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Review Article

The aeromagnetic method as a tool to identify Cenozoic magmatism in the West Antarctic Rift System beneath the West Antarctic Ice Sheet — A review; Thiel subglacial volcano as possible source of the ash layer in the WAISCORE

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A B S T R A C T

The West Antarctic Ice Sheet (WAIS) flows through the volcanically active West Antarctic Rift System (WARS). The aeromagnetic method has been the most useful geophysical tool for identification of subglacial volcanic rocks, since 1959–64 surveys, particularly combined with 1978 radar ice-sounding. The unique 1991–97 Central West Antarctica (CWA) aerogeophysical survey covering 354,000 km^2 over the WAIS, (5-km line-spaced, orthogonal lines of aeromagnetic, radar ice-sounding, and aerogravity measurements), still provides invaluable information on subglacial volcanic rocks, particularly combined with the older aeromagnetic profiles. These data indicate numerous 100–>1000 nT, 5–50-km width, shallow-source, magnetic anomalies over an area greater than 1.2×10^6 km^2, mostly from subglacial volcanic sources. I interpreted the CWA anomalies as defining about 1000 "volcanic centers" requiring high remanent normal magnetizations in the present field direction. About 400 anomaly sources correlate with bed topography. At least 80% of these sources have less than 200 m relief at the WAIS bed. They appear modified by moving ice, requiring a younger age than the WAIS (about 25 Ma).

Exposed volcanoes in the WARS are <34 Ma, but at least four are active. If a few buried volcanic centers are active, subglacial volcanism may well affect the WAIS regime. Aerogeophysical data (Blankenship et al., 1993, Mt. Casertz; Corr and Vaughan, 2008, near Hudson Mts.) indicated active subglacial volcanism. Magnetic data indicate a caldera and a surrounding "low" in the WAISCORE vicinity possibly the result of a shallow Curie isotherm. High heat flow reported from temperature logging in the WAISCORE (Conway et al., 2011; Clow, personal commun.) and a volcanic ash layer (Dunbar, 2012) are consistent with this interpretation. A subaerially erupted subglacial volcano, (Mt Thiel), about 100 km distant, may be the ash source.

The present rapid changes resulting from global warming, could be accelerated by subglacial volcanism.

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1. Introduction

The aeromagnetic method has proven the most useful geophysical tool for studying subglacial volcanic rocks associated with the West Antarctic Rift System (WARS) beneath the WAIS from early surveys in the 1950s and 1960s (Behrendt, 1964, 2005, Behrendt and Wold, 1963), to the unique Central West Antarctica (CWA) survey (Figs. 1–3) comprising a 5-km orthogonal flight line set of aeromagnetic, aerogravity, and radar ice sounding collected in the 1990s. This tight grid of flight lines obviated aliasing of the magnetic data, because it is approximately equivalent to the flight elevation above the ice surface plus the ice thickness. In this paper, I illustrate the utility of this method

