CASERTZ aeromagnetic data reveal late Cenozoic flood basalts(?) in the West Antarctic rift system

John C. Behrendt
U.S. Geological Survey, MS 964, Federal Center, Denver, Colorado 80225
Donald D. Blankenship
Institute for Geophysics, University of Texas, Austin, Texas 78759
Carol A. Finn
U.S. Geological Survey, MS 964, Denver, Colorado 80225
Robin E. Bell
Lamont-Doherty Earth Observatory, Columbia University, Palisades, New York 10964
Ronald E. Sweeney
U.S. Geological Survey, MS 964, Denver, Colorado 80225
Steven M. Hodge
U.S. Geological Survey, Tacoma, Washington 98416
John M. Brozena
Naval Research Laboratory, Washington, D.C. 20375

ABSTRACT

The late Cenozoic volcanic and tectonic activity of the enigmatic West Antarctic rift system, the least understood of the great active continental rifts, has been suggested to be plume driven. In 1991–1992, as part of the CASERTZ (Corridor Aerogeophysics of the Southeast Ross Transect Zone) program, an ~25 000 km aeromagnetic survey over the ice-covered Byrd subglacial basin shows magnetic "texture" critical to interpretations of the underlying extended volcanic terrane. The aeromagnetic data reveal numerous semicircular anomalies ~100–1100 nT in amplitude, interpreted as having volcanic sources at the base of the ice sheet; they are concentrated along north-trending magnetic lineations interpreted as rift fabric. Models constrained by coincident radar ice soundings indicate highly magnetic sources, with a probable high remanent magnetization in the present field direction, strongly suggesting a late Cenozoic age. Magnetic anomalies over exposed late Cenozoic volcanic rocks along part of the rift shoulder and in coastal Marie Byrd Land are similar in form and amplitude. The CASERTZ aeromagnetic results, combined with >100 000 km of widely spaced aeromagnetic profiles, indicate at least 10^6 km^3 of probable late Cenozoic volcanic rock (flood basalt?) in the West Antarctic rift beneath the ice sheet and Ross Ice Shelf. Comparison with other plumes in active rift areas (e.g., Yellowstone and East Africa) indicates that this volume estimate lies in the range of magma generation found in these other low-extension continental rifts.

CASERTZ AEROMAGNETIC SURVEY

In 1991–1992 and 1992–1993 the CASERTZ program collected 50 000 km of radar ice-sounding, laser-altimeter, aerogravity, and aeromagnetic profiles on a 5 km orthogonal grid over the West Antarctic ice sheet. Here we report the first results of the ~25 000 km 1991–1992 aeromagnetic survey (Figs. 1 and 2), which are the only magnetic data compiled at this time. This is the first state-of-the-art magnetic survey over the West Antarctic ice sheet. With this detail, we are now able to compare the magnetic "texture" with that over the Ross Sea part of the West Antarctic rift system (Behrendt et al., 1991).

WEST ANTARCTIC RIFT SYSTEM

The nearly aseismic, yet tectonically and volcanically active, asymmetric West Antarctic rift system (LeMasurier, 1990; Behrendt et al., 1991) is largely covered with ice and spans ~3000 km (Fig. 1). The West Antarctic ice sheet flows through the Byrd Subglacial Basin into the Ross Ice Shelf, and its regime is probably partially controlled by rift tectonism and rift-shoulder mountain uplift. Episodic rift activity, including formation of the rift basins beneath the Ross Sea continental shelf, has been associated with West Antarctic crustal extension since the late Mesozoic (Cooper et al., 1991), when most of the extension took place, possibly syntectonically with rifting of New Zealand and the Campbell Plateau from Antarctica, or earlier (Wilson, 1992). A later stage of rifting (LeMasurier, 1990; Behrendt et al., 1991; Cooper et al., 1991) with limited extension (Lawver et al., 1991; Behrendt et al., 1991) is characterized by reactivated basin downfaulting beneath the Ross Sea continental shelf, accelerated rift-shoulder uplift, and associated bimodal alkalic volcanism throughout the area indicated in Figure 1. This activity started in the late Cenozoic (about Oligocene time) and continues to the present. No part of the rift can be considered inactive. Most of the exposed volcanic rocks related to the West Antarctic rift (Fig. 1) were extruded in the late Cenozoic (LeMasurier, 1990), not at the time of separation of New Zealand and the Campbell Plateau, which was ~85 Ma (Bradshaw, 1989). Behrendt et al. (1992) suggested that this was a consequence of rift capture by a mantle plume head roughly coincident in area with the West Antarctic rift (Fig. 1) on the basis of topography, geophysical data, and ocean-island-basalt chemistry of the exposed alkalic volcanic rocks (Behrendt et al., 1991; Hole and LeMasurier, 1994). If the mantle plume hypothesis is correct, we would expect evidence since ~30 Ma of extensive rift-related volcanism (flood basalts?) beneath the West Antarctic ice sheet and the Ross Ice Shelf, as well as that partially exposed in coastal Marie Byrd Land and on part of the rift shoulder (Fig. 1).

