TECTONICS, VOL. 15, NO. 2, PAGES, 660-676, JUNE 1996

Patterns of late Cenozoic volcanic and tectonic activity in the West Antarctic rift system revealed by aeromagnetic surveys

John C. Behrendt,[1] Richard Saltus,[1] Detlef Damaske,[2] Anne McCafferty,[1] Carol A. Finn,[1] Donald Blankenship,[3] and Robin E. Bell[4]

Abstract. Aeromagnetic surveys, spaced ≤5 km, over widely separated areas of the largely ice- and sea-covered West Antarctic rift system, reveal similar patterns of 100- to 1700-nT, shallow-source magnetic anomalies interpreted as evidence of extensive late Cenozoic volcanism. We use the aeromagnetic data to extend the volcanic rift interpretation over West Antarctica starting with anomalies over (1) exposures of highly magnetic, late Cenozoic volcanic rocks several kilometers thick in the McMurdo-Ross Island area and elsewhere; continuing through (2) volcanoes and subvolcanic intrusions directly beneath the Ross Sea continental shelf defined by marine magnetic and seismic reflection data and aeromagnetic data and (3) volcanic structures interpreted beneath the Ross Ice Shelf partly controlled by seismic reflection determinations of seafloor depth to (4) an area of similar magnetic pattern over the West Antarctic Ice Sheet (400 km from the nearest exposed volcanic rock), where interpretations of late Cenozoic volcanic rocks at the base of the ice are controlled in part by radar ice sounding. North trending magnetic rift fabric in the Ross Sea-Ross Ice Shelf and Corridor Aerogeophysics of the Southeast Ross Transect Zone (CASERTZ) areas, revealed by the aeromagnetic surveys, is probably a reactivation of older rift trends (late Mesozoic?) and is superimposed on still older crosscutting structural trends revealed by magnetic terrace maps calculated from horizontal gradient of pseudogravity. Long-wavelength (~100-km wide) magnetic terraces from sources within the subvolcanic basement cross the detailed survey areas. One of these extends across the Ross Sea survey from the front of the Transantarctic Mountains with an east-southeast trend crossing the north trending rift fabric. The Ross Sea-Ross Ice Shelf survey area is characterized by highly magnetic northern and southern zones which are separated by magnetically defined faults from a more moderately magnetic central zone. Aeromagnetic data in the south delineate the Ross fault of unknown age. The extension of the southern Central Basin south of the Ross fault is associated with an 825-nT magnetic anomaly over the Ross Ice Shelf requiring inferred late Cenozoic volcanic rock essentially at the seafloor at its south end, as shown by magnetic models. Models show that the thickness of magnetic volcanic rocks beneath Hut Point Peninsula at McMurdo Station is probably <2 km. The detailed surveys, combined with data from >100,000 km of widely spaced aeromagnetic profiles, led to the interpretation of the mostly subglacial West Antarctic flood basalts(?) or their subglacially erupted and intruded equivalent. The volume of the exposed volcanos is small in contrast to the much greater volume (>10^6 km^3) of late Cenozoic magmatic rock remaining at volcanic centers beneath the continental shelf, Ross Ice Shelf and West Antarctic Ice Sheet. We suggest as an alternative or supplemental explanation to the previously proposed mantle plume hypothesis for the late Cenozoic volcanism significantly greater lower lithosphere (mantle) stretching resulting in greater decompression melting than the limited Cenozoic crustal extension allows. However, this implies a space problem that is not obviously resolved, because the Antarctic Plate is essentially surrounded by spreading centers.

[1]U.S. Geological Survey, Denver, Colorado.
[2]German Federal Institute for Geosciences and Natural Resources, Hannover.
[3]Institute for Geophysics, University of Texas, Austin.
[4]Lamont Doherty Earth Observatory, Columbia University, Palisades, New York.

Paper number 95TC03500.
0278-7407/96/95TC-03500$12.00

Introduction

The vast, enigmatic, ice-covered West Antarctic rift system is characterized by extensive exposures (Figure 1) of bimodal (largely basaltic) alkaline volcanic rocks [*LeMasurier*, 1990] ranging in age from about 30 Ma to the present. Volcanic activity can be expected throughout. The asymmetrical rift system is marked, on one flank, by a 3000-km-long, 4- to 5-km-high rift shoulder escarpment (the highest in the world, Figure 1) extending along the Transantarctic Mountains from northern Victoria Land diverging to the Ellsworth Mountains. Uplift rates of the order of ~1 km/m.y. have been proposed for the highest blocks of the escarpment [*Behrendt and Cooper*, 1991]; however, this interpretation is controversial [*Wilch et al.*, 1993; *Behrendt and Cooper*, 1994].

The West Antarctic Ice Sheet and the late Cenozoic volcanic activity in the West Antarctic rift system, through which it flows, have been active since about Miocene time [*LeMasurier and Thomson*, 1990; *Behrendt et al.*, 1991b]. *Lemasurier* [1990] reported hyaloclastites from volcanic exposures (Figure 1) throughout the West Antarctic rift system as evidence of subglacial eruptions. *Blankenship et al.* [1993] reported geophysical evidence of an active volcano in the 1991-1992 Corridor Aerogeophysics of the Southeast Ross Transect Zone (CASERTZ) survey (Figure 1) discussed below. High-amplitude magnetic anomalies have been long known [e.g. *Behrendt*, 1964] to mark volcanic

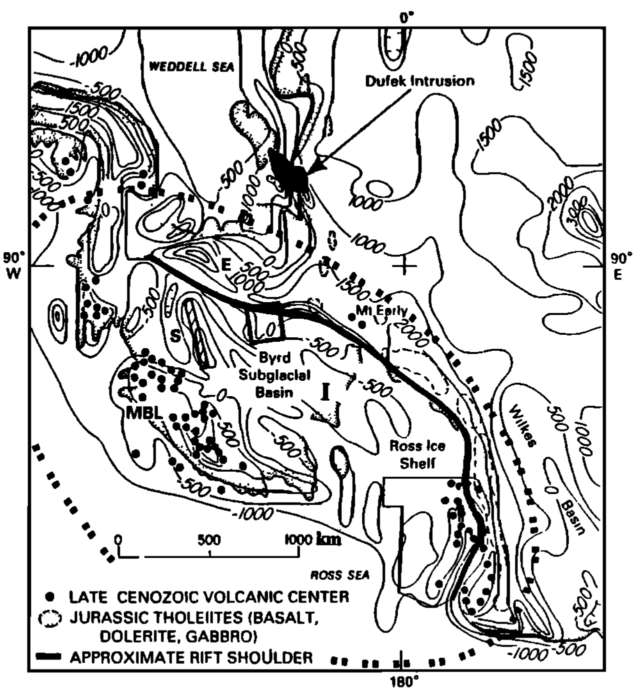

Figure 1. Generalized isostatically compensated (after ice removal) bedrock elevation map of part of Antarctica [from *Behrendt et al.*, 1992] (modified from *Drewry* [1983]). Contour interval is 500 m. Stipple indicates edge of present grounded ice. Thick line represents interpreted shoulder of West Antarctic rift system. Area above 0-m contour in coastal Marie Byrd Land (MBL), which surrounds cluster of late Cenozoic volcanic centers, is tectono-magmatic dome [*Behrendt et al.*, 1992; *Hole and LeMasurier*, 1994]. Dashed line, which surrounds rift system, indicates suggested area of mantle plume head [*Behrendt et al.*, 1992]. E is Ellsworth Mountains; S is 1200-nT Sinuous Ridge magnetic anomaly. Irregular box in Ross Sea area indicates the 1984-85 and 1990-91 German Antarctic North Victoria Land Expedition (GANOVEX)-U.S. Geological Survey (USGS) aeromagnetic surveys (Plate 1). Square box indicates area of the 1991-1992 Corridor Aerogeophysics of the Southeast Ross Transect Zone (CASERTZ) survey, shown in Plate 2. The 0° meridian (grid north) is at the top of the map following usual convention for small- scale maps of Antarctica; in contrast, true north is at top of all other maps. Therefore note orientation of these two aeromagnetic surveys in viewing Plates 1-5 and Figure 3.

exposures in the rift. Interpretations of widely spaced aeromagnetic profiles compared with detailed aeromagnetic surveys (Figure 1) over the Ross Sea and the CASERTZ survey indicate extensive late Cenozoic volcanic rock on the Ross Sea continental shelf and beneath the West Antarctic Ice Sheet [*Behrendt et al.*, 1991a; 1994]. The great volume of these magnetic, inferred late Cenozoic volcanic rocks beneath the ice sheet ($>10^6$ km^3) [*Behrendt et al.*,1994] and the extensive distribution of the exposed late Cenozoic alkaline volcanic rocks and their ocean island basalt chemistry were cited as evidence for a mantle plume head [*Behrendt et al*, 1991b; 1992; *Hole and LeMasurier*, 1994] (Figure 1) beneath the West Antarctic rift system.

A review [*Behrendt et al.*, 1991c] of seismicity, including an M_b 4.9 earthquake in northern Victoria Land, concluded that the West Antarctic rift system is seismically active at a low level. On May 31, 1993 an M_b 5.3 earthquake occurred in the western Ross Sea (Figure 2). Poorly constrained solutions of this earthquake from teleseismic data [*Dziewonski et al.*, 1981; U.S. Geological Survey National Earthquake Information Center, unpublished data, 1994] suggest transtension.

The Victoria Land Basin (Figure 2) contains either (1) 14 km of sedimentary section [*Cooper et al.*, 1987a] or (2) a combined section [*Behrendt et al.*, 1991b] of sedimentary rock above volcanic flows as indicated by the lower 6-8 kilometers of layered reflectors which have seismic velocities >5.6 km/s. Based on vertical incidence [*Cooper et al.*, 1991] and large offset seismic data [*Tréhu et al.*, 1993] the narrower Central Basin (Figure 2) contains a 7- to 8-km-thick sedimentary section of similar age as the Victoria Land Basin and may be underlain by a thin volcanic section.

Large offset seismic investigations in the Ross Sea [*McGinnis et al.*, 1985; *Cooper et al.*, 1987b; *Behrendt et al.*, 1991a; *Tréhu et al.*, 1993; *O'Connell and Stepp*, 1993] and on the Ross Ice Shelf [*Beaudoin et al.*,1992; *ten Brink et al.*, 1993] indicate an ~18- to 22-km-thick (Figure 2), extended continental crust. Gravity data suggest [*Behrendt et al.*, 1991a, b] that this extended crust of similar thickness probably underlies the Ross Ice Shelf and Byrd Subglacial Basin areas of the West Antarctic rift system as well. Early interpretations of crustal thickness from gravity data in the Ross Sea-Byrd Subglacial Basin area [*Bentley et al.*, 1960; *Robinson*, 1964; *Hayes and Davey*, 1975] indicated about 28-30 km.

Behrendt et al. [1995] suggested that the large exposed volcanoes in the West Antarctic rift system (e.g., in the McMurdo and Marie Byrd land areas, Figure 1) may be the exceptions and that the glacially "removed" volcanic edifices originally consisting of subglacially erupted debris (mostly pillow breccias and hyaloclastites) underlain by volcanic centers marked by prominent magnetic anomalies over the West Antarctic Ice Sheet, Ross Ice Shelf, and Ross Sea, may be the general case.