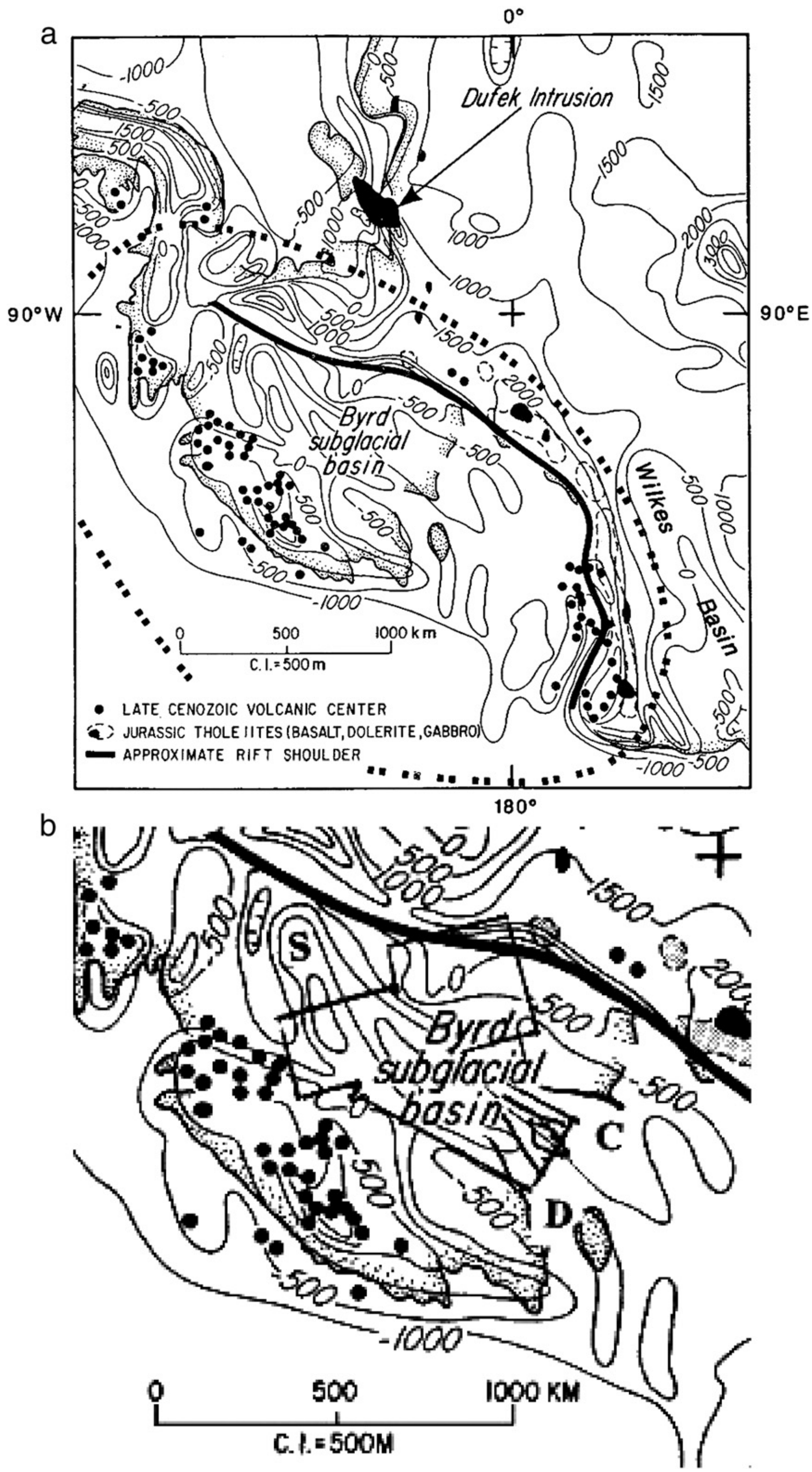


Fig. 1. Generalized isostatically compensated (after ice removal) bedrock elevation map of part of Antarctica (from Behrendt et al., 1992; 2004, modified from Drewry, 1983). Interpreted mantle plume boundary indicated by dashed oval, which includes late Cenozoic alkaline volcanic exposures characterized by ocean island basalts chemistry. Stippled pattern shows edge of present grounded ice. Cross marks South Pole. S indicates the high topography of the Sinuous Ridge (Jankowski et al., 1983), beneath the divide of the WAIS. Ice Streams C and D are indicated. b. Irregular box centered over subsea level area indicates the CWA survey (Figs. 2 and 3) from Behrendt et al. (2004).

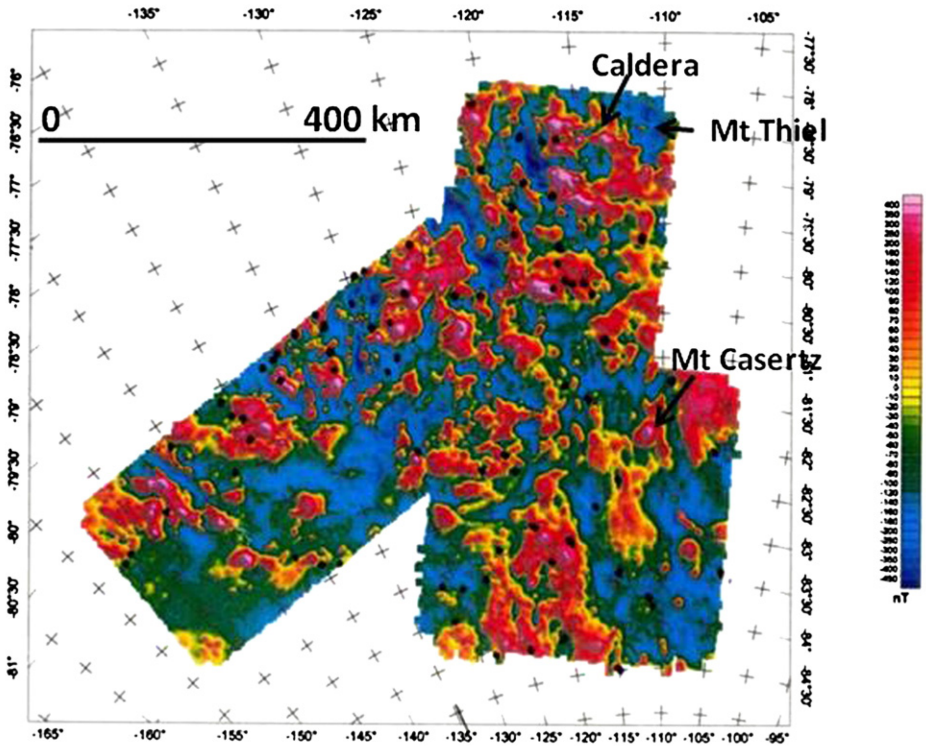


Fig. 2. CWA aeromagnetic anomaly map, 10-nT contour interval (CI) The steep-gradient, high-amplitude magnetic anomaly field is indicative of the shallow source volcanic centers interpreted to underlie most of this area of the WAIS. Black dots indicate locations of negative magnetic anomalies. Modified from Behrendt et al., 2007.

by discussing several important tectonic results obtained over these decades.