RESULTS OF PREVIOUS AEROMAGNETIC SURVEYS

More than 100 000 km of widely spaced aeromagnetic profiles (Behrendt, 1964; Jankowski et al., 1983; Behrendt et al., 1991) (mostly ~1 km above the ice) show many 100–>1000 nT anomalies with estimated depths within 1 km of the base of the 2–4-km-thick West Antarctic ice sheet, interpreted as evidence of widespread presence of late Cenozoic volcanic rocks. These volcanic rocks probably continue to the area of the ice streams flowing into the Ross Ice Shelf (Bindschadler and Scambos, 1991), where shallow-source anomalies as high as 700 nT have been reported (Behrendt, 1964). An aeromagnetic survey over the western Ross Sea continental shelf

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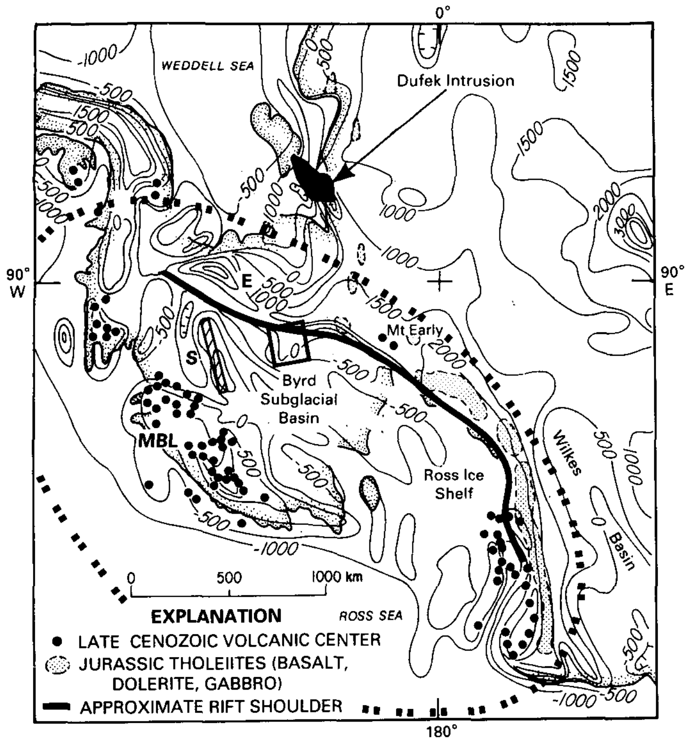

Figure 1. Generalized, isostatically compensated (after ice removal) bedrock-elevation map of part of Antarctica (from Behrendt et al., 1992; modified from Drewry, 1983). Stipple indicates edge of present grounded ice. Thick line represents Cenozoic shoulder of interpreted West Antarctic rift system. Dashed line, which surrounds rift system, indicates suggested area of mantle-plume head. 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). Box indicates area of the 1991–1992 CASERTZ (Corridor Aerogeophysics of the Southeast Ross Transect Zone) survey, shown in Figure 2. Area below sea level is probably underlain by extended crust ~20 km thick, according to interpretation of (1) Ross Sea seismic data (Behrendt et al., 1991) and (2) 150 mgal (relative) positive Bouguer anomaly that is mostly due to contrast between thin extended crust and rift shoulder but also partly due to underplating(?) and flood basalts(?) (Behrendt et al., 1991, 1992). E—Ellsworth Mountains; S—1200 nT Sinuous Ridge magnetic anomaly. The 0° meridian (grid north) is at top of map following usual convention for small-scale maps of Antarctica. Contour interval = 500 m.

showed linear anomaly patterns indicative of rift fabric and discrete circular anomalies along north-northwest–trending zones suggestive of numerous submarine volcanoes (Behrendt et al., 1991). Marine seismic reflection and magnetic profiles crossing eight anomalies support the volcanic interpretation and demonstrate a Holocene age for one feature (Behrendt et al., 1991).