Results of Aeromagnetic Surveys

In this paper we compare similar magnetic patterns (Plates 1-5) in the 1984-1985 German Federal Institute for Geosciences and Natural Resources-U.S. Geological Survey (BGR-USGS) Ross Sea continental shelf [*Behrendt et al.*, 1991a and c] aeromagnetic survey combined with a new survey by the same group made in 1990-91 [*Damaske et al.*, 1994] over the northern Ross Ice Shelf with the CASERTZ 1991-1992 survey [*Behrendt et al.*, 1994] overlying part of the Byrd Subglacial Basin close to the rift shoulder beneath the West Antarctic Ice Sheet. The exposed volcanic rocks (Figure 1) can be directly correlated with the aeromagnetic anomalies in the Ross Sea-Ross Ice Shelf and northern Victoria Land surveys [e.g. *Behrendt et al.*, 1991c, Plates 1 and 2]. Widely spaced aeromagnetic profiles throughout the area of the West Antarctic rift system show many high-amplitude anomalies [*Behrendt*, 1964; *Jankowski et al.* 1983;

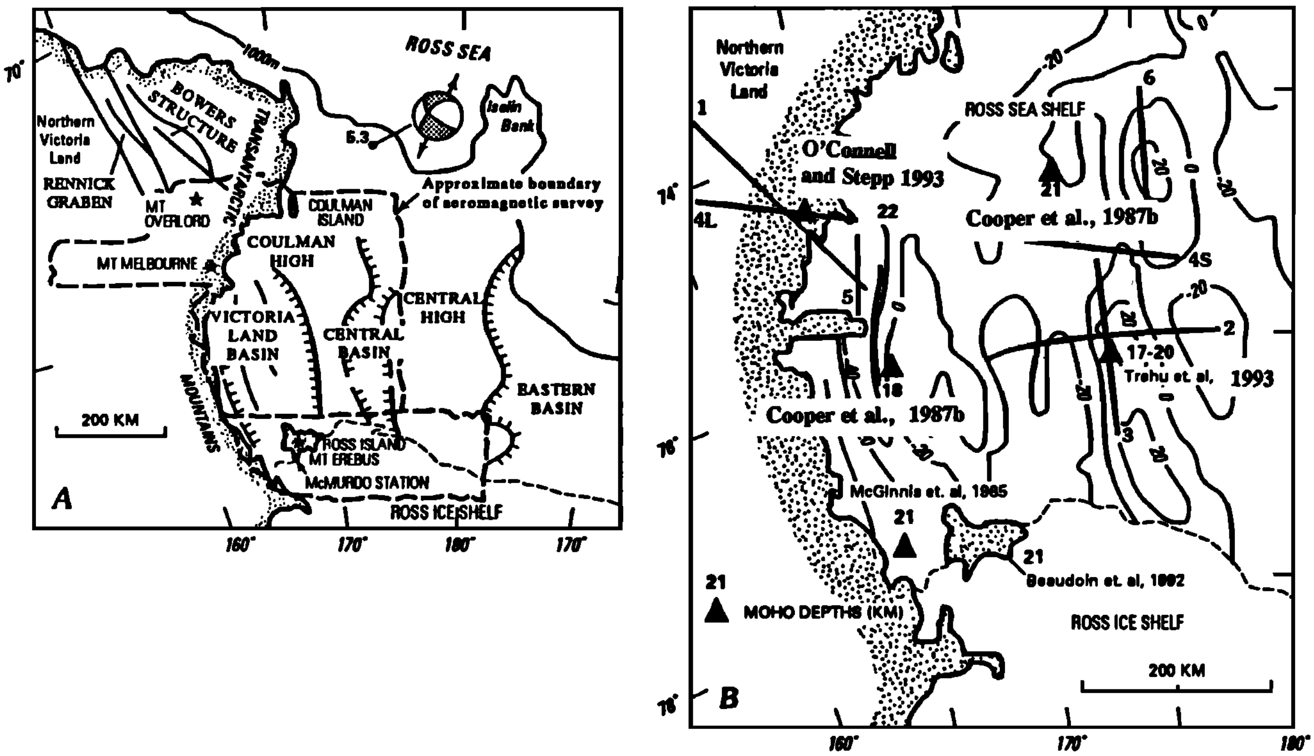

Figure 2. (a) Index map of structures and geographic locations discussed in the Ross Sea continental shelf-Ross Ice Shelf area, modified from *Behrendt et al.* [1991b]. Areas of 1984-1985 (north) and 1991-1992 (south) aeromagnetic surveys are shown. Active volcanoes Mt. Erebus and Mt. Melbourne are indicated. The 1000-m bathymetric contour is shown. Earthquake associated with the active rifting is indicated (M_b 5.3, 1993, unpublished data, USGS). (b) The 1988-1989 large offset seismic profiles and selected depths to Moho superimposed on 20-mGal-free air gravity contours are modified from *Behrendt et al.* [1991b]. Profile 3 [*Tréhu et al.*, 1993] is along strike of Southern Central Basin marked by a positive gravity anomaly.

Pederson et al.,1981; *Behrendt et al.*, 1991b and c] where they cross >1-km-thick late Cenozoic volcanic exposures (Figure 1). Seismic reflection and refraction surveys and core holes from the Ross Sea allow extension of the volcanic interpretation of the aeromagnetic data to the seafloor [*Behrendt et al.*, 1991a and c]. Seismic reflection surveys of the seafloor depth beneath the Ross Ice Shelf provide sufficient control to interpret the aeromagnetic evidence of underlying widespread volcanism there. Finally, similarity of the magnetic anomaly patterns in a close spaced survey over the West Antarctic Ice Sheet, constrained only by radar ice-sounding and other widely spaced geophysical data, allows extension with some confidence of our volcanic rift interpretation (Figure 1) to this geologically unsampled area.

Results from >100,000 km of aeromagnetic profiles including widely spaced lines flown in the 1950s and 1960s [*Behrendt*, 1964] and 50- to 100-km spaced radar ice-sounding and aeromagnetic profiles collected in 1978-1979 [*Jankowski et al.*, 1983] showed numerous short-wavelength, shallow-source, 100- to >1000-nT amplitude anomalies over the Ross Sea, Ross Ice Shelf and West Antarctic Ice Sheet (e.g., the Sinuous Ridge anomaly, Figure 1). These amplitudes are remarkably high considering the flight elevation ranged from 2 to 4 km above the shallowest possible sources beneath the ice and sea. These observations imply that most of the shallow-source, high-amplitude anomalies over the West Antarctic Ice Sheet are caused by buried volcanic rocks.

Ross Sea-Northwestern Ross Ice Shelf Survey

Behrendt et al. [1991b,c, 1994] and *Damaske et al.* [1994] discussed aeromagnetic data, along lines spaced ≤5 km apart (acquired in 1984-1985 and 1990-1991, Fig. 2 and 1991-1992]. About 100, 1- to 10-km wide, roughly circular anomalies, having amplitudes from ~100 to >1000 nT, were interpreted [*Behrendt et al.*, 1991a] as evidence of late Cenozoic submarine volcanoes essentially at the seafloor. These circular "volcano" anomalies are located along linear patterns in the magnetic field having north-northwest trends (Plate 1] and interpreted as rift fabric based on their appearance [*Behrendt et al.*, 1991a, b, and c). Ten of these "volcano" anomalies are crossed by seismic reflection and marine magnetic gradiometer profiles (Plate 1; *Behrendt et al.*, 1987] which show that the rocks corresponding to the anomalies penetrate the thick sedimentary section [*Cooper et al.*, 1987a] and crop out at the seafloor. Models fit to several of these anomalies [*Behrendt et al.*, 1987] as constrained by the reflection profiles, indicate that magnetic sources coincide with the seismically defined volcanic structures.

Late Cenozoic volcanic Coulman Island (Figure 2), associated with a high-amplitude magnetic anomaly [*Bosum et al.*, 1989; *Behrendt et al.*, 1991b], lies at the north edge of the east-northeast trending, 200+ km-long, 1700-nT Polar 3 anomaly (Plates 1 and 4); the probable source of this anomaly is late Cenozoic volcanic rock. *Wörner et al.* [1989] and *Behrendt et al.* [1991b] independently interpreted this anomaly as evidence of a transfer fault (i.e. a transform fault in continental crust, *Etheridge et al.*, 1985]).

Behrendt et al. [1991a,b] interpreted the negative 80- to 100-nT anomaly over the Victoria Land Basin (compare Figure 2 and Plate 1) as caused by nonmagnetic sedimentary rock contrasted to the magnetic basement, with a possible contribution from an upwarped Curie isotherm resulting from active volcanism An alternative is the possibility of predominant reversed magnetization in the high seismic velocity postulated volcanic flows [*Behrendt et al.*, 1991b] comprising the lower 6-8 km.

The complex, two-part (Figure 2) Central Basin is marked by a complex, two-part (mainly positive ~80-100 nT) magnetic anomaly (Plate 1) (and a complex two part 30- to 50-mGal positive gravity anomaly, Figure 2). *Tréhu et al.* [1993] interpreted the gravity anomaly (first modeled by *Hayes and Davey* [1975] as the result of the "rift pillow" underplated at the base of the extended lower crust as interpreted from their large offset seismic data. We infer that the magnetic anomaly has the same source.

Although the northwestern Ross Ice Shelf survey (Figure 2) covers a much smaller area than the 1984-85 survey, the additional information provided is striking (compare *Behrendt et al.*, 1991c, Plate 2 with Plate 1 of this paper). The north trending rift fabric [*Behrendt et al.*, 1991b] continues into the new survey area. There is a pronounced east-northeast trending break in the magnetic pattern (R, Plates 1, 3, and 4) just north of the front of the Ross Ice Shelf. A suggestion of lateral offset of the magnetic anomalies across this break gives the appearance of strike slip. We name this magnetic break the Ross fault zone, because of its proximity to the front of the Ross Ice Shelf. Whether the Ross fault is a transfer fault [*Damaske et al.*, 1994] is uncertain as is addressed in the discussion section.

The aeromagnetic map of Plate 1 can be divided by anomaly characteristics into three distinctly different parts: (1) a northern area (north of 74° 30' S) of very high anomaly amplitudes (2) a central area of subdued amplitudes and (3) a southern area (south of the Ross fault zone) of higher amplitudes, similar to the northern area. These differences may be in part the result of either (1) a thicker section of sedimentary rock in the central area [*Cooper et al.*, 1987a, 1991] or (2) a more extensive pile of magnetic volcanic flows and associated intrusions in the northern and southern parts. If the first explanation were true, then rocks in the central area should be as magnetic as in the north and south and simply at greater depth. However, downward continuation of the magnetic field indicated that this is not the case. Therefore we prefer the latter explanation.

Considering the 600-m flight elevation of the survey (Plate 1) and the 500- to 900-m depth of the continental shelf below the ice shelf [*Robertson et al.*, 1982] the 400- to 900-nT anomalies south of the Ross fault indicate highly magnetic sources. These sources are almost certainly late Cenozoic volcanic rock and associated intrusions and probably equivalent to the Erebus volcanic province [*Kyle*, 1990; *LeMasurier and Thomson*, 1990] exposed on Ross Island and elsewhere (Figure 1).

About 130 km east of Ross Island is a 50-km diameter, circular, 950-nT anomaly (V, in Plates 3 and 4; also apparent in Plate 1) that we interpret as indications of a volcano beneath the ice shelf. The steep gradients define a source essentially at the approximately 800- to 1000-m deep seafloor [*Stern et al.*, 1991] beneath the 300-m thick ice shelf. At the southeast edge of the survey (Plates 1, 3, and 4) is a linear 130-km long north trending, 400- to 800 nT anomaly (X) over the inferred southern extension of the Central Basin (compare Figure 2 and Plate 1). Although the survey is incomplete over anomaly X, careful examination of the large-scale compilations convinced us that the gradient along its west edge is indeed linear rather than circular like anomaly V. We interpret V and X and other circular and linear high-amplitude anomalies as indicating volcanic sources essentially at the seafloor because of their very steep gradients.

The Victoria Land Basin negative anomaly is not obvious south of the Ross fault zone possibly because (1) the anomalies caused by exposed volcanic rocks may obscure magnetic evidence of the underlying sedimentary section or (2) the basin may never have extended south of the Ross fault zone location. *Beaudoin et al.* [1992] reported (from a 58-km multichannel seismic reflection profile, Figure 2) a several-kilometer-thick sedimentary wedge southeast of Ross Island, which thins to the southeast. Unfortunately, their profile crosses only one anomaly at an oblique angle, does not cross its magnetic boundary, and does not aid the magnetic interpretation. *Stern et al.* [1991] report a bathymetric (from seismic reflection) and gravity profile extending 220 km southeast from Ross Island on the Ross Ice Shelf. This profile is located south of the anomalies X and V.

CASERTZ Aeromagnetic Survey

Figure 1 and Plates 2 and 5 show the 1991-1992 CASERTZ aeromagnetic survey over the ice-covered Byrd Subglacial Basin. These data were continued downward 1 km to nearly the same relative altitude (Plate 2) above the base of the grounded ice sheet as the Ross Sea-Northwest Ross Ice Shelf surveys (Plate 1) are above the seafloor. Although the CASERTZ survey covers a smaller area than Plate 1, the similarities in the two are quite apparent. Plate 2 reveals complex 100- to 1000-nT (before downward continuation, *Behrendt et al.*, 1994]) anomalies typical of interpreted extended volcanic terrane beneath the West Antarctic Ice Sheet. These amplitudes are very high considering that the aircraft was about 3 km above the shallowest possible sources at the base of the 2-km-thick ice and are comparable to those in the northern and southern parts of Plate 1. The numerous anomalies, interpreted to indicate mostly late Cenozoic volcanic sources at the base of the ice sheet [*Behrendt et al.*, 1994], are also concentrated along anomalously north trending magnetic rift fabric. Possibly the rift fabric direction is due to transtension in a strike-slip system as suggested for parts of the West Antarctic rift system [*Kellogg and Rowley*, 1989; *Storey*, 1991; *Wilson*, 1995].

The CASERTZ anomalies are similar in amplitude, size, shape, and distribution to anomalies interpreted as caused by submarine volcanic rocks in the Ross Sea-Ross Ice Shelf survey, particularly south of the Ross fault (Plate 3 and 6). Also similar to Plate 1 are 100- to 300-nT composite anomalies 50 to >70 km wide (e.g., the two at the northeast and southwest corners of Plate 2) suggestive of clusters of volcanic centers and associated subvolcanic intrusions. The "active" magnetic field contrasts to the "flat" field over the thick, nonmagnetic Paleozoic sedimentary section adjacent to the Ellsworth Mountains (E in Figure 1; *Behrendt*, 1964; *Maslanjy et al.*, 1991].