Short-wavelength, shallow-source, high-amplitude (100–>1000 nT) magnetic anomalies observed (ranging from 5 to 20 km width at half amplitude) about 1 km above the 2–3-km thick moving ice, were early recognized as requiring extremely high magnetizations, probably associated with subglacial volcanic rocks, as these were observed exposed at sparse nunataks (Fig. 1) throughout the area of the Ross Sea and WAIS now recognized as the WARS (Behrendt, 1964; Behrendt and Wold, 1963). These volcanic outcrops had associated very high-amplitude magnetic anomalies of comparable width, where crossed by the early profiles. When combined with widely separated (50–100 km) coincident radar ice sounding profiles in 1979 by Scott Polar Research Institute (SPRI)-USGS (Drewry, 1983; Jankowski et al., 1983) comparison of shallow magnetic sources with glacial bed topography observed along flight lines became possible.

2. Overview of Central West Antarctica (CWA) aerogeophysical survey area

From 1990 to 1997, a team of researchers from USGS; Institute for Geophysics, University of Texas; Lamont Doherty Earth Observatory, Columbia University; and US Naval Research Laboratory made the 5-km orthogonally line-spaced Central West Antarctica (CWA) aerogeophysical survey (Blankenship et al., 1993; Behrendt et al., 1994, 1996, 2004, 2006; Bell et al., 1998; and other papers). See Behrendt et al. (2004) for additional references. This survey, (Corridor Aerogeophysics of the South East Ross Transect Zone, CASERTZ, and Support Office for Aerogeophysical Research, SOAR, Figs. 1–4) allowed direct comparison of three-dimensional bed topography from radar ice-sounding with aeromagnetic anomalies from the tops of the shallow subglacial volcanic sources at the bed of the WAIS. The magnetic and radar ice-sounding data, sampled essentially continuously, have enabled detailed modeling (e.g. Figs. 5–7, 9, 12, and 13) of specific high-amplitude, steep gradient anomalies having tops of their sources directly at the bed of the ice (e.g. Behrendt et al, 1994, 1996, 2004). Coincident aerogravity observations required smoothing over several minutes of flight time. Therefore, only longer wavelength aeromagnetic and gravity anomalies could be directly compared, such as those originating from subglacial sedimentary basins (e.g. Bell et al., 1998).

In addition to the CWA aeromagnetic and radar ice sounding survey flight line 5-km grid, other 4- and 5-km line spaced magnetic (but no radar bed elevation or bathymetric depths) profile data sets exist in Antarctica with widely spaced tie lines; (e.g. Behrendt et al, 1991; Bosum et al., 1991) over northern Victoria Land and the western Ross Sea continental shelf. Other roughly comparable combined radar ice-sounding, aeromagnetic and aerogravity surveys in Antarctica are published by Ferraccioli et al. (2002); and Luyendyk et al. (2003) over Edward VI Peninsula and the Ford Ranges area of coastal Marie Byrd Land. Bell et al. (2011), and Ferraccioli et al. (2011) reported on similar surveys over the Gamburtsev Mountains in East Antarctica.

3. Subglacial volcanic rocks

Analysis of the CWA block of coincident aeromagnetic and radar ice sounding data (Blankenship et al., 1993; Behrendt et al., 1996; 2002, 2004; 2006; and papers referenced therein) reveal ~1000 50–>1000-nT short-wavelength magnetic anomalies. These anomalies are interpreted as caused primarily by subglacial, subvolcanic intrusions, (Behrendt et al., 2004), associated with the Oligocene to Recent (LeMasurier, 2006), bimodal, alkaline volcanism of the West Antarctic rift system (Fig. 1). The flight elevation was about 1 km above the ice surface and the ice is 2–3 km thick, so these magnetic amplitudes are unusually high. The steep gradients of these anomalies require their sources to be essentially at the glacier bed (Behrendt et al., 2004) as demonstrated by a number of models (e.g. Figs. 5–7) shown in these cited papers. About 400 of these anomalies (conservatively selected) have topographic expression as revealed by comparison to

