting. During the propagation of rifting around East Antarctica, the indicated West Antarctic microplates became organized to their general present configuration by 100 Ma. The generalized location of the failed Jurassic Transantarctic rift, contemporaneous with the separation of Africa, is also included. The indicated approximate dates of separation are in Ma from various sources summarized in Behrendt *et al.* (1991c). The suggested propagation of the spreading center into West Antarctica started with the separation of New Zealand and the Campbell Plateau from Antarctica and continued with a spreading center jump after a gap in time indicated by the dashes, into the Cenozoic.

near as possible to the plume center. Kent (1991) and Hill (1991) refer to "capture" of a spreading center by a large plume system.

Hill (1991) points out that if the lower crust and lithosphere are already hot, active extension may be apparent before eruption of basalts begins. We believe this to be the case for West Antarctica, where reorganization of crustal blocks (Dalziel and Elliot, 1982; Storey *et al.*, 1989; Grunow *et al.*, 1991) during the Mesozoic prior to 100 Ma left a relatively weak, hot lithosphere compared to East Antarctica. The rifting of New Zealand and the Campbell Plateau from Antarctica and the extension in the West Antarctic rift system in the late Cretaceous was possibly localized by the weakened, hot lithosphere. Hill (1991) notes that where a plume begins to interact with the lithosphere beneath a craton (e.g. Greenland) plume material would be deflected laterally to preferentially displace weak lithosphere (beneath Paleozoic mobile belts in the Greenland case). The Stern and ten Brink (1989) model postulated high flexural rigidity beneath the East Antarctic cratonic area.

We speculate that a possible plume underlying the West Antarctic rift system may either (1) have originated as the result of a plume episode (Hill *et al.*, 1992) in the Cenozoic, or (2) have been originally beneath the East Antarctic craton, deflected laterally and been entrained into the rifting in West Antarctica, or (3) be the result of chance unroofing of a preexisting plume beneath West Antarctica following lithospheric extension (Storey and Alabaster, 1991). Although most of the extension and crustal thinning in the West Antarctic rift took place in the late Cretaceous, coeval with separation of New Zealand and the Campbell Plateau, a lesser but significant amount is required in the Cenozoic to account for the late Cenozoic volcanism. Additional evidence for the late Cenozoic rifting is the existence of the structural deformation revealed by seismic reflection data over the Ross Sea continental shelf (Cooper *et al.*, 1987a, 1991) and the rapid, episodic uplift of the rift shoulder (Fitzgerald, 1989, 1992; Behrendt and Cooper, 1991).

Conclusions

We infer that Gondwana breakup and the West Antarctic rift system are a continuation of a propagating rift (Fig. 5) that started in the Jurassic when Africa separated from East Antarctica (including the failed Jurassic Transantarctic rift). Rifting proceeded clockwise (Behrendt *et al.*, 1991b; Lawver *et al.*, 1991) around East Antarctica to the separation of New Zealand and the Campbell Plateau about 72–85 Ma and has continued with a spreading center jump to its present location in the Ross Embayment and West Antarctica as suggested in Fig. 5. Davey (1981) suggested something similar in a figure, but did not discuss the idea.

The Cenozoic activity of the West Antarctic rift system appears to be a continuation of rifting in the same area that began in the Late Mesozoic, when extension of the West Antarctic lithosphere commenced. The approximately stationary Antarctic plate became essentially surrounded by spreading centers in the Cenozoic; these spreading centers must have migrated radially away from Antarctica as sea floor spreading proceeded. Although the deviatoric stresses associated with any asthenospheric doming by the suggested plume may not have been sufficient to cause rifting, the plume possibly caused reorganization of the existing ridge system through a ridge jump to the hot, extended, weakened lithosphere present in the Ross Embayment-Byrd Subglacial Basin area at the end of the Cretaceous. We suggest that a plume beneath West Antarctica caused the initiation of a new spreading center in West Antarctica (Fig. 5) as the New Zealand-Antarctic ridge migrated away from Antarctica. In other words the propagating rift may have been "captured" by the thermal plume in West Antarctica.

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