Magnetic sources of the high-amplitude short-wavelength anomalies seen in Plates 1 and 2 could be any age, but we would not expect to observe [e.g., *Behrendt et al.*, 1991c] significant anomalies at the flight elevation and ice thickness from the thin Jurassic Ferrar dolerite sills which may be present beneath the ice. High-amplitude magnetic anomalies may also result from several-kilometer-thick Jurassic intrusions such as the Dufek intrusion (Figure 1), magnetic granitoids [*Maslanjy et al.*, 1991] or a thick pile of Kirkpatrick basalt flows [*Behrendt et al.*, 1991b, c]. A significant component of remanent magnetization, which would be likely for volcanic rocks and some plutonic rocks (Q in the Dufek intrusion ranges from 1.3 to 5 [*Beck and Griffin*, 1971]), would not produce anomalies characteristic of the present field direction as we observe [*Behrendt et al.*, 1994]. Because the Antarctic plate has been essentially stationary for the past 100 m.y., Late Cretaceous magnetic granitoids, for example, can not be ruled out based on magnetization directions; however, we would not expect magnetizations or susceptibilities as high as are required to produce the observed anomalies.

The nearest (400 km) exposed volcanic centers (Figure 1) to the CASERTZ survey along the rift shoulder (e.g., Mt. Early) are 16-19 Ma and contain hyaloclastite and pillow breccias [*Stump et al.*, 1990]. We infer that the Mt. Early exposures are examples of the late Cenozoic subglacial volcanic rocks interpreted as underlying the CASERTZ survey.

Derivative Maps

Magnetic Boundaries From Pseudogravity

We computed the local maxima of horizontal gradient of pseudogravity, which define the boundaries (Plates 3, 4, and 5) of anomaly sources [*Baranov*, 1957; *Grauch and Cordell*, 1987] from the data in Plates 1 and 2. The Ross fault is apparent primarily in the striking break in the horizonal gradient of pseudogravity (Plate 3, compare Plate 1). Circular and semicircular boundaries in Plates 3, 4, and 5, delineate structures that we interpret as large (approaching 50-km diameter) submarine and subglacial volcanoes.

Plate 3 shows magnetic boundaries for the southern part of Plates 1 and 4 at the same scale as Plates 2 and 5. Compare the semicircular ~35- to 40-km diameter "volcano" anomalies (e.g., D) in the CASERTZ survey (Plate 2 and 7), and Shallow-source anomaly V over the Ross Ice Shelf (Plates 3 and 4). There is a poorly defined (because of widely spaced data) positive Bouguer gravity anomaly [*Robertson et al.*, 1982] over this inferred volcano. We correlate the volcanic source of anomaly V with the 40-km-wide source of the >3000-nT anomaly [*Pederson et al.*, 1981] observed about 300 m above the nearly 3800-m-high active Mt. Erebus (Figure 2) and numerous other >1000-nT anomalies over the exposed Erebus volcanic rocks [*Kyle*, 1990; *LeMasurier and Thomson*, 1990]. However, the edifice of the volcanic source of anomaly V was probably glacially "removed" [*Behrendt et al.*, 1995] as it was erupted. The magnetic boundaries of shallow-source anomaly X in the east in Plate 1 are well defined (Plate 3). Faults interpreted from magnetic boundaries (Plates 3 and 4) in the Victoria Land Basin can be correlated with faults crossed in a few seismic profiles [*Cooper et al.*, 1987a] and possibly in the deeper part of the Central Basin [*Cooper et al.*, 1991; *Tréhu et al.*, 1993].

The similar pattern of semicircular and linear magnetic boundaries in the CASERTZ data over the West Antarctic Ice Sheet (Plate 5) reinforces the interpretation of volcanic sources for this part of the West Antarctic rift system. The nearly circular magnetic boundary well defines the 35-km-wide, active [*Blankenship et al.*, 1993] volcanic structure causing anomaly D [*Behrendt et al.*, 1994]. Other similar 10- to 30-km diameter circular magnetic boundaries (Plate 5) better illustrate the interpreted volcanoes beneath the ice sheet. The composite anomalies at the northeast and southwest corners of this survey (Plate 2) are resolved into semicircular and linear source boundaries in Plate 5.

Terrace Magnetization Maps

We applied the magnetic terracing method [*Cordell and McCafferty*, 1989] to the pseudogravity data, using the magnetic boundaries discussed above, to help define geologic structures and or physical-property domains underlying the sea, ice, and nonmagnetic sedimentary rock. The amplitude range of the terrace function is identical to that of the range of the input anomalies because we did not define the thickness of the magnetic units. However, the units "nT" would not be appropriate for Plates 4 and 5. The terrace levels are first approximation three-dimensional magnetic models.

In the Ross Sea-Ross Ice Shelf survey (Plate 4), the amplitudes of the terraces north of the Polar 3 anomaly and south of the Ross fault are significantly higher than over the central area. Negative apparent values correspond to areas of thick sedimentary rock section in the Victoria Land Basin (Figure 2). There are obvious east northeast trends associated with the Polar 3 Anomaly in the Ross Sea (Plate 4), which comprises an elongate composite of circular boundaries supporting the interpretation of its source as volcanic.

In the center of Plate 4, superposed on the north trending dominant rift fabric (emphasized by the magnetic boundaries shown), is an east-southeast trending positive zone, about 100 km wide extending across the entire map at about 76°S. We interpret this anomalous zone, which overlies the thick section of nonmagnetic sedimentary rock in the Victoria

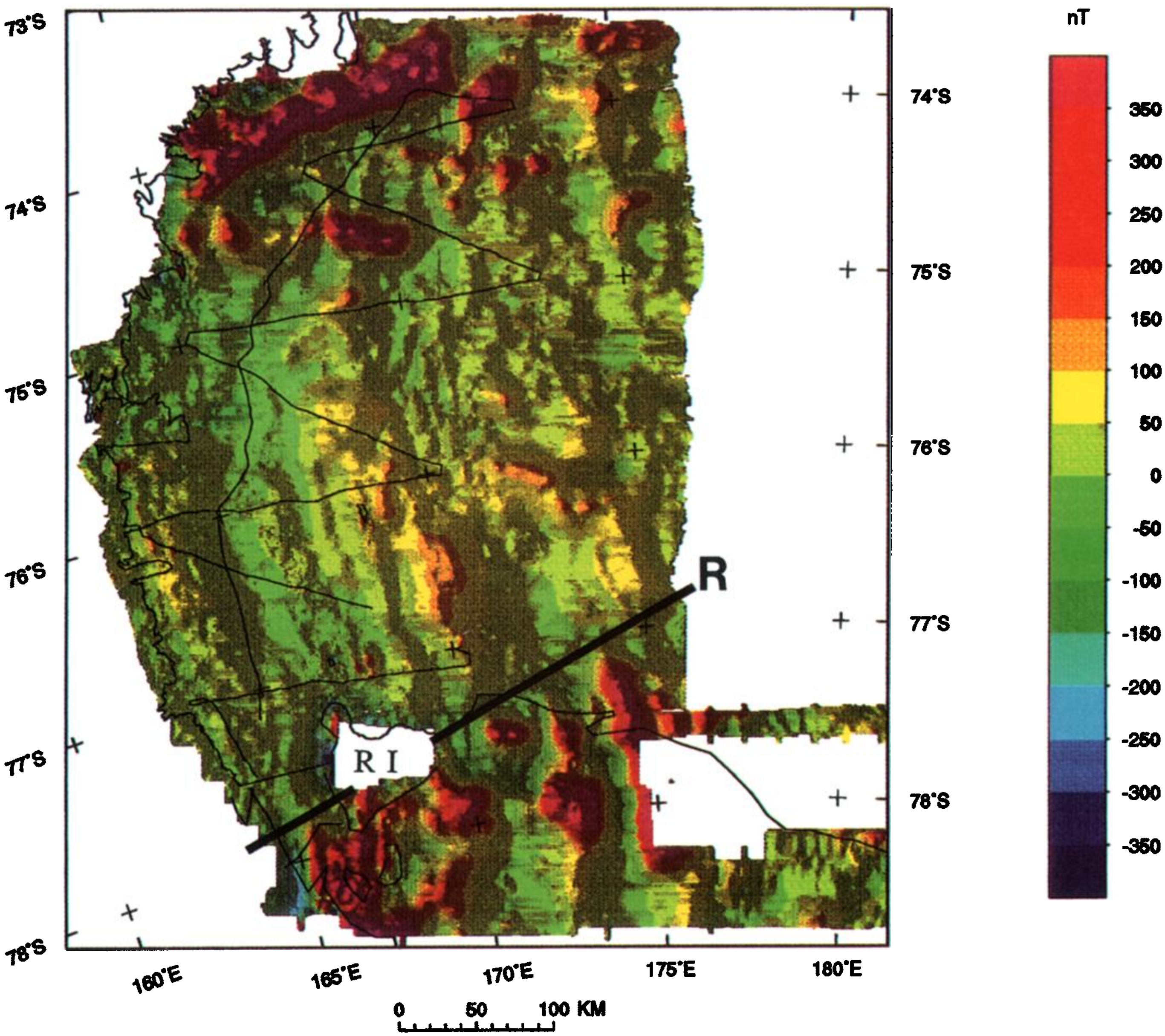

Plate 1. Merged Ross Sea 1984-1985 and 1990-1991 Northwest Ross Ice Shelf total intensity aeromagnetic surveys [*Behrendt et al.*, 1991a; *Damaske et al.*, 1994]. East trending flight lines are spaced 4.4 km. Flight elevation is 600 m. Color contour interval 50 nT is from +250 to -250 nT; extreme high amplitudes are in red. The maximum magnetic relief is about 1700 nT (the Polar 3 anomaly, the 200-km long east-northeast trending anomaly at the top of the map). The total field is ~64,000 nT; inclination is ~-82°; declination ~141°E. RI is Ross Island. R is the trend of Ross fault. The edge of the Ross Ice Shelf (Figure 1) is indicated. Marine seismic reflection and magnetic gradiometer profiles over the Victoria Land Basin area are indicated.

Plate 2. CASERTZ 1991-1992 total intensity aeromagnetic survey, of the area in the box in Figure 1, continued downward 1 km from observed field 1 km above the 1800 m elevation snow surface [*Behrendt et al.*, 1994]. Flight lines are 5-km spaced orthogonal, north and east trending. The ice sheet is ~2 km thick. The total field is ~57,000 nT; inclination is ~-73°; declination is ~70°E. Color contour interval 50 nT is between +250 and -250 nT; extreme high amplitudes are in red. Anomaly D marks an active volcano [*Blankenship et al.*, 1993; *Behrendt et al.*, 1994]. Maximum magnetic relief in survey before downward continuation was about 1000 nT at anomaly A.

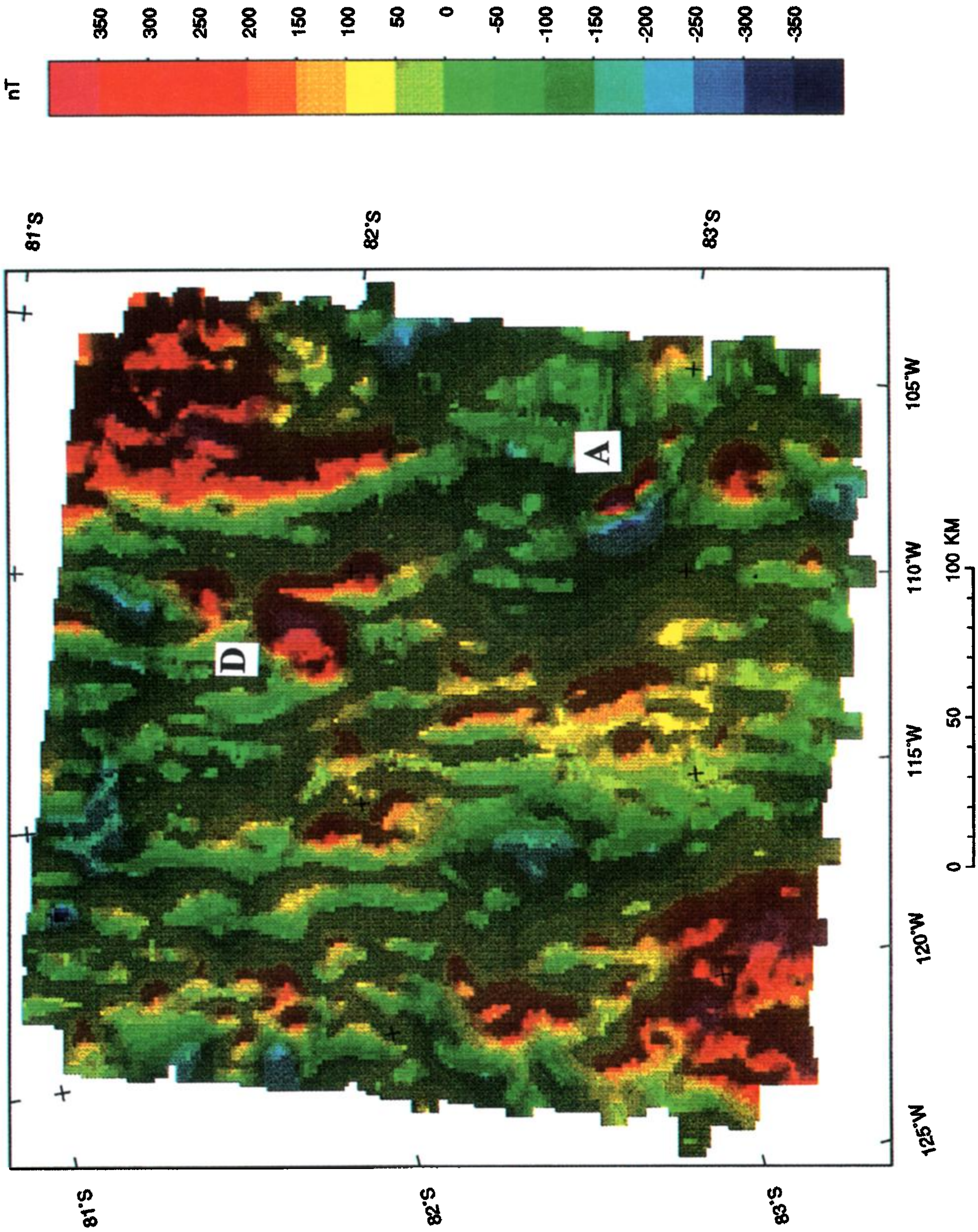
nT
350
300
250
200
150
100
50
0
-50
-100
-150
-200
-250
-300
-350
81°S
82°S
83°S
105°W
110°W
115°W
120°W
125°W
A
D
0
50
100 KM

Plate 2.