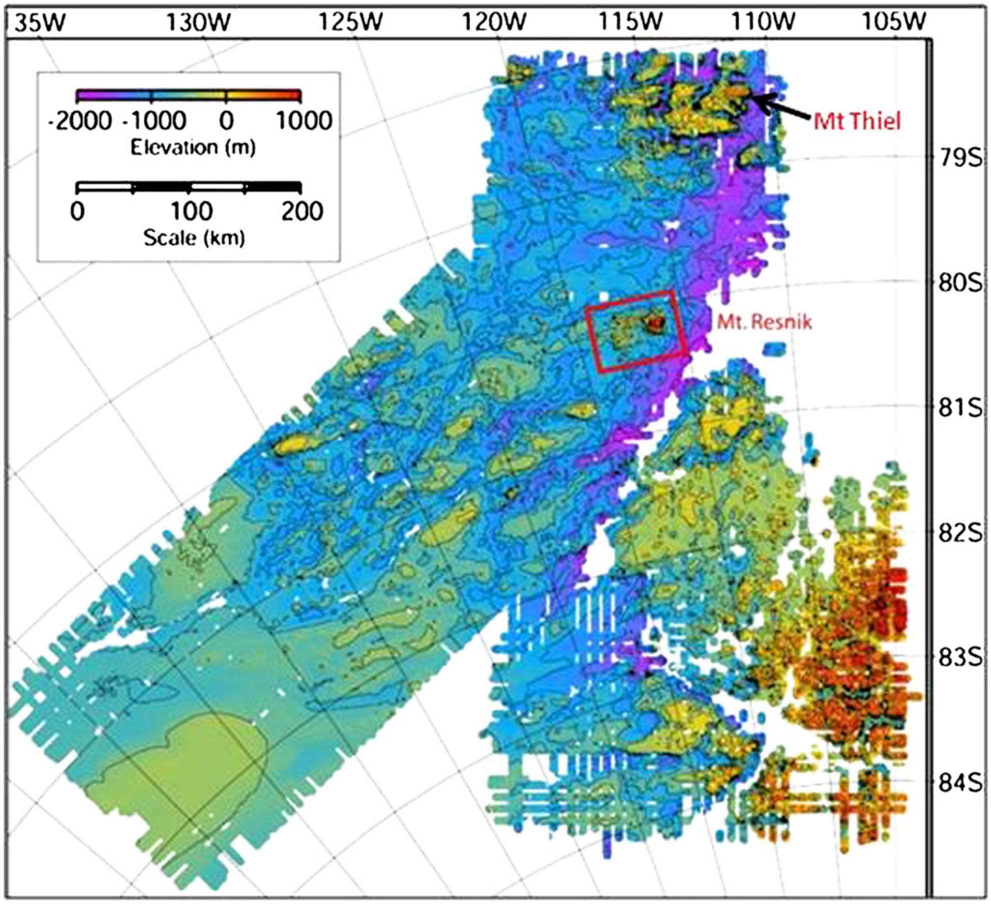


Fig. 3. Bed topography of same area and scale as Fig. 2. Depth contours indicated by color bar. Large scale maps (e.g. Figs. 5–7), illustrate the detail available at the 20-m contour interval. Modified from Behrendt et al. (2005); Morse et al. (2001).

the 20-m contour-interval glacier bed elevation map (Fig. 3) at a large scale (e.g. Figs. 5–7).

I interpret these anomalies as indicative of the relative abundance of subglacial volcanic rocks. The great bulk (Fig. 8) of these ~400 (40–1200-nT) anomaly sources at the base of the ice have low bed relief (60–600 m, with about 80% <200 m). Behrendt et al. (1995, 2002, 2004) interpreted this relief as an indication of residual topography after glacial removal of volcanic edifices comprising hyaloclastite, pillow breccia, and other volcanic debris erupted into the moving ice during volcanism since the initiation of the WAIS ~25 m.y. ago. This low relief, even if extremely magnetic, could not produce the observed overlying anomalies at the 3–4 km observation elevation above them; the sources must have thicknesses of the order of several kilometers. The active subglacial volcano (Behrendt et al., 1994, 1995; Blankenship et al., 1993) Mt. Casertz (Figs. 2 and 9) is an interpreted example of this process taking place at the present, similar to the case in Iceland (Behrendt et al., 2002; Bourgeois et al., 2000; Gudmundsson, et al., 1997). No repeat survey of Mt. Casertz is available; one might expect observable change in the ice surface and bed topography since the original survey in 1991–92 field-season (Blankenship et al., 1993) two decades ago.

Of course, deeper source magnetic anomalies are present, but these have longer wavelengths, lower gradients, and mostly lower amplitudes from those caused by the highly magnetic late Cenozoic volcanic centers. An important example of a significant lower amplitude is the magnetic "low" surrounding the interpreted caldera(?) complex of magnetic anomalies (Fig. 4). Behrendt et al. (1998) interpreted this "low" as evidence of a shallow Curie isotherm as discussed further below.

Magnetic models fit (e.g. Figs. 5–7) to anomalies over the "volcanic centers" require 1–2-km thick bodies having apparent susceptibilities as great as 0.3 SI (e.g. Behrendt et al., 2004), imply a very high remanent component in the present field direction. Several hundred meter-thick volcanic flows or sills could not produce these anomalies (see examples and discussion in Behrendt et al., 1991). These very high apparent susceptibilities and remanent magnetizations fall in the ranges measured for volcanic rocks in the McMurdo area (Behrendt et al., 1996). Because the Antarctic plate has been essentially stationary since 100 Ma, the sources could be that old and still have present field direction. However, Jurassic age intrusive and extrusive tholeiitic rocks associated with initial rifting of Gondwanaland (e.g. the Dufek intrusion and other Jurassic exposures along the rift shoulder, Fig. 1) would be unlikely as sources because they would be expected to cause anomalies incompatible with the present field direction, for the high Q (ratio of remanent to induced magnetization) rocks beneath the WAIS apparently required. For this reason, Paleozoic or older intrusions would also be very unlikely as sources even were they to have the subtle topographic expression observed at the glacier bed.