RESULTS OF THE 1991–1992 AEROMAGNETIC SURVEY

There are about 30–40 semicircular, steep-gradient anomalies 5–40 km in diameter (Fig. 2[1]), typical of extended volcanic terrane. The amplitudes range from ~100 to ~1100 nT, very high considering that the aircraft was ~3 km above the shallowest possible sources at the base of the ice. These anomalies are similar in size, shape, and distribution to anomalies interpreted to be caused by submarine volcanoes in the Ross Sea survey (Behrendt et al., 1991). Blankenship et al. (1993) showed an example of these magnetic data observed over an active volcano beneath the ice sheet, interpreted from radar ice sounding and laser snow-surface altimetry. We interpret the north-trending linear "grain" of the map (Fig. 2) to be rift fabric similar to that in the Ross Sea (Behrendt et al., 1991). However, this trend appears to be rotated ~20°–30° counterclockwise from that of the approximate rift shoulder (Fig. 1). Possibly this is due to transtension in a strike-slip system, as suggested by Kellogg and Rowley (1989) and Storey (1991). Also similar to the Ross Sea data are 100–300 nT composite anomalies 50–>70 km wide (e.g., the two at the northeast and southwest corners of Fig. 2) that are suggestive of volcanic centers and associated subvolcanic intrusions. Magnetic sources could be of any age, but we would not expect to observe (Behrendt et al., 1991) significant anomalies from the thin Jurassic Ferrar dolerite sills (Fig. 1) possibly present beneath the ice. However, if there were Jurassic intrusions several kilometres thick—such as the Dufek intrusion or the Butcher Ridge igneous complex (Behrendt et al., 1994), magnetic granitoids (e.g., Maslanyj et al., 1991), or the Kirkpatrick basalts (Behrendt et al., 1991)—these also could produce high-amplitude magnetic anomalies.

Most of the anomalies are positive and generally have associated low-amplitude negative lobes on their west-southwest sides, as expected for anomalies caused by induced magnetization or dominant normal remanent, high-Q (Königsberger ratio) magnetization in the present Earth field direction (Fig. 2). The "active" magnetic field (Fig. 2) contrasts to the "flat" field over the thick, nonmagnetic Paleozoic section adjacent to the Ellsworth Mountains (Behrendt, 1964; Behrendt et al., 1991; Maslanyj et al., 1991). Linear negative anomalies (blue and G in Fig. 2) suggest grabens, which are likely throughout the ice-covered area of the West Antarctic rift (e.g., Jankowski et al., 1983; LeMasurier, 1990; Cooper et al., 1991).

MAGNETIC MODELS

Primarily from radar ice-sounding and laser-altimeter data, Blankenship et al. (1993) interpreted the presence of a subglacial active volcano, on the basis of a 6-km-wide, roughly conical peak 650 m above the surrounding bedrock and an overlying circular 48 m snow-surface depression. Figure 3 (model D) shows this feature and an adjacent associated 40-km-wide (Fig. 2) 500 nT positive magnetic anomaly. Model D shows that the small active volcano has a low apparent susceptibility compared to the source of the 500 nT anomaly. An alternate model (E, Fig. 3) seems geologically less reasonable because of the high susceptibility at its base, but it is within the range measured in the Dufek intrusion (Beck and Griffin, 1971).

We interpret model D as showing the highly magnetic root of an active volcanic center. The low or nonmagnetic (Fig. 3) character of the small peak is possibly the result of (1) temperature above the Curie isotherm over the active (Blankenship et al., 1993) volcanic peak, (2) destruction of effective remanent magnetization by shattering and mixing of the subglacial flows at the time of extrusion, or (3) hydrothermal alteration. From comparison with seismic reflection profiles over interpreted submarine volcanoes on the Ross Sea continental shelf (Behrendt et al., 1991), we can infer that the moving ice continuously erodes the small volcanic peaks (probably quite easily eroded hyaloclastite and pillow breccia; S. Borg, 1993, personal commun.; W. E. LeMasurier, 1993, personal commun.) that are episodically erupted beneath it.

Model A (Fig. 4), fit to a high-amplitude anomaly (location in Fig. 2), is suggestive of a possible eroded volcanic center (note the vertical exaggeration). The apparent susceptibility required seems unreasonably high for volcanic rocks (e.g., Hildenbrand et al., 1993) and higher than the means of susceptibilities measured for late Cenozoic volcanic rocks in the McMurdo area (Pederson et al., 1981); this implies a high remanent magnetization in the present field di-

[1]Loose insert: Figure 2 is on a separate sheet accompanying this issue.