Land Basin, as evidence of underlying, more magnetic, older (early Paleozoic?) basement lithology. Comparison with Plate 1, shows previously unrecognized evidence of this feature in the total intensity map as well. *Behrendt et al.* [1991a] fit models to a profile across the Victoria Land Basin, underlain by this positive magnetic basement terrane, which showed a moderate apparent susceptibility of 0.009-0.010 S.I.

Bozzo et al. [1995] displayed aeromagnetic data over the adjacent area of Victoria Land which do not show this east-southeast trending anomalous zone to extend there. This significant break suggests strike-slip displacement of unknown direction or offset along the mountain front as inferred in Jurassic time [*Schmidt and Rowley*, 1986] or late Cenozoic-present time [*Wilson*, 1995]. The solution of the 1993 earthquake (Figure 2) suggests transtension may be present today.

In the terrace map of the CASERTZ data (Plate 5), the north trending rift fabric and the previously noted (Plate 2), high-amplitude areas in the northeast and southwest corners are obvious, but other subtle features can be seen as well. There is a broad low-amplitude positive terrace extending from the southwest to the northeast corner subparallel to the rift shoulder (Figure 1) connecting the high-amplitude areas. This feature appears to be interrupted by a north-south trending area (a basin?) parallel to the rift fabric (in the southwest part of the map). In addition to the volcanic anomaly-producing structures, we are probably seeing evidence of underlying variation in magnetic properties of the older crystalline basement.

Magnetic Models

Hut Point Anomaly

We fit theoretical models to the magnetic data starting in areas of the most geologic information (Figures 3 and 4), where a profile crosses an outcrop of volcanic rock on Ross Island, from which measurements of magnetic properties have been reported [*Mankinen and Cox*, 1988]. We continue to progressively lesser known areas over the Ross Sea (models by *Behrendt et al.* [1987] and *Bosum et al.* [1989]), Ross Ice Shelf (Figures 5 and 6) and the West Antarctic Ice Sheet (models by *Behrendt et al.* [1994]).

Figure 4 shows a 35-km-long section (Figure 3) from McMurdo Sound to the Ross Ice Shelf (Figure 2), crossing Hut Point Peninsula, the site of the U.S. McMurdo Station. We interpret the models of Figure 4 to indicate high Q remanent magnetizations (normal and reversed) to dominate the field consistent with measured samples. Q averages 8.6 and ranges from 2.7 to 27.4 [E. Mankinen, personal communication, 1994]. The apparent susceptibilities indicated are within the ranges corresponding to reported normal and reversed magnetizations in the present field direction sampled from exposed flows nearby. *Mankinen and Cox*, 1988 reported that all of the trachytes comprising Observation Hill, at McMurdo Station, are reversely magnetized. All 15 units overlying the basal pyroclastic sequence cored at a Dry Valley Drilling Project (DVDP) Hole on Hut Point Peninsula near McMurdo Station are reversely magnetized [*McMahon and Spall*, 1974] and were erupted in less than 200,000 years.

There has been speculation that one could sample the sedimentary rock in the underlying Victoria Land Basin by drilling through the volcanic flows at or near Hut Point, where logistic facilities are most accessible. Figure 4 suggests this would be possible. Examination of Figure 3 shows only a few tens of nannoteslas anomaly over the north tip of Black Island suggesting to us that the volcanic rock exposed there [*Kyle*, 1990] is very thin. Sedimentary rocks might be penetrated by drilling to a very shallow depth beneath the surface outcrop of these volcanic flows. The models in Figure 4 well illustrate that volcanic flows <1 km thick could not produce >100-nT anomalies over the ice- and sea-covered areas of the West Antarctic rift system, where the survey aircraft were a minimum of 1-3 km above the shallowest possible sources in all cases.

Central Basin Anomaly

The magnetic maps (Plates 1, 3, and 4) show 470- to 825-nT anomaly X having north-south boundaries apparently terminated by the Ross fault zone. This anomaly north of the front of the Ross Ice Shelf overlies the southernmost part of the southern Central Basin [*Hinz and Kristoffersen*, 1987]. There appears to be about a 40-km offset (in a right lateral sense) from the $\sim$80-nT anomaly over the southern Central Basin $\sim$50 km to the north northeast (Figure 2 and Plate 1). Models fit to two profiles crossing anomaly X (Plate 3 and Figures 5, and 6) suggest late Cenozoic magmatic and volcanic activity south of the Ross fault zone.

Figure 5 shows three models fit to anomaly X along profile 2-04 which all require very steep boundaries for the intrusion underlying the basin. The models in Figure 5 were calculated for the present field direction, implying induced magnetization, or normal remanent magnetization in the present field direction. The apparent susceptibility of model c seems unrealistically high, suggesting that models a or b may be more appropriate. The geometry of models a and b are similar but model b suggests that underplating is as shallow in the crust as the bottom of the sedimentary basin. The only alternative to the steep sides for the magnetic bodies in Figure 5 is to have a substantial volcanic section in the Central basin similar to the models of Figure 6. This is apparently ruled out by the seismic reflection interpretation of a section of sedimentary rock filling the basin in this area [*Hinz and Kristoffersen*, 1987], just to the north of the front of the Ross ice Shelf (Plate 3). Is it possible that the reflectors filling the Central Basin overlain by the northern part of anomaly X are volcanic flows rather than the interpreted sedimentary rock?

We could infer from the models shown (Figure 5) that the intrusion causing the 470-nT anomaly is syntectonic with rifting associated with late Mesozoic [*Cooper et al.*, 1991; *Tréhu et al.*, 1993] basin development. This is probably the case for the more poorly defined, much lower amplitude ($\sim$80-100 nT) anomaly over the Southern Central Basin north of the Ross fault zone whose source is probably the "rift cushion" determined by seismic data interpreted to be the source of the positive gravity anomaly [*Tréhu et al.*, 1993]. In contrast, the high 470-nT amplitude observed over

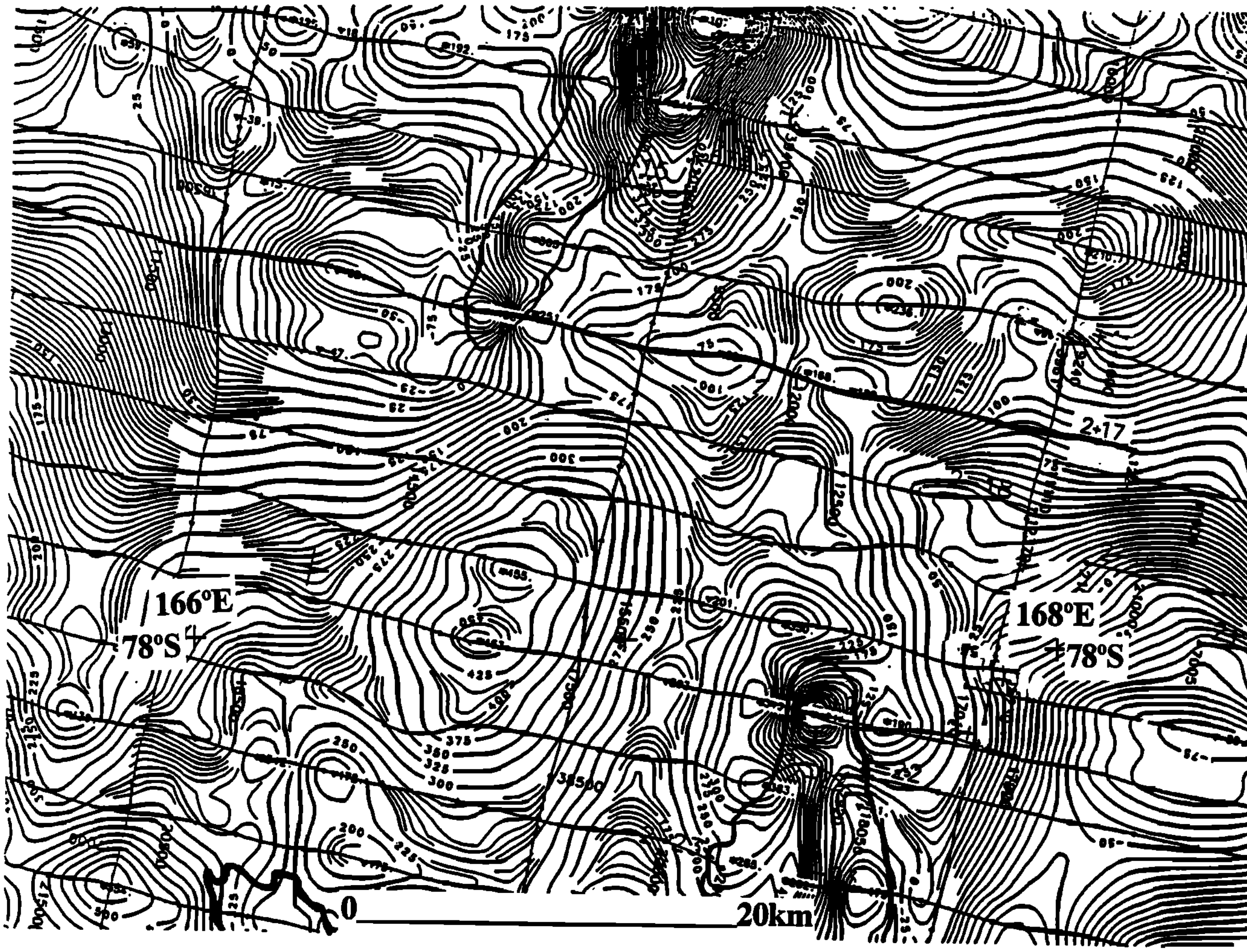

Figure 3. Large scale example of the total intensity aeromagnetic map in the area of McMurdo Station. Parts of Hut Point Peninsula of Ross Island (at north), Black Island (at southwest) and White Island (at southeast) are outlined. Note only a few tens of nannotesla amplitude anomaly over late Cenozoic volcanic exposures at north end of Black Island <300 m below the survey elevation. Contour interval is 5 nT and is greater in areas of steep gradient. Profile 2-17, modeled in Figure 4, is indicated. Compare Plates 1, 2, and 3.

anomaly X where crossed by line 2-04, compared with ~80-100 nT to the north, suggests that late Cenozoic magmatic (volcanic?) activity may also be a possible explanation. However, the highest amplitude (825 nT) and steeper gradient (Figure 6) of anomaly X where crossed by line 2-21, as discussed below requires magmatic rock essentially at the seafloor, strongly implying a late Cenozoic age for its source there. Even if a high remanent magnetization is responsible for the high amplitude of anomaly X, which is likely, it does not completely resolve the age ambiguity because the stationary Antarctic plate since the Late Cretaceous would result in a similar direction of remanent magnetization.

Anomaly X, where crossed by profile 2-21 (Plate 3 and Figure 6) about 100 km south of profile 2-04 (Plate 3 and Figure 5), has a two-part gradient on each flank requiring a complex two-part (shallow and deep) source, unlike the simple source in Figure 5. Models a-d (Figure 6) assume that the basin modeled in Figure 5 extends along anomaly X to its southern end; however, there is no seismic reflection control. Model e assumes no basin. It was not possible to fit the anomaly in Figure 6 with a significant thickness of nonmagnetic sedimentary basin fill (e.g., model b) without an unrealistically high magnetization for the underlying rocks. Therefore we reject any models that could be computed for profile 2-21 having a thick, shallow, younger, overlying, sedimentary rock section similar to the models of Figure 5. The models of Figure 6 suggest a complex source that could be partly of two (or more) ages.