4. Subaerially erupted volcanoes

Eighteen of the anomalies examined (Fig. 8a), about half concentrated in the area of the WAIS divide (Fig. 8b), have high topographic expression as great as 400 m above sea level and high relief, 1800 m, (e.g. Mt. Thiel; Behrendt, 2012) in the divide area (Figs. 4 and 7), and 1500 m above sea level and 1600 m relief (Mt Resnick, Figs. 3 and 10). All of these high-topography anomaly-sources at the base of the ice would isostatically rebound to elevations above sea level

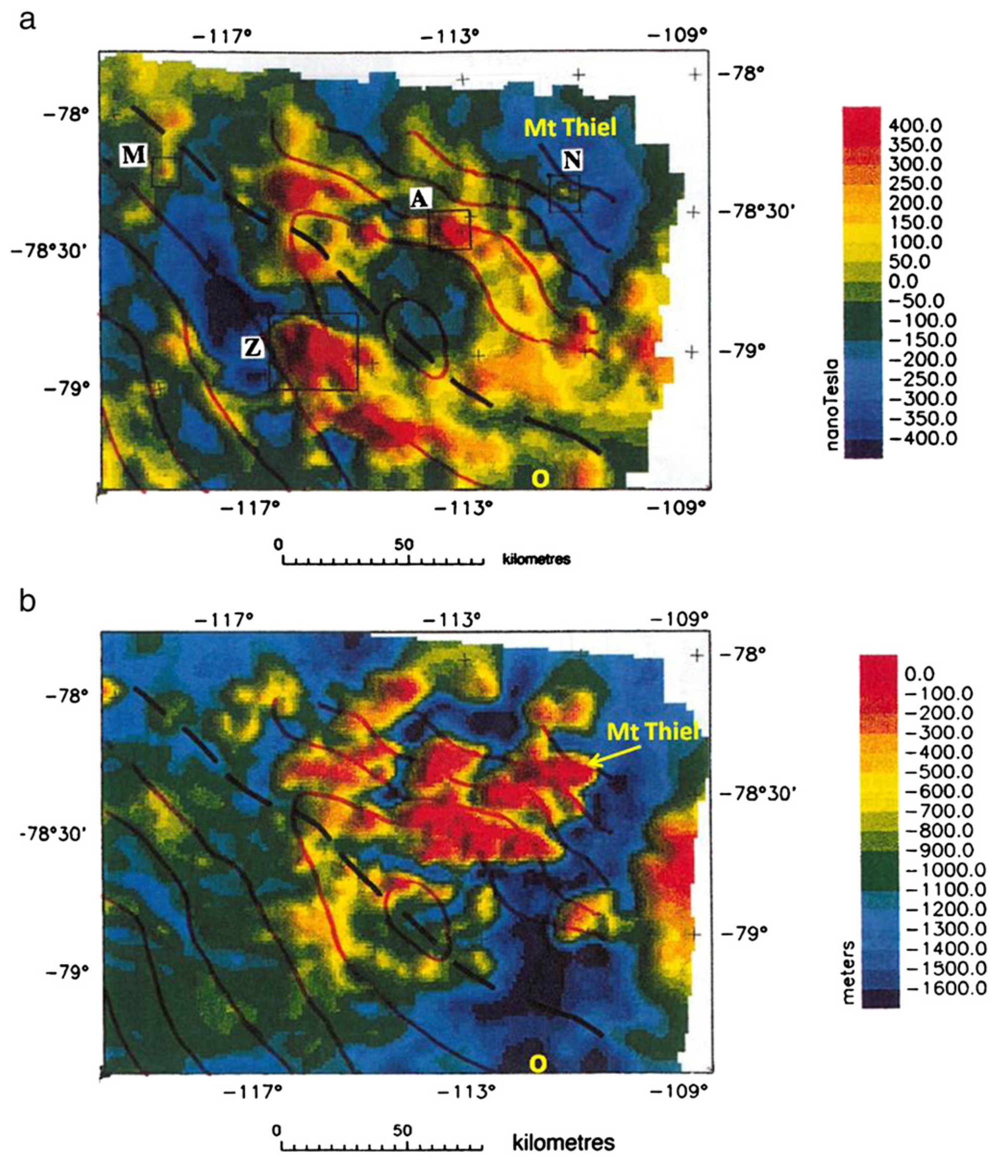


Fig. 4. (a) Shaded relief aeromagnetic anomaly map and bed maps of WAIS divide area of Fig. 2 modified from Behrendt et al., 2002. Circular group of anomalies define the interpreted caldera. Anomalies N, M, and N (Mt. Thiel) are modeled as shown in Figs. 5–7 respectively. Anomaly A is modeled as shown in Behrendt et al., 2002. Location of WAISCORE is indicated by "o". WAIS divide (dashed black line) and 50-m snow surface contours are indicated; the dome elevation is 1800 m. Anomaly N overlies the subaerially erupted volcano Mt Thiel. b. Shaded bed relief of WAIS divide area (Fig. 3), modified from Behrendt et al., 2002. Note smoothed caldera rim. Detailed bed topography of Mt. Thiel (bed elevation ~440 m; bed relief ~1800 m) is shown in Fig. 7. Other features as in (a).

were the ice removed. I interpret these 18 anomaly-sources as evidence of subaerial eruption of volcanoes whose topography was protected from erosion by competent volcanic flows similar to prominent volcanic peaks that are exposed above the surface of the WAIS (Fig. 1). Further, these volcanoes were likely erupted at a time when the WAIS was absent.