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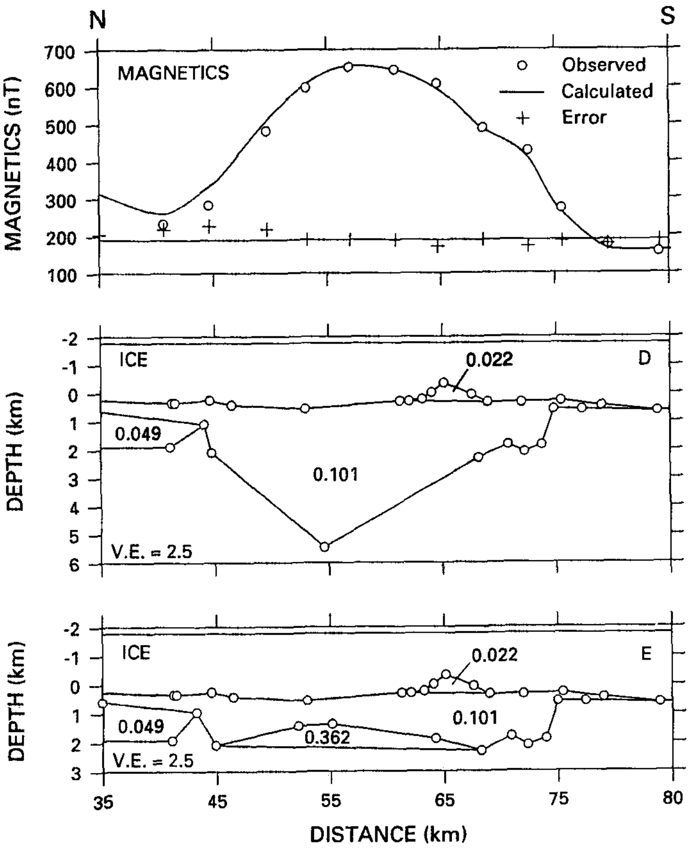

Figure 3. Magnetic models across anomaly D caused by interpreted 40-km-wide subglacial volcano, associated with 6-km-wide active subglacial volcanic peak (Blankenship et al., 1993). Location is indicated in Figure 2. Flight elevation is 1 km above ice surface. Apparent susceptibilities are indicated in volume SI units. Bedrock is indicated from coincident radar ice-sounding measurements. Ice is moving approximately toward viewer. Small volcanic edifice has low or zero effective susceptibility contrast and no observable magnetic anomaly. Model D indicates a thickened volcanic pile; model E indicates a very highly magnetic intrusion at base of volcano. Calculated points for E are essentially the same as those shown for D. In 2½ D ("dimensional") calculation, length of small upper body along strike used was +3 and −3 km; for lower bodies, length along strike was +15 and −5 km.

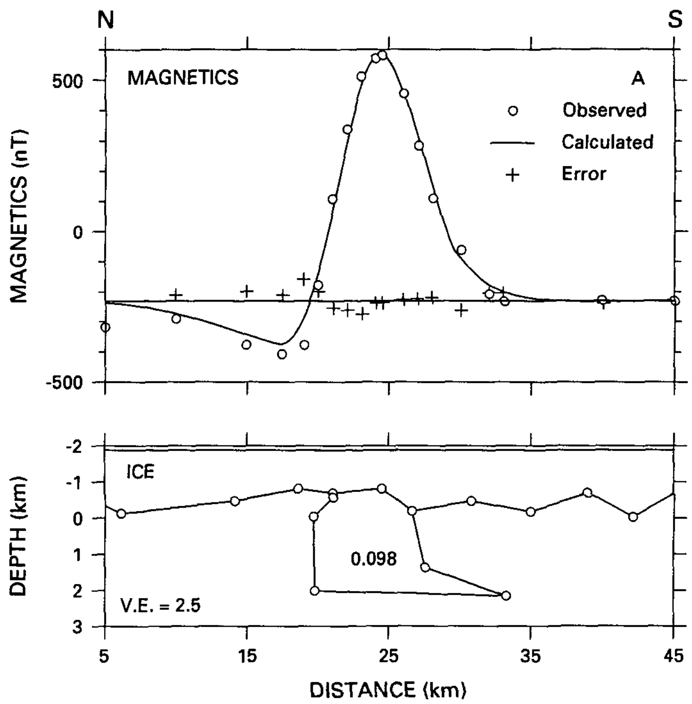

Figure 4. Magnetic model A fit to observed profile as in Figure 3; location is indicated in Figure 2. Bedrock is indicated from coincident radar ice-sounding measurements. Model A fits highest amplitude anomaly (A) in Figure 2, possibly a subglacial volcano. In 2½ D ("dimensional") calculation, length of body along strike used was +5 and −5 km. Note that adjacent bedrock relief appears to be nonmagnetic.

rection, as measured for late Cenozoic volcanic rocks in the McMurdo area (Mankinen and Cox, 1988). These models, and others not shown, indicate sources of the magnetic anomalies essentially at the base of the ice, as is the case for the sources of most of the high-amplitude, short-wavelength, steep-gradient anomalies of Figure 2.