Our preferred interpretation is based on models a, c and d in Figure 6. Part of the source of the south end (and therefore possibly the entire length) of anomaly X must be shallow and have a high magnetization (remanent or induced) in the present field direction. Considering the proximity of

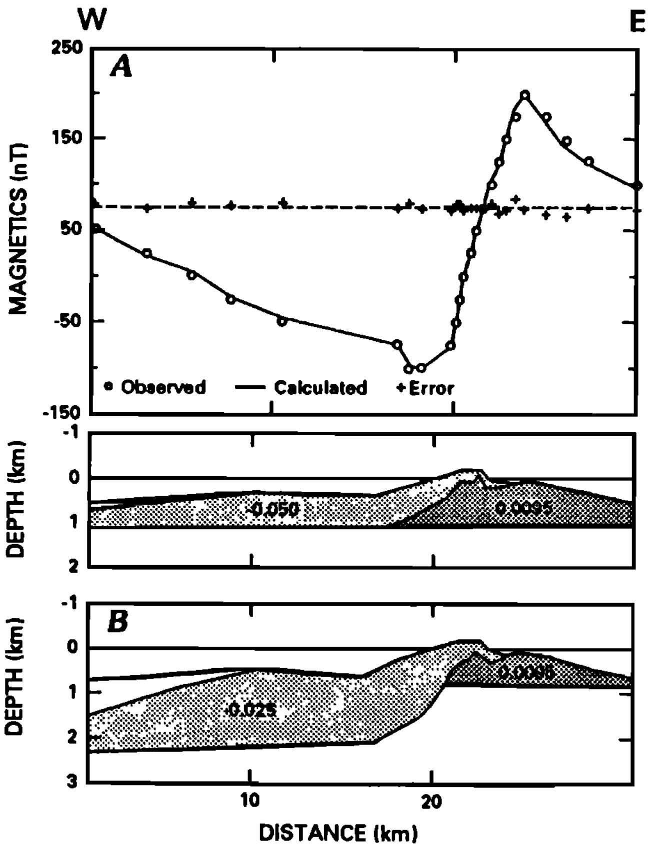

Figure 4. Magnetic models (2-D) for line 2-17 crossing part of McMurdo Sound, Hut Point Peninsula (the site of McMurdo Station), and part of the Ross Ice Shelf. Apparent susceptibilities are in S.I. units. Simplified topography of volcanic rocks comprising Hut Point Peninsula and bathymetry in McMurdo sound at west end is from U.S. Geological Survey topographic map; seismic reflection bedrock extrapolated from 1958-1959 Victoria Land Traverse and *Stern et al.* [1991] provides control at east end beneath Ross Ice Shelf. Upper nonmagnetic layer consists of seawater on west and shelf ice and underlying seawater at east. Location of profile is shown in Figure 3. Models a and b fit observed profile within a few nannotesla standard deviation; computed profile for b is not shown. Negative apparent susceptibility shown in models indicates dominant reversed remanent magnetization.

anomaly X to exposures of late Cenozoic volcanic rocks and the seismic evidence of late Cenozoic volcanic activity penetrating the sedimentary rock section [*Behrendt et al.*, 1987; *Cooper et al.*, 1987a] in the Victoria Land Basin area (Figure 2), its source is probably late Cenozoic in age as well. The low gradient part of anomaly X (Figure 5) may be associated with underplating or lower crustal intrusion (sheeted dikes?).

Apparently, for whatever reason, there is a much greater volume of late Cenozoic volcanic rock south of the Ross fault zone in the area of high-amplitude anomalies (e.g., Plates 1, 3, and 4). The Polar 3 anomaly in the more magnetic northern section of the Ross Sea survey (Plates 1 and 4) is also evidence of a higher apparent volume of shallow late Cenozoic volcanic rock (including subvolcanic intrusions) than the central region (Plate 1).

West Antarctic Ice Sheet Anomalies

A number of models calculated to fit anomalies in the area of the CASERTZ survey (Plate 2 and 5) about 1400 km away from the area of the northwest Ross Ice Shelf survey were controlled by radar ice-sounding of the bedrock surface. All required >2-km thick subvolcanic intrusions

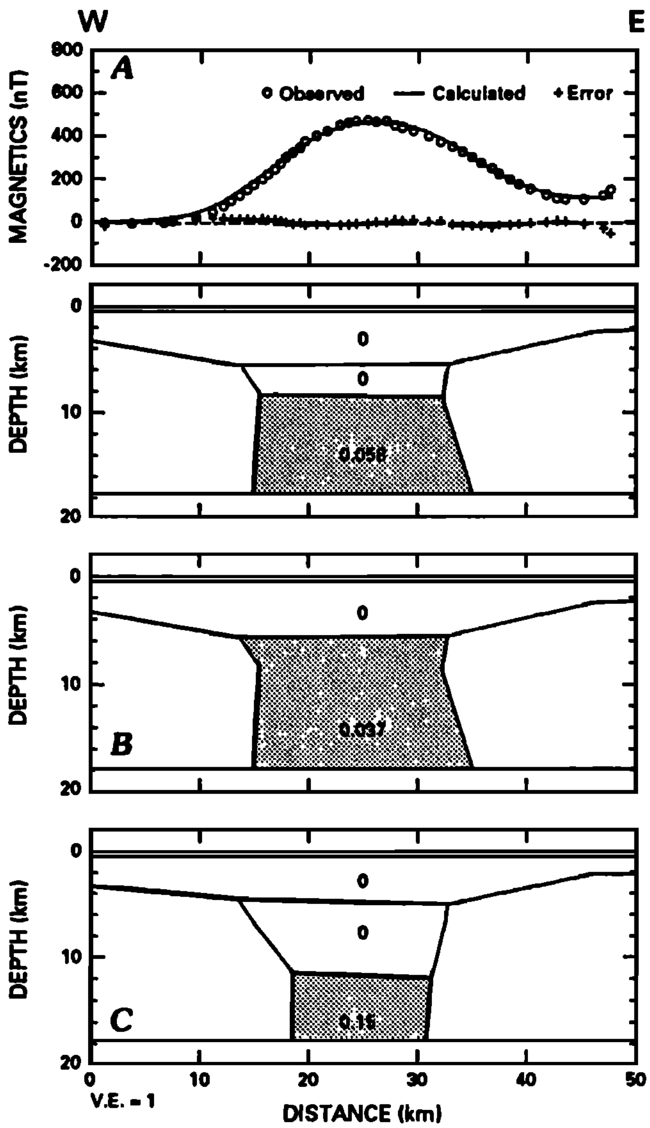

Figure 5. Magnetic models (2-D) fit to anomaly X (Plate 3) along flight line 2-04. Apparent susceptibilities indicated in S.I. units. Each of models fit observed profile within a few nannotesla standard deviation; computed profile for model a only is shown. Depth to the seafloor beneath the ice shelf from *Robertson et al.* [1982]. Upper nonmagnetic late Cenozoic and older sedimentary rock is indicated approximately from the seismic reflection interpretation of *Hinz and Kristoffersen* [1987].

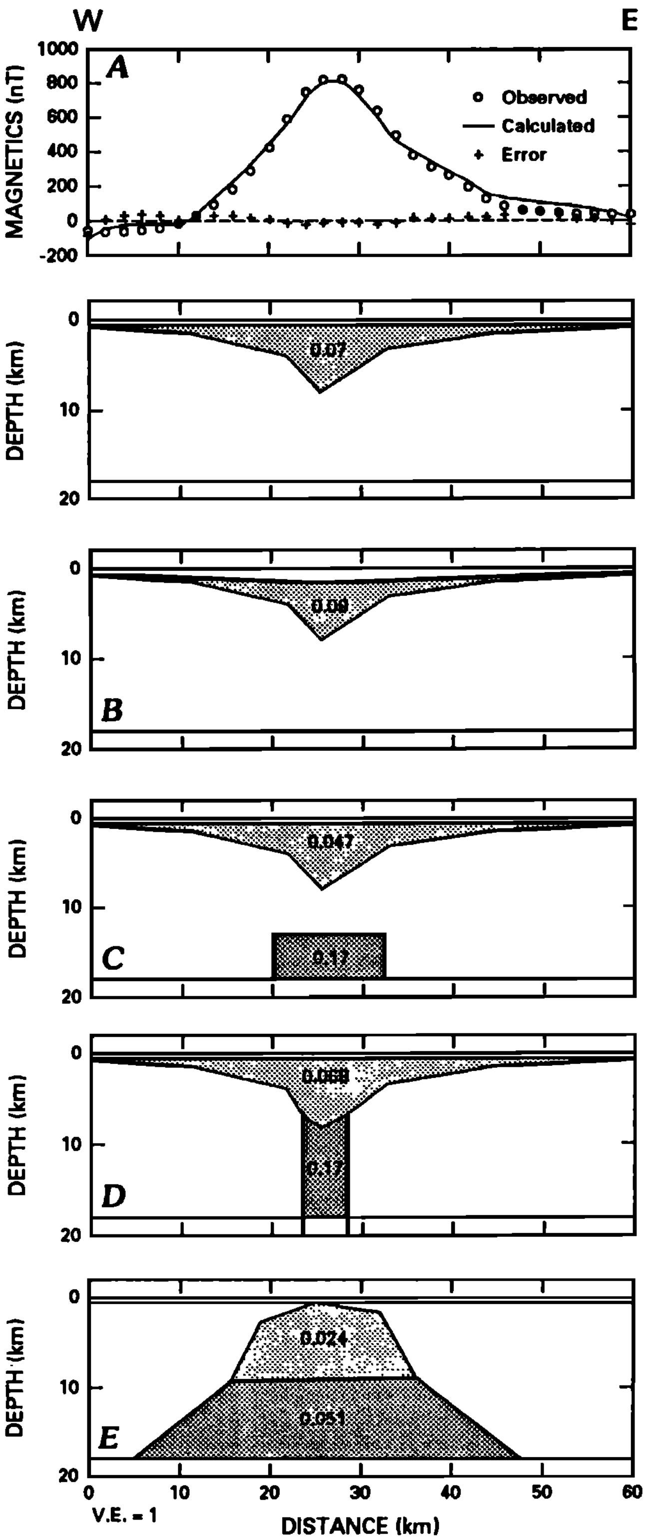

Figure 6. Magnetic models (2½-D) fit to anomaly X (Plate 3) along flight line 2-21. Apparent susceptibilities are in S.I. units. Each of the models fit observed profile within a few nT standard deviation; computed profile for model a only is shown. In 2½ D calculation, length of upper body along strike was infinity to the north and 5 km to the south; for lower bodies in c and e length along strike was infinity to the north and 15 km to the south; for lower body in d length along strike was + 2.5 km and -2.5 km.

beneath the largely "removed" volcanic edifices [*Behrendt et al.*, 1995] underlying the ice sheet with tops of sources at the base of the ice similar to the sources of most of the high-amplitude, short-wavelength, steep-gradient anomalies of Plate 2. *Behrendt et al.* [1994] showed two such models for anomalies A and D (Plate 2), They interpreted anomaly D as the highly magnetic root of an active (*Blankenship et al.*, 1993] volcanic center as either a caldera or a subvolcanic intrusion. The model for 1000-nT anomaly A [*Behrendt et al.*, 1994] required a several kilometer thick magnetic mass below the low subglacial topographic relief defined by the radar ice-sounding profiles.

Apparent susceptibilities (ranging from 0.098-0.362 SI; *Behrendt et al.*, 1994]) required for the models for anomalies A and D and other anomalies in Plate 2, are unreasonably high for volcanic rocks and higher than the means of susceptibilities measured for late Cenozoic volcanic rocks in the McMurdo area [*Pederson et al.*, 1981; E. Mankinen, personal communication., 1994]; this implies a high remanent magnetization in the present field direction.

Discussion

Transfer Faults

Fitzgerald [1992] interpreted an inflection point in the trend of the Transantarctic Mountain front as evidence for a major transfer fault on trend with the Ross fault (Plate 1]. As noted by *Kyle* [1990], Wright-Grassham interpreted a northeast trending major lineament of vents at the southwest of Figure 2 through Black and White Islands (Figure 5) as a "transfer or transform fault" parallel to the Ross fault and about 50 km to the south. *Borg and DePaolo* [1994] showed a speculative, right-lateral, strike-slip fault across the front of the Transantarctic Mountains in the same general area based on isotopic data from rocks at least 500 Ma (including xenoliths from late Cenozoic volcanic rocks). We consider all of these hypothesized northeast trending lineaments in this area as tectonically related.

The apparent 40-km right-lateral offset of the magnetic anomaly over the Central Basin across the Ross fault (Plate 1) does not prove that this is a transfer fault [*Damaske et al.*, 1994]. In contrast, the inference that the Polar 3 anomaly is a transfer fault [*Behrendt et al.*, 1991b] was based on the interpreted existence of extension in the Victoria Land Basin and inferred extension in another basin (only partly known at that time from BGR reflection profiles), north of the east end of the Polar 3 anomaly. This interpretation would require left-lateral offset in the segment represented by the Polar 3 anomaly. Similar reasoning requires the segment of the Ross fault between parts of the Southern Central Basin on either side of the fault to have undergone left-lateral displacement (not the apparent right-lateral displacement) during active extension of these basin segments. Only if future investigations demonstrate this sense of movement could the Ross fault be proven as a transform fault.