5. Mt Thiel

As mentioned above, magnetic data indicate a caldera (Fig. 4) and a surrounding broad "low", (Behrendt et al., 1998) suggested as caused by a shallow Curie isotherm in the area of the WAIS divide and the WAISCORE (Fig 4). High heat flow inferred from temperature logging in the WAISCORE (Clow, personnel commun.; Conway et al., 2011) and a prominent volcanic ash layer in the core (Dunbar et al., 2011; and personal communication, 2012) are consistent with the magnetic data. I suggest that the prominent subaerially erupted subglacial, volcano, Mt Thiel (Fig. 7), about 100 km distant, may be the source of the ash layer. From its appearance (and the moat surrounding it) Mt. Thiel has subsided somewhat since eruption as is the case for Mt. Erebus and the Hawaiian Island chain.

6. Mt. Resnik

Mt. Resnik is a ~1.6-km local-relief peak (Figs. 3 and 9) centered at 80^o 9′ S, 116^o 20′ W only 300-m below the WAIS surface (Behrendt et al., 2006; Morse et al., 2001) and has an associated complex 350-nT magnetic anomaly (Figs. 10 and 11). The high bed topography (about 1.5 km above sea level, high bed relief conical form, and associated magnetic anomaly indicate to us that this peak is a subaerially erupted volcano similar to the other 17 inferred subaerially erupted volcanoes (Fig 8) in the CWA survey (Behrendt et al., 2004). Several models calculated to fit the anomaly (one is shown in Fig. 12) led to our interpretation that Mt. Resnik was erupted during a period of magnetic reversal. The reversed magnetism, required to fit the anomaly indicates that this peak was partially erupted prior the Brunhes-Matuyama reversal