DISCUSSION

We interpret most of the shallow-source, high-amplitude anomalies (Fig. 2) to be caused by late Cenozoic volcanic rocks (subvolcanic plutons or thick flows) associated with rifting, on the basis of their association with magnetic rift fabric (Fig. 2). The nearest exposed volcanic centers (Fig. 1), 400 km from the CASERTZ survey along the rift shoulder (e.g., Mt. Early, 16–19 Ma; Stump et al., 1990), contain hyaloclastite, pillow breccias, and basalts. We infer that the Mt. Early exposures (no magnetic properties were measured) are examples of the subglacial volcanic rocks interpreted as underlying the CASERTZ survey area. Behrendt (1964) and Jankowski et al. (1983) reported that a number of profiles that cross the exposed Marie Byrd Land volcanic rocks have high-amplitude magnetic anomalies, which led to their interpretations that the shallow-source anomalies over the West Antarctic ice sheet are caused by buried volcanic rocks. For example, coincident radar and aeromagnetic data (Jankowski et al., 1983) allowed modeling of the 400-km-long Sinuous Ridge anomaly—which bisects the Byrd Subglacial Basin (S in Fig. 1)—as having a volcanic source. LeMasurier (1990) reported hyaloclastites from exposures throughout the West Antarctic rift system and interpreted these as evidence for subglacial eruptions. Obviously, the interpreted active volcano (Fig. 3) is evidence of present activity there, and operation of a portable seismograph (or several) near its location might provide valuable confirmation.

An active plume head beneath the West Antarctic rift, active since ~30 Ma, would episodically extrude magma throughout its area (Fig. 1). A range of ages of activity within a specific volcanic province beneath the ice would be reasonable and has been reported (LeMasurier, 1990) from the exposed late Cenozoic volcanic centers (Fig. 1), but we would expect the main period of activity for flood basalts to last for only a few million years. Behrendt et al. (1992) inferred that as spreading centers surrounding the stationary Antarctic plate migrated away from Antarctica, rifting in West Antarctica continuing to the present was focused by a mantle plume to the hot, thin, extended, weakened lithosphere in the Ross Embayment–Byrd Subglacial Basin area at the end of the Cretaceous. The high rift shoulder (Fig. 1) developed because of the contrast with the cold, old, much thicker lithosphere at this boundary, which has a much higher flexural rigidity (Stern and ten Brink, 1989). The northern edge of the suggested plume head is not marked by a rift shoulder, probably because it is bounded by relatively young oceanic lithosphere (Fig. 1).

Magnetic data over flood basalts elsewhere (e.g., the Columbia River basalts, A. McCafferty, unpublished) show anomaly patterns and amplitudes similar to those in Figure 2. Our measurement of the

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area of Figure 2 shows that 43% of it consists of high-amplitude magnetic "volcanic" anomalies. From the map of Behrendt et al. (1991), based on >100 000 km of widely spaced aeromagnetic profiles over the West Antarctic rift system, at least 1.2×10^6 km^2 of the rift area beneath the West Antarctic ice sheet and Ross Ice Shelf contains high-amplitude short-wavelength magnetic anomalies (averaged over $1° \times 1°$ square areas) suggested to be caused by late Cenozoic volcanic rocks. If the 43% value from the CASERTZ survey is typical, the minimum estimated area of volcanic rocks is 0.5×10^6 km^2. If these inferred flood basalts (or their subglacial equivalents) are at least 2 km thick (e.g., Figs. 3 and 4), their volume is at least 10^6 km^3. Both values are comparable to other great areas of flood basalts interpreted as evidence of plume heads (White and McKenzie, 1989). Westaway (1993) analyzed forces associated with plumes and noted crustal extension of only ~2 mm/yr for Yellowstone, less than ~1 mm/yr for Baikal, and ~0.7 mm/yr for East Africa and a volume flux of ~50 m^3/s for the three areas. For ~5% magma generation (Westaway, 1993), this flux results in $\sim 0.8 \times 10^6$ km^3/m.y. We estimate that the West Antarctic rift lies within the range of these plumes, partly on the basis of its low magnitude of late Cenozoic extension; the expected magma generated in a few million years is on the same order as that estimated from the magnetic data. We interpret the CASERTZ aeromagnetic results, combined with the widely spaced profiles, to indicate a substantial volume of volcanic rock beneath the West Antarctic ice sheet and the Ross Ice Shelf and to support the plume hypothesis proposed for the late Cenozoic rifting in the West Antarctic rift.

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