To further complicate interpretation of the Ross fault, various lines of evidence stated above suggest that the Ross fault lineation is an old feature probably reactivated several times (in different senses?) since the earliest suggested offset at about 500 Ma [*Borg and DePaolo*, 1994]. Any influence

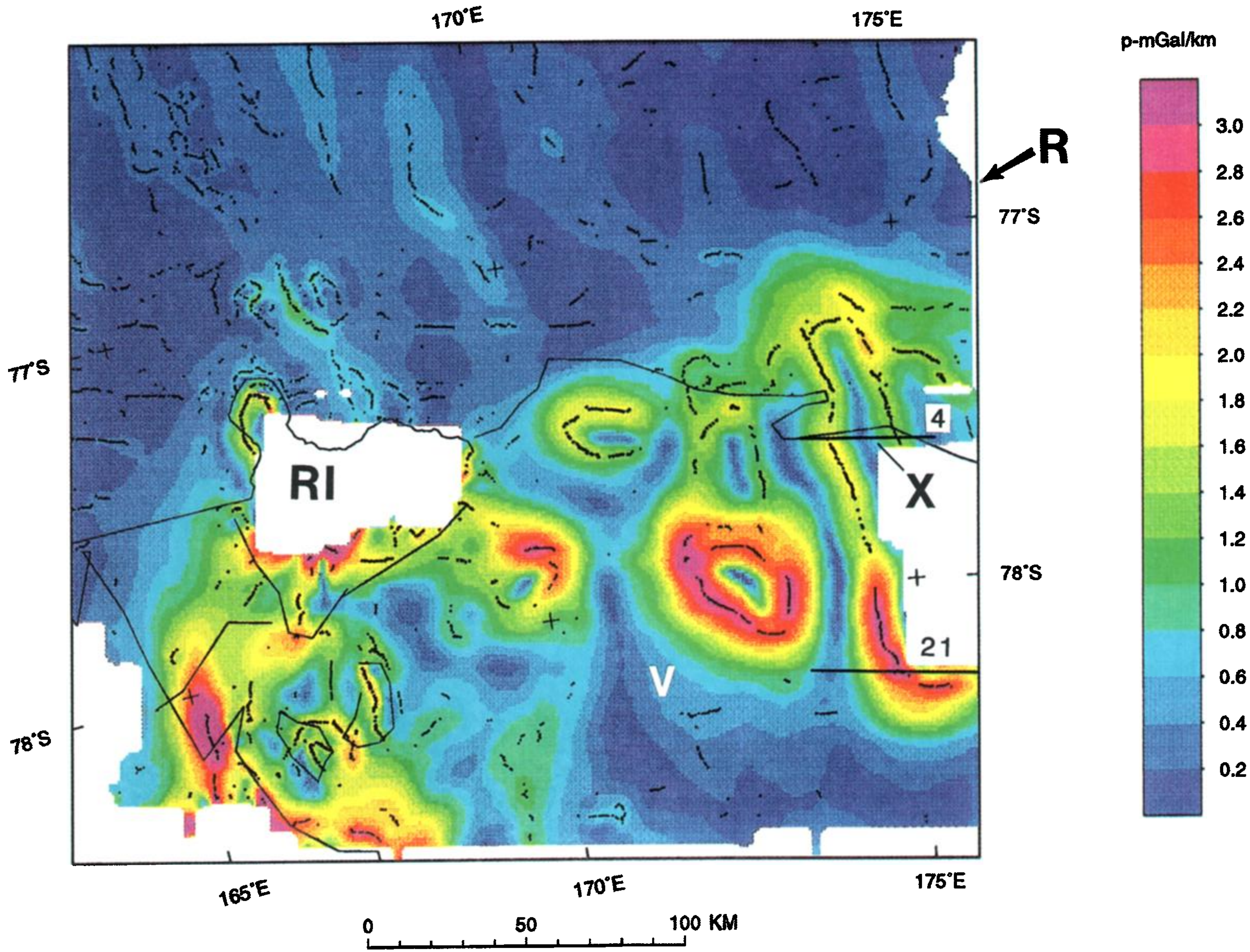

Plate 3. Magnetic boundaries in southern part of Plates 1 and 4 superimposed on horizontal gradient of pseudogravity at same scale as Plates 2 and 5; compare Plates 1 and 4. Anomaly X overlies the inferred southern extension of the southern Central basin (Figure 2). Anomaly V marks an interpreted eroded volcano beneath the ice shelf. R-trend of Ross fault. RI-Ross Island. Lines 4 and 21 indicate locations of aeromagnetic profiles 2-04 and 2-21 modeled in Figures 5 and 6 respectively.

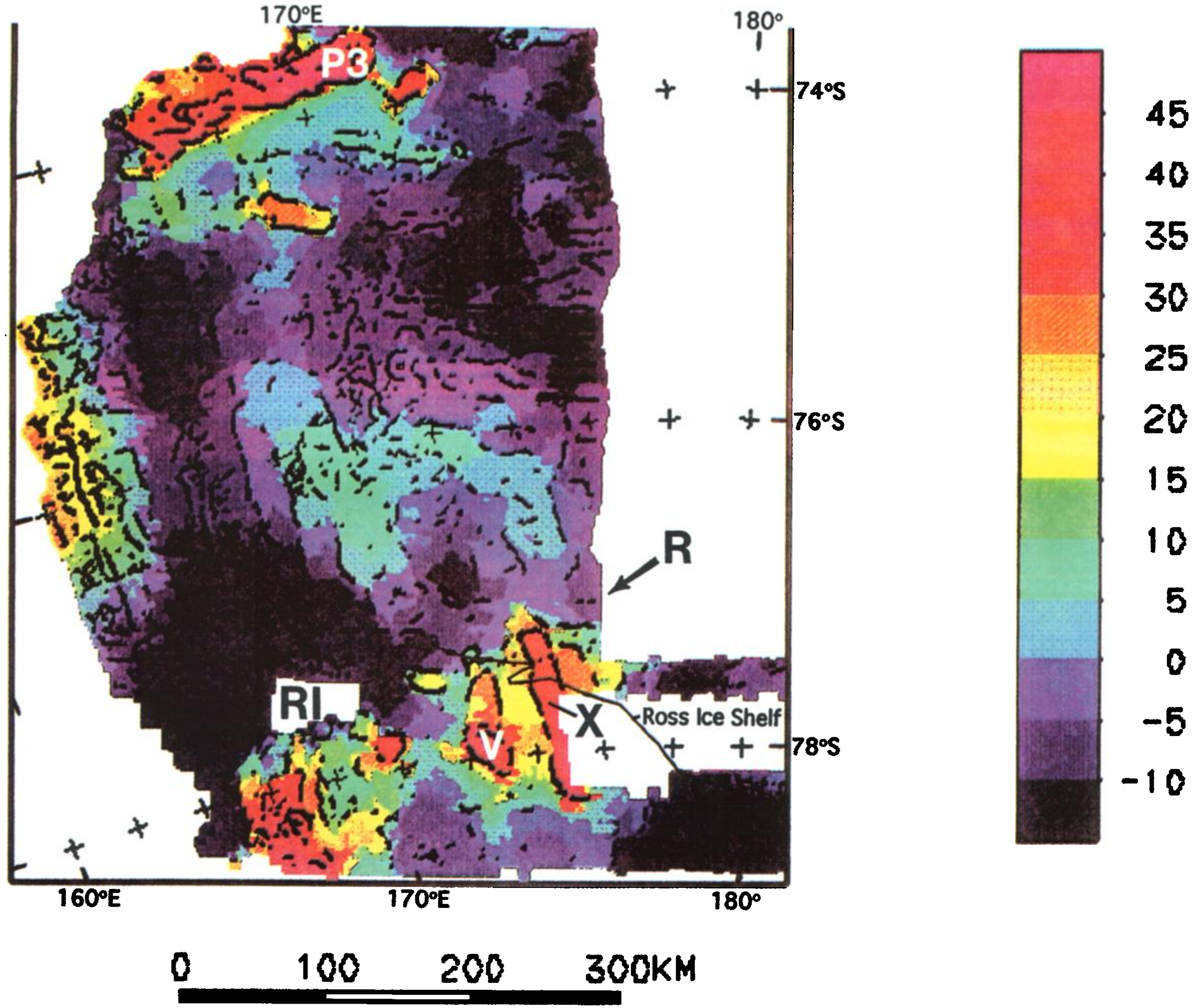

Plate 4. Terrace map of Ross Sea-northern Ross Ice Shelf magnetic data (Plate 3), calculated from pseudogravity. Magnetic boundaries (black dots and lines) outlining the terraces are local maxima of horizontal gradient of pseudogravity as in Plate 3. Amplitude of color terrace levels is identical to that of the range of the input anomalies. Anomalies V, X, and P3 (Polar 3) are indicated. R is the trend of Ross RI is Ross Island.

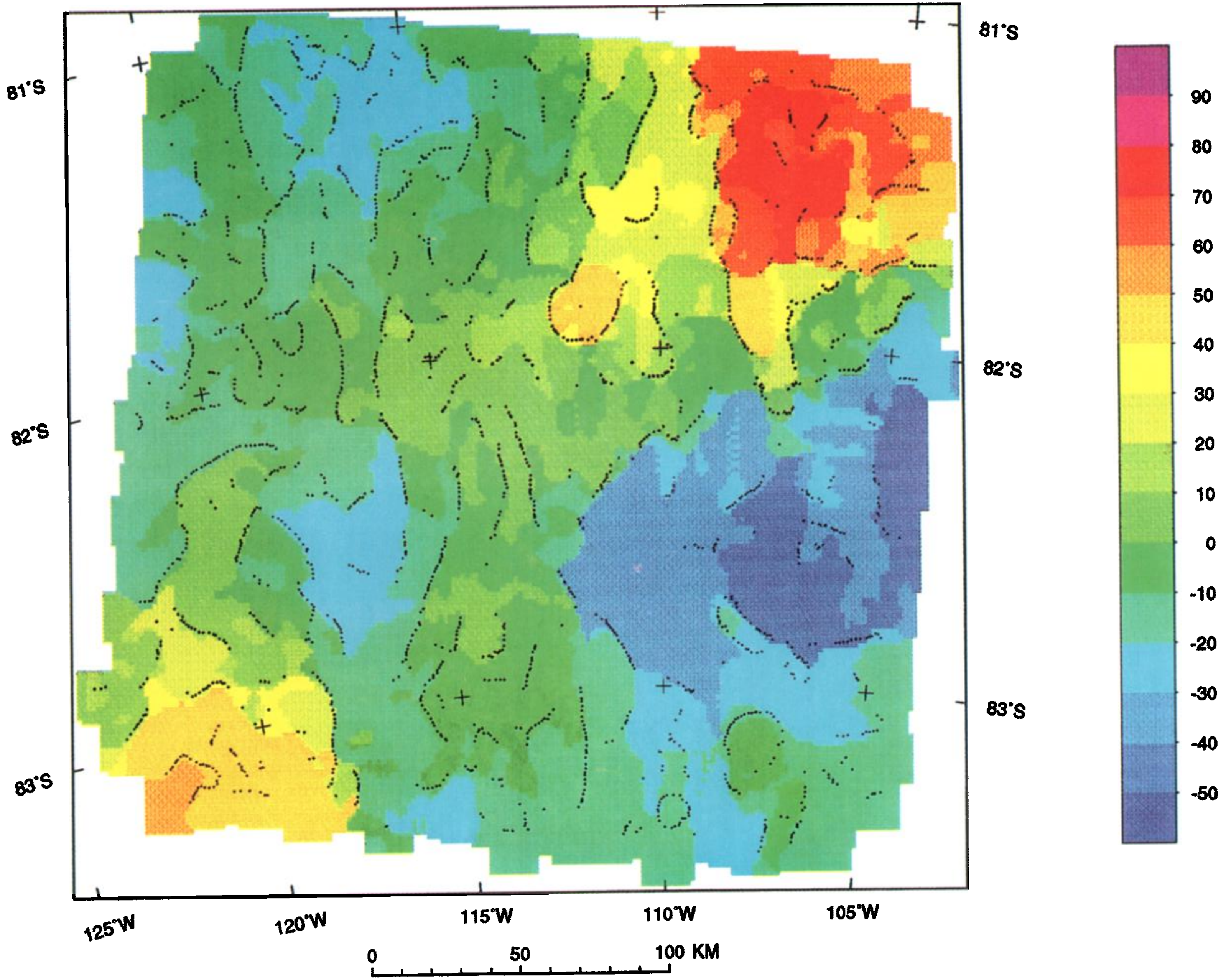

Plate 5. Terrace map of West Antarctic Ice Sheet-CASERTZ area calculated from pseudogravity as in Plate 4. Magnetic boundaries (black dots and lines) outlining the terraces are local maxima of horizontal gradient of pseudogravity as in Plates 3 and 4. Anomaly D marks an active volcano [*Blankenship et al.*, 1993; *Behrendt et al.*, 1994].

on late Cenozoic magmatic activity is the result of reactivation of these older structures. In any case, unlike transform faults in young oceanic crust, the Ross fault could have been a transfer fault at one time and not another in its 500? Ma history.

The north trending rift fabric in the Ross Sea-Ross Ice Shelf (and CASERTZ) area, revealed by the aeromagnetic surveys, is probably a reactivation of older rift trends (late Mesozoic?) and is superimposed on still older crosscutting structural trends. The ~100-km wide, east-southeast-trending magnetic terrace crossing the Ross Sea survey (Plate 4) was suggested as evidence of strike slip parallel and at the front of the Transantarctic Mountains. This may appear to contradict the evidence of *Borg and DePaolo* [1994] of a fault dated at 500 Ma at the front of the present Transantarctic Mountains parallel to the Ross fault.