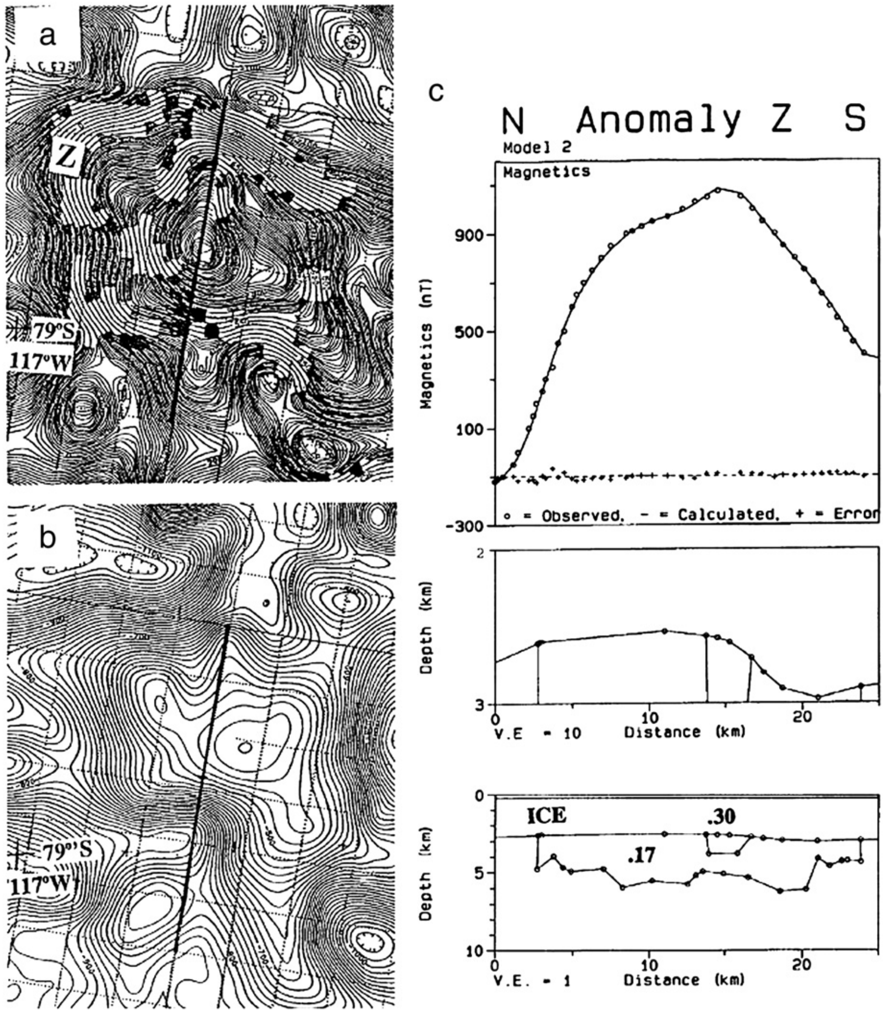


Fig. 5. (a) Detailed aeromagnetic map of area of anomaly Z; from Behrendt et al. (2002). Contour interval 10 nT. Grid survey lines are spaced at 5 km, and the long edges of the map trend true north. Location of modeled profile is indicated. (b) Bedrock elevation in area of anomaly Z. Contour interval (CI) 20 m. Grid lines are the same as in (a). Location of modeled profile is shown. (c) Theoretical 2 1/2 D (two-and-one-half-dimensional, a special case of three-dimensional model in common usage) model fit to aeromagnetic profile for anomaly Z. Apparent susceptibilities indicated in SI. Central body has strike length of 3 km to east and 3 km to west; outside body has strike length of 10 km to east and 10 km to west. VE = vertical exaggeration. Irregular base of model results from forcing (by inversion) the top of the model to conform to glacier bed from radar ice-sounding, because the bed relief is known to a few meters precision. The magnetization is no doubt variable and could be forced to fit the model as well, to make the base of the model smooth. The bed relief and model thickness is indicated at 0 and 10 times vertical exaggeration.

at 780 ka but it could be very much older. Behrendt et al. (1996) reported an anomaly and calculated models similar to that over Mt. Resnik over Hut Point at Ross Island, Antarctica (also part of the West Antarctic rift system), which required both normal and reversed magnetizations. At Hut Point, rocks having both normal and reversed magnetizations are exposed and were recovered in drill holes (Kyle, 1990a,b with ages > the Brunhes-Matuyama boundary (780 ka).

Mt. Resnik and the 17 other high-altitude, high-relief subaerially erupted volcanoes (Behrendt et al., 2004) observed in the CWA survey beneath the WAIS (half in the area of the WAIS divide as mentioned above) were interpreted as having been erupted during a period when the WAIS was absent. The WAIS and the late Cenozoic volcanic activity in the West Antarctic rift system have been coeval since at least Miocene time, although the area has been deglaciated at times during this period as recently as 125 Ka (e.g. Pollard and De Conto, 2009, Scherer, 1991, Scherer, et al. 1998). Therefore it is not unexpected to find evidence of subaerial volcanic eruption of Mt. Resnik prior to 780 Ka when the WAIS may also have been absent. Because of its association with a glacially smoothed source of the anomaly to the west (Profiles C–D, in Figs. 10, 11 and 13 from Behrendt et al., 2006). I believe it likely that Mt. Resnik erupted since the origin of the WAIS (> 25 Ma) no matter what its age within this range.

7. Negative anomalies

I examined each of the ~400 nT shallow-source, steep-gradient, anomalies in the CWA survey over the WAIS (Fig. 1) interpreted as caused by volcanic centers having topographic expression at the bed (Fig. 8). About 100 of these anomalies (Fig. 2), have strong negative components similar to Mt Resnik (Figs. 3, 11, and 12); the sources of all but one other (not discussed here) have <400 m of bed relief indicating they were erupted into the WAIS and their edifices comprising of hyaloclastite and other volcanic debris were removed by the moving ice (Behrendt et al., 1995). In general, the negative magnetic anomalies are uniformly distributed throughout the aeromagnetic survey area. I do not infer post-Brunhes-Matuyama volcanism for the approximately 75% of anomalies showing normal magnetization, because magnetic anomalies occur over volcanic exposures in the WAIS area older than 10 Ma (Behrendt et al., 1996). Licht, et al. (2011) reported a cobble of vesicular basalt upstream from the southernmost volcanic exposure in Fig. 1, and interpreted a volcanic source at 150°W, 87.89°S associated with a −745 nT magnetic anomaly at that location.

The question remains as to why the remainder of the anomalies, correlated with bed topography, are not approximately 50% negative.