Aeromagnetic Evidence of Rift Complexity

The significant differences between the central area of the Ross Sea continental shelf-Ross Ice Shelf aeromagnetic surveys and the northern and southern areas suggest significant variation in volumes (and rates?) of late Cenozoic volcanism and associated magmatic activity among these areas (e.g., Plates 1 and 4). The CASERTZ aeromagnetic survey (e.g., Plates 2 and 5 compared with Plates 1, 3, and 4) is more similar to the area south of the Ross fault zone and to the northern part of the Ross Sea continental shelf survey. Perhaps the variations in late Cenozoic uplift of different blocks of the rift shoulder along strike (Figure 1) [*Behrendt and Cooper*, 1991; 1994] are related to relative variations in thermal stresses driving the late Cenozoic uplift [*Stern and ten Brink*, 1989], in contrast to earlier uplift (e.g., *Fitzgerald*, 1992]. We expect that as additional aeromagnetic coverage is obtained over the ice- and sea-covered area of the West Antarctic rift system, this complex pattern will be typical throughout, as in the Basin and Range and East African rift systems of comparable size.

Mantle Plume

New Zealand and the Campbell Plateau rifted from Antarctica at 72-85 Ma [*Bradshaw*, 1989] and the seafloor basalts separating them at present recorded the subsequent history [e.g., *McAdoo and Marks*, 1992]. There is, however, relatively little volcanic rock exposed in Marie Byrd Land associated with this event [*LeMasurier*, 1990; *Hole and LeMasurier*, 1994]. In contrast, large amounts of late Cenozoic volcanic rock are exposed throughout the West Antarctic rift system (Figure 1) associated with uplift of the rift shoulder and late Cenozoic faulting (e.g., the Victoria Land Basin [*Cooper et al.*, 1987a]). Limited crustal extension (<300 km in the late Cenozoic [*Lawver et al.*, 1991]) does not allow associated decompression melting to account for the extensive late Cenozoic volcanism [*Behrendt et al.*, 1992].

Behrendt et al. [1992; 1994] used geophysical evidence of the great amounts of subglacial and submarine volcanic rocks of inferred late Cenozoic age in the West Antarctic rift system as evidence for a mantle plume origin. *Hole and LeMasurier* [1994] inferred the ocean island basalt chemistry of these rocks as indicative of a mantle plume. *Behrendt et al.* [1994] calculated a minimum area of 0.5×10^6 km^2, and a minimum volume of 10^6 km^3 of late Cenozoic volcanic rocks (flood basalts? or their subglacially erupted equivalent) beneath the West Antarctic Ice Sheet and Ross Ice Shelf. Both values are comparable to other great areas of flood basalts interpreted as evidence of plume heads [*White and McKenzie*, 1989].

Rifting is inferred to have been focused by a mantle plume to the hot, thin, extended, lithosphere in the Ross Embayment-Byrd Subglacial Basin area which was weakened by the end of the Cretaceous by rifting of New Zealand-Campbell Plateau from Antarctica. As spreading centers surrounding the stationary Antarctic Plate migrated away from Antarctica, late Cenozoic rifting in West Antarctica continued to the present. The high rift shoulder (Figure 1) developed as lateral heat transfer affected the cold, old, much thicker lithosphere of the East Antarctic side of this boundary, which has a very much higher flexural rigidity [*Stern and ten Brink*, 1989]. The north side of the asymmetric West Antarctic rift system is bounded by relatively young oceanic lithosphere (Figure 1), which may explain the absence of a comparable rift shoulder there.

Westaway [1993] discussed extension of only ~2 mm/yr for the Yellowstone, <~1 mm/yr for the Baikal, and ~0.7 mm/yr for the East Africa plumes and a volume flux of ~50 m^3/s for each of the three areas. For ~5% magma generation [*Westaway*, 1993] this results in ~0.8×10^6 km^3/m.y. In an Ar^{40}-Ar^{39} study of the Parana-Etendeka continental flood basalts, *Turner et al.* [1994] found that they were erupted over a period of 10 m.y. at a minimum overall rate of ~0.1×10^6 km^3/m.y. They noted that this is an order of magnitude less than previously proposed for this area and also for the Deccan and Siberian continental flood basalt provinces. *Turner et al.* [1994] noted that this value is similar to estimates for Hawaii, Iceland, and the Columbia River basalts.

Despite many available radiometric ages from volcanic exposures in the West Antarctic rift system [*LeMasurier and Thomson*, 1990], it is difficult to accurately estimate when the bulk of late Cenozoic volcanic rock in the West Antarctic rift system were erupted. Inaccessibility of the volcanic exposures and the fact that the majority of the volcanic rocks lie beneath the sea, ice shelf, and the West Antarctic Ice Sheet limit the database. Although published ages extend from the present back to about 30 Ma, magma production from plumes calculated by *Westaway* [1993], ~$.8 \times 10^6$ km^3/m.y., and the order of magnitude lower value of *Turner et al.* [1994], ~0.1×10^6 km^3/m.y., would easily accommodate the formation of the West Antarctic continental flood(?) basalts (or their subglacial equivalent) in a 1-10 m.y. period.

Lower Lithospheric Extension?

Keen et al. [1994] refer to two end-member categories of rifted continental margins. One end member represents margins that are little affected by magmatism and most clearly display extension-normal faulting and crustal thinning. The separation of New Zealand and the Campbell Plateau from Antarctica seems to fit this case. At the other end, volcanic margins, large thicknesses of basalt are interpreted to underplate or intrude thinned continental crust provided temperatures in the asthenosphere are 100°-200° C higher probably requiring a mantle plume to provide the excess heat. A small increase in asthenospheric temperature can produce significantly greater melt thicknesses [e.g., *White and McKenzie*, 1989]. Many margins (e.g., the Canadian Atlantic [*Keen et al.*, 1994]) do not fit these two end members.

Keen et al. [1994] proposed a model considering separate stretching factors (β and δ) for the crust and lower lithosphere, respectively; crustal stretching may be significantly less than that in the lower lithosphere. One case that they consider as typical has a $\beta = 2$ and $\delta = 5$. They note that crustal stretching is relatively less important than mantle stretching as the latter controls to a greater extent the position where melting is located [*Keen et al.*, 1994]. This could be a significant point to consider for the alkalic volcanism in the West Antarctic rift. Various lines of evidence, e.g., low flexural rigidity, thin elastic lithosphere [*Stern and ten Brink*, 1989], and high heat flow [e.g., *Berg*, 1991; *Dell Vedova et al.*, 1992] suggest that the asthenosphere may be at a very shallow depth [*Stern and ten Brink*, 1989] beneath the 18-20-km deep Moho in the Ross Sea area (Figure 2). This suggests to us that there may have been significantly greater stretching of the lower lithosphere than of the crust in the late Cenozoic. Considering that the major crustal extension in the West Antarctic rift system probably occurred in the Late Cretaceous [*Behrendt et al.*, 1991b; *Lawver et al.*, 1991] the elevated temperature associated with this extension may not have cooled prior the episode of lower lithospheric extension in the late Cenozoic. As pointed out by *Keen et al.*, [1994] the warmer conditions favor melt generation at the start of the second episode. Lower lithospheric extension with resulting decompression melting might better account for the unusually large area of late Cenozoic alkalic ocean island basalt volcanism interpreted as the plume head (Figure 1).

We would argue more strongly for late Cenozoic lower lithospheric stretching as an alternative or supplement to the mantle plume hypothesis for the great volume of inferred volcanism in the West Antarctic rift system were there not a space problem. *Keen et al.* [1994] postulate entrainment of lower lithospheric material into the asthenosphere as a mechanism around this space problem, but we do not immediately see how this concept applies in the West Antarctic rift area considering that the Antarctic Plate is essentially surrounded by spreading centers. However, considering that the lower (mantle) lithosphere may have been significantly thicker than the crust prior to stretching in the late Cenozoic, a small amount of horizontal extension δ could possibly result in a great volume of decompression melting. Separation of thick lower (mantle) lithosphere from the crust and sinking it into the asthenosphere in some unknown place is intellectually unsatisfying, but possibly the space problem could be resolved in this way.

Acknowledgments. We thank our colleagues who participated in the Ross Sea-Ross Ice Shelf and CASERTZ field operations. Uri ten Brink, Lisa Morgan, F. J. Davey, and A. C. Johnson reviewed various versions of the manuscript. James Dewey pointed out the 1993 earthquake in the Ross Sea. Edward Mankinen provided additional unpublished data on the magnetic properties of volcanic rocks in the McMurdo area. Herbert Hoppe was co-investigator in the 1990-1991 GANOVEX work and Steven Hodge and John Brozena were coinvestigators in the CASERTZ surveys. The U.S. National Science Foundation partially funded the research and provided extensive logistic support for the three surveys. The German Alfred Wegener Institute for Polar Research provided the German survey aircraft and furnished other support.

References

Baranov, V., A new method for interpretation of aeromagnetic maps: pseudo-gravimetric anomalies, *Geophysics, 22*, 359-383, 1957.

Beaudoin, B. C., U. S. ten Brink, and T. A. Stern, Characteristics and processing of seismic data collected on thick, floating ice: Results from the Ross Ice Shelf, Antarctica, *Geophysics (57)*, 1359-1372, 1992.

Beck, M. E., Jr. and N. L. Griffin, Magnetic intensities in a differentiated gabbroic body, the Dufek intrusion, Pensacola Mountains, Antarctica, in *Geological Survey Research, U.S. Geol. Surv. Prof. Pap. 750-B*, B117-B121, 1971.

Behrendt, J. C., Distribution of narrow-width magnetic anomalies in Antarctica, *Science, 144*, 995-999, 1964.

Behrendt, J.C., and A. K. Cooper, Evidence of rapid Cenozoic uplift of theshoulder of the West Antarctic rift system and a speculation on possible climate forcing, *Geology, 19*, 315-319, 1991.

Behrendt, J. C., and A. K. Cooper, COMMENT on Minimal Pliocene-Pleistocene uplift of the dry valleys sector of the Transantarctic mountains: A key parameter in ice-sheet reconstructions, by T. I. Wilch, D. R. Lux, G. H. Denton, and W. C. McIntosh, *Geology, 22*, 668-669, 1994.

Behrendt, J. C., A. K. Cooper, and A. Yuan, Interpretation of marine magnetic gradiometer and multichannel seismicreflection observations over the western Ross Sea shelf, Antarctica, in *The Antarctic Continental Margin Geology and Geophysics of the Western Ross Sea*, Circum-Pacific Council for Energy and Natural Resour. Earth Sci. Ser., 5B, vol. edited by A. K. Cooper, and F. J. Davey, pp. 155-178, Houston, Tex., 1987.

Behrendt, J. C., H. J. Duerbaum, D. Damaske, R. W. Saltus, W. Bosum, and A. K. Cooper, Extensive volcanism and related tectonism beneath the western Ross Sea continental shelf, Antarctic, Interpretation of an aeromagnetic survey, in *Geological evolution of Antarctica*, edited by M. R. A. Thomson, J. A. Crame, and J. W. Thomson, Cambridge Univ. Press, New York, pp. 299-304, 1991a.

Behrendt, J. C., W. E. LeMasurier, A. K. Cooper, F. Tessensohn, A. Tréhu, and D. Damaske, Geophysical studies of the West Antarctic rift system, *Tectonics 10(6)*, 1257-1273, 1991b.

Behrendt, J. C., W. E. LeMasurier, A. K. Cooper, F. Tessensohn,and D. Damaske, The West Antarctic Rift System--A Review of Geophysical Investigations, in *Contributions to Antarctic Research II, Antarct. Res. Ser.*, vol. 53, edited by D.H. Elliot, pp. 67-112, 1991c.

Behrendt, J.C., W. E. LeMasurier, and A. K. Cooper, The West Antarctic rift system--A propagating rift "captured" by a mantle plume, in *Recent Progress in Antarctic Earth Science*, edited by K. Kaminuma and Y. Yoshida, Terra Sci., pp. 315-32, Tokyo, 1992.

Behrendt, J. C., D. D. Blankenship, C. A. Finn, R. E. Bell, R. E. Sweeney, S. R. Hodge, and J. M. Brozena, Evidence for late Cenozoic Flood Basalts(?) in the West Antarctic Rift System revealed by the CASERTZ Aeromagnetic Survey, *Geology, 22*, 527-530, 1994.

Behrendt, J. C., D. D. Blankenship, D. Damaske, and A. K. Cooper, Removal of late Cenozoic subglacially emplaced volcanic edifices by the West Antarctic Ice Sheet, *Geology, 23*, 1111-1114, 1995.

Bentley, C.R., A.P. Crary, E. Thiel, and N.A. Ostenso, Structure of West Antarctica, *Science, 131*, 131-136, 1960.

Berg, J. H., Geology, petrology and tectonic implications of crustal xenoliths in Cenozoic volcanic rocks of southern Victoria land, in *Geological evolution of Antarctica*, edited by M. R. A. Thomson, J. A. Crame, and J. W. Thomson, Cambridge Univ. Press, New York, pp. 311-315, 1991.

Blankenship, D. D., R. E. Bell, S. M. Hodge, J. M. Brozena, J.C. Behrendt, and C. A. Finn, Active volcanism beneath the West Antarctic Ice Sheet, *Nature, 361*, 526-529, 1993.

Borg, S.G. and D.J. DePaolo, Laurentia, Australia, and Antarctica as a late Proterozoic supercontinent: Constraints from isotopic mapping, *Geology, 22*, 307-310, 1994.

Bosum, W., D. Damaske, N. W. Roland, J. C. Behrendt, and R. W. Saltus, The GANOVEX IV Victoria Land/Ross Sea aeromagnetic survey: interpretation of anomalies, *Geol. Jahrb., Reihe E, 38*, 153-230, 1989.

Bozzo, E., G. Caneva, A. Colla, F. Ferraccioli, M. Gambetta, M. Chiappini, A. Meloni, and D. Damaske, Aeromagnetics in the area between Terra Nova Bay and Granite Harbour, Victoria Land (Antarctica): Data processing and production of magnetic maps, paper presented at XXI IUGG General Assembly, Int. Union of Geod. and Geophys., Boulder, Colo., 1995.

Bradshaw, J. D., Cretaceous geotectonic patterns in the New Zealand region, *Tectonics, 8(4)*, 803-820, 1989.

Cooper, A.K., F. J. Davey, and J.C. Behrendt, Seismic stratigraphy and structure of the Victoria Land Basin, western Ross Sea, Antarctica, in *The Antarctic Continental Margin Geology and Geophysics of the Western Ross Sea, Circum-Pacific Council for Energy and Natural Resour. Earth Sci. Ser.*, 5B, vol. edited by A. K. Cooper, and F. J. Davey, pp. 27-76, Houston, Tex., 1987a.

Cooper, A.K., Davey, F.J., and Cochrane, G.R., Structure of extensionally rifted crust beneath the western Ross Sea and Iselin Bank, Antarctica, from sonobuoy seismic data, in *The Antarctic Continental Margin Geology and Geophysics of the Western Ross Sea, Circum--Pacific Council for Energy and Natural Resour. Earth Sci. Ser.*, 5B, vol. edited by A. K. Cooper, and F. J. Davey, pp. 27-76, Houston, Tex., 1987b.

Cooper, A. K., F. J. Davey, and K. Hinz, Crustal extension and origin of sedimentary basins beneath the Ross Sea and Ross Ice shelf, Antarctica, in *Geological evolution of Antarctica,* edited by M. R. A. Thomson, J. A. Crame, and J. W. Thomson, Cambridge Univ. Press, New York, pp. 285-292, 1991.

Cordell, L., and A. E. McCafferty, A terracing operator for physical property mapping with potential field data, *Geophysics, 54*, 621-634, 1989.

Damaske, D., J. C. Behrendt, A. E. McCafferty, R. W. Saltus, and U. Meyer, Transfer faults in the west Ross Sea: New evidence from the McMurdo sound/Ross Ice Shelf aeromagnetic survey (GANOVEX VI), *Antarct. Sci., 6(3)*, 359-364, 1994.

Della Vedova, B., G. Pellis, L. Lawver, L., and G. Brancolini, Heat flow and tectonics of the Western Ross Sea, in *Recent Progress in Antarctic Earth Science*, edited by K. Kaminuma and Y. Yoshida, Terra Sci., pp. 627-637, Tokyo, 1992.

Drewry, D. J., Antarctica: Glaciological and geophysical folio, 9 sheets, Scott Polar Res. Inst., Cambridge Univ., Cambridge, England, 1983.

Dziewonski, A. M., T. A. Chou, and J. H. Woodhouse, Determination of earthquake source parameters from waveform data for studies of global and regional seismicity, *J. Geophys. Res., 86(B4)*, 2825-2852, 1981.

Etheridge, M. A., J. C. Branscon, and P. G. Stuart-Smith, Extensional basin forming structures in Bass Straight and their importance for hydrocarbon exploration, *J. Aust. Pet. Assoc., 25*, 344-361, 1985.

Fitzgerald, P. G., The Transantarctic Mountains of southern Victoria Land: The application of apatite fission analysis to a rift shoulder uplift, *Tectonics, 11(3)*, 634-662, 1992.

Grauch, V. J. S. and L. Cordell, Limitations of determining density or magnetic boundaries from the horizontal gradient of gravity or pseudogravity, *Geophysics, 52*, 118-121, 1987.

Hayes, D.E., and F.J. Davey, A geophysical study of the Ross Sea, Antarctica, in *Initial Rep. Deep Sea Drill. Proj., 28*, 887-907, 1975.

Hinz, K., and Y. Kristoffersen, Antarctica recent advances in the understanding of the continental shelf, *Geol. Jahrb., Reihe E, 37*, 1-54, 1987.

Hole, M. J., and W. E. LeMasurier, Tectonic controls on the geochemical composition of Cenozoic alkali basalts from West Antarctica, *Contrib. to Mineral. and Petrol., 117*, 187-202, 1994.

Jankowski, E. J., D. J. Drewry, and J. C. Behrendt, Magnetic studies of upper crustal structure, in *Antarctic Earth Science*, edited by R. L. Oliver et al., pp.197-203, Aust. Acad. of Sci., Canberra, 1983.

Keen, C. E., R. C. Courtney, S. A. Dehler, and M.-C. Williamson, Decompression melting at rifted margins: Comparison of model predictions with the distribution of igneous rocks on the eastern Canadian margin, *Earth Planet. Sci. Lett., 121*, 403-416, 1994.

Kellogg, K. S., and P. D. Rowley, Structural geology and tectonics of the Orville Coast region, Southern Antarctic Peninsula, Antarctica, *U.S. Geol. Surv. Prof. Pap. 1498*, 25, 1989.

Kyle, P. R., McMurdo volcanic group-western Ross Embayment--Introduction in Volcanoes of the Antarctic plate and southern oceans, in *Volcanoes of the Antarctic Plate and Southern Oceans, Antarct. Res. Ser.*, vol. 48, edited by W. E. LeMasurier, and J. W. Thomson J.W., pp. 19-25, AGU, Washington, D.C., 1990., 1991.

Lawver, L. A., J. Y. Royer, D. T. Sandwell, and C. R. Scotese, Evolution of the Antarctic continental margin, in *Geological evolution of Antarctica,* edited by M. R. A. Thomson, J. A. Crame, and J. W. Thomson, Cambridge Univ. Press, New York, pp. 533-540, 1991.

LeMasurier, W. E., Late Cenozoic volcanism on the Antarctic plate--An overview, in *Volcanoes of the Antarctic Plate and Southern Oceans, Antarct. Res. Ser.*, vol. 48, edited by W. E. LeMasurier, and J. W. Thomson J.W., pp. 1-19, AGU, Washington D.C., 1990.

LeMasurier W. E., and J. W. Thomson (eds.), *Volcanoes of the Antarctic Plate and Southern Oceans, Antarct. Res. Ser.*, vol. 48, edited by W. E. LeMasurier, and J. W. Thomson J.W., 487 pp., AGU, Washington D.C., 1990.

Mankinen, E. A., and A. Cox, Paleomagnetic investigation of some volcanic rocks from the McMurdo volcanic province, Antarctica, *J. Geophys. Res., 93(B10)*, 11,599-11,612, 1988.

Maslanyj, M. P., S. W. Garrett, A. C. Johnson, R. G. B. Renner, and A. M. Smith, Aeromagnetic map of West Antarctica (Weddell Sea Sector), BAS GEOMAP Series, Sheet 2, Scale 1:2,500,000, Brit. Antarct. Surv., Cambridge, England, 1991.

McAdoo, D.C., and K. M. Marks, Gravity fields of the Southern Ocean from Geosat data, *J. Geophys. Res., 97(B3)*, 32547-32605, 1992.

McGinnis, L. D., R. H. Bowen, J. M. Erickson, B. J. Allred, and J. L. Kreamer, East-West Antarctic boundary in McMurdo Sound, *Tectonophysics, 114*, 341-356, 1985.

McMahon, B. E., and H. Spall, Paleomagnetic data from unit 13, DVDP hole 2, Ross Island, *Antarctic J. U.S., 9*, 229-232, 1974.

O'Connell, D. R. H., and T. M. Stepp, Structure and evolution of the crust at the Transantarctic Mountains-Ross Sea crustal transition: results from Tourmaline Plateau seismic array of the GANOVEX V ship to shore seismic refraction experiment, *Geolog. Jahrb., Heft, 47*, 229-276, 1993.

Pederson, D. R., G. E. Montgomery, L. D. McGinnis, and C. P. Ervin, Aeromagnetic survey of Ross Island, McMurdo Sound, and the Dry Valleys, *Dry Valleys Drilling Project, Antarct. Res. Ser., vol. 33*, edited by L. D. McGinnis, pp. 7-25, AGU Washington, D.C., 1981.

Robertson, J. D., C. R. Bentley, J. W. Clough, and L. L. Greischer, Sea-bottom topography and crustal structure below the Ross Ice Shelf, Antarctica, in *Antarctic Geoscience*, edited by C. Craddock, pp. 1083-1090, Univ. of Wisconsin Press, Madison, 1982.

Robinson, E.S., Geological structure of the Transantarctic Mountains and adjacent ice covered areas, Antarctica, Ph.D. dissertation, 291 pp., Univ. of Wisconsin, Madison, 1964.

Schmidt, D. L., and P. D. Rowley, Continental rifting and transform faulting along the Jurassic Transantarctic rift, Antarctica, *Tectonics, 5(2)*, 279-291, 1986.

Stern, T. A. and U. S. ten Brink, Flexural uplift of the Transantarctic Mountains, *J. Geophys. Res., 94(B8)*, 10315-10330, 1989.

Stern, T. A., F. J. Davey, and G. Delisle, Lithospheric flexure induced by the load of Ross Archipelago, southern Victoria Land, Antarctica, in *Geological evolution of Antarctica,* edited by M. R. A. Thomson, J. A. Crame, and J. W. Thomson, Cambridge Univ. Press, New York, pp. 323-328, 1991.

Storey, B. C., The crustal blocks within Antarctica within Gondwana: Reconstruction and breakup model, in *Geological evolution of Antarctica,* edited by M. R. A. Thomson, J. A. Crame, and J. W. Thomson, Cambridge Univ. Press, New York, pp. 587-592, 1991.

Stump, E., S. G. Borg, and M. F. Sheridan, A. IV. Southernmost Ross Embayment, in *Volcanoes of the Antarctic Plate and Southern Oceans, Antarct. Res. Ser.*, vol. 48, edited by W. E. LeMasurier, and J. W. Thomson J.W., pp. 136-139, AGU, Washington D.C., 1990.

ten Brink, U.S., B. C. Beaudoin, and T. A. Stern, Geophysical investigations of the tectonic boundary between East and West Antarctica, *Science, 261*, 45-50, 1993.

Tréhu, A. M., J. C. Behrendt, and J. C. Fritsch, Crustal structure of the Central Basin, Ross Sea, Antarctica, edited by D. Damaske, and J. C. Fritsch, GANOVEX V, *Geologisches Jahrb., Reihe E, 47*, 291-312, 1993.

Turner, S., M. Regelous, S. Kelley, C. Hawkesworth, and M. Mantovani, Magmatism and continental break-up in the South Atlantic: High precision ^{40}Ar-^{39}Ar geochronology, *Earth Planet. Sci. Lett., 121*, 334-348, 1994.

Westaway, R., Forces associated with mantle plumes, *Earth Planet. Sci. Lett., 119*, 331-348, 1993.

White, R. S., and D. P. McKenzie, Magmatism at rift zones: The generation of volcanic continental margins and flood basalts, *J. Geophys. Res., 94(B6)*, 7685-7729, 1989.

Wilch, T. I., D. R. Lux, G. H. Denton, and W. C. McIntosh, Minimal Pliocene-Pleistocene uplift of the dry valleys sector of the Transantarctic Mountains: A key parameter in ice sheet reconstructions, *Geology, 21*, 841-844, 1993.

Wilson, T.J., Cenozoic transtension along the Transantarctic Mountains-West Antarctic rift boundary, southern Victoria land, Antarctica, *Tectonics, 14(2)*, 531-545, 1995.

Wörner, G., L. Viereck, J. Hertogen, and H. Niephaus, H., The Mt. Melbourne volcanic field (Victoria Land, Antarctica) II geochemistry and magma genesis, *Geol. Jahrb. Reihe E, 38*, 395-433, 1989.

J.C. Behrendt, C. Finn, A. McCafferty, and R. Saltus, U.S. Geological Survey, MS 964, Federal Center, Denver CO 80225. (e-mail: jbehrend@musette.cr.usgs.gov). Behrendt also at: Institute of Arctic and Alpine Research, University of Colorado, Boulder, CO 80309-0450.

R. Bell, Lamont-Doherty Earth Observatory, Palisades, NY 10964.

D. Blankenship, Institute for Geophysics, University of Texas, 8701 North Mopac Boulevard, Austin, TX 78759.

D. Damaske, Bunsesanstalt fur Geowissenschaften und Rohstoffe, Alfred-Bentz-Haus, Postfach 51 01 53, 3000 Hannover, Germany.

(Received October 23, 1995;
accepted November 1, 1995.)