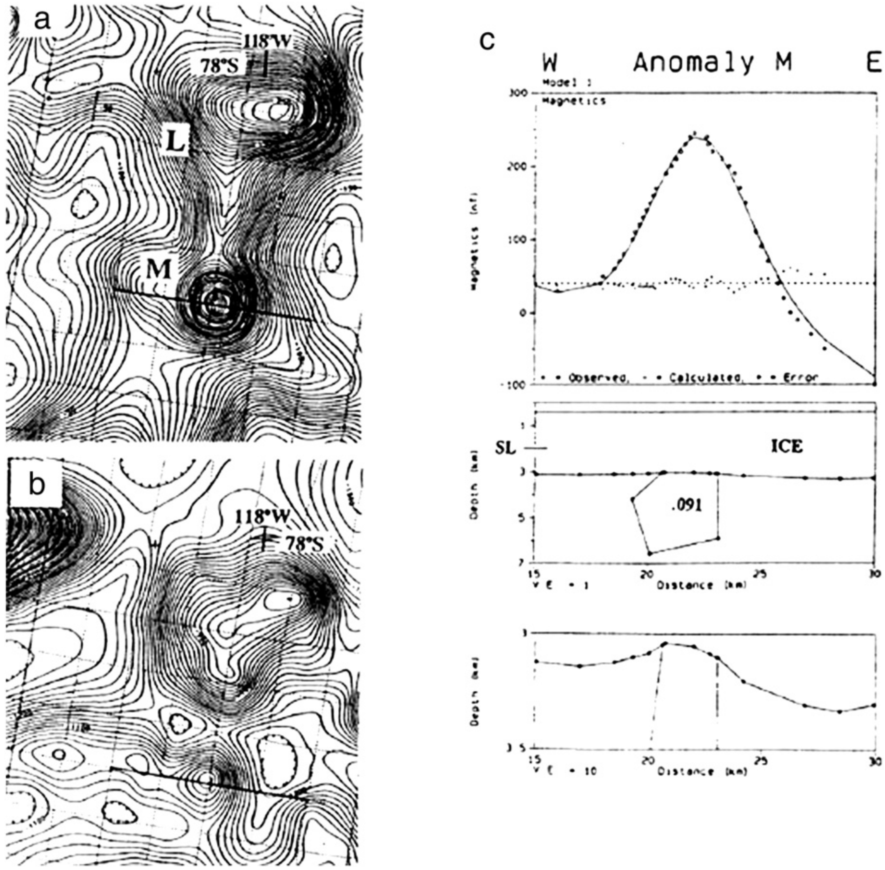


Fig. 6. Aeromagnetic (a) and bedrock elevation (b) maps of area of anomaly M; from Behrendt et al., 2002. (c) Theoretical 2 1/2 D model fit to aeromagnetic profile for anomaly M. Susceptibilities indicated in SI. Body has strike length of 2.5 km to north and south respectively. Other parameters as in Fig. 5.

I see two possible explanations: (1) Volcanic activity resulting in these ~100 anomalies occurred in a predominantly normal field, which appears unlikely. (2) Most of the ~100 anomalies have sources, whose tops are at the bed of the ice, have essentially a combination of induced and remanent magnetization such that the resultant anomalies are of low amplitude (induced cancels remanent) and are not recognized because they have <100 nT amplitude. This second explanation seems the most probable. Recall that the 400 (of ~1000 anomalies examined in the CWA survey) were very conservatively selected. As noted above, only sources with very high magnetizations, probably dominantly remanent would produce anomalies 100–>1000 nT that are observed ~3–4 km (flight altitude plus ice thickness) above the sources.

8. Volume of volcanic centers

When only about 10% of the CWA aeromagnetic survey was complete, the early, results (Behrendt et al., 1994) indicated about 43% of the area of the magnetic contour map surveyed at that time is covered by the high-amplitude "volcanic" anomalies. Behrendt et al. (1994) calculated an estimated minimum area of volcanic rocks of 0.5×10^6 km ^{2}. This calculation was made by counting the number of short-wavelength, shallow-source, high-amplitude magnetic anomalies observed along >100,000 km of widely-spaced aeromagnetic profiles and acquired in the early 1960s and late 1970s (Behrendt, 1964; Behrendt et al., 1991). Weighted averages of number of anomalies per 100 km of flight lines over $1^o\times1^o$ (of latitude) square areas, showed that at least 1.2×10^6 km^2 of the rift area beneath the WAIS contains the short-wavelength, high-amplitude anomalies. If 43% of this area contained "volcanic" anomalies, the 0.5×10^6 km^2 area resulted. If the minimum thickness of the anomaly sources is 2 km, their volume is at least 10^6 km^3.

Using the entire CWA data set, I recalculated the estimated volume of "volcanic centers" (subvolcanic intrusions) beneath the WAIS. The area of the CWA survey (Figs. 1–3) is $.354\times10^6$ km^2. The total area within the CWA survey covered by short-wavelength, high-amplitude "volcanic" anomalies is 1.57×10^6 km^2, or 44% of the area. Using the same total rift area beneath the WAIS that contains the short-wavelength, high-amplitude anomalies of about 1.2×10^6 km^2 extrapolated as described in the above paragraph, an area of 0.51×10^6 km^2 of anomalies defining "volcanic" centers, and volume of 10^6 km^3 results. This value is the same as obtained by Behrendt et al. (1994), but is more reliable as a minimum volume of late Cenozoic volcanism associated the West Antarctic rift system, because ten times more data from the completed CWA survey were used here. Thus the earlier conclusion of a flood basalt province (Behrendt et al., 1994) or better phrased a large igneous province (e.g. Mahoney & Coffin, 1997) associated with the rift through which the WAIS flows, still appears valid if the magmatic activity occurred during as short a period as 1–10 m.y. (as discussed by Behrendt et al, 1994). Although not used in the above calculation, the magnetic anomalies interpreted as caused by subglacial volcanic rocks in the Edward Peninsula-Ford ranges area (Ferraccioli et al., 2002; Luyendyk et al., 2003) fit into the general conclusion, considering all of the other uncertainties.

Behrendt et al., 1992, and Hole and LeMasurier (1994) interpreted the Cenozoic magmatic activity observed from exposed volcanic rocks, their ocean island basaltic chemistry and the subglacial sources of magnetic anomalies as having a mantle plume origin as indicated in Fig. 1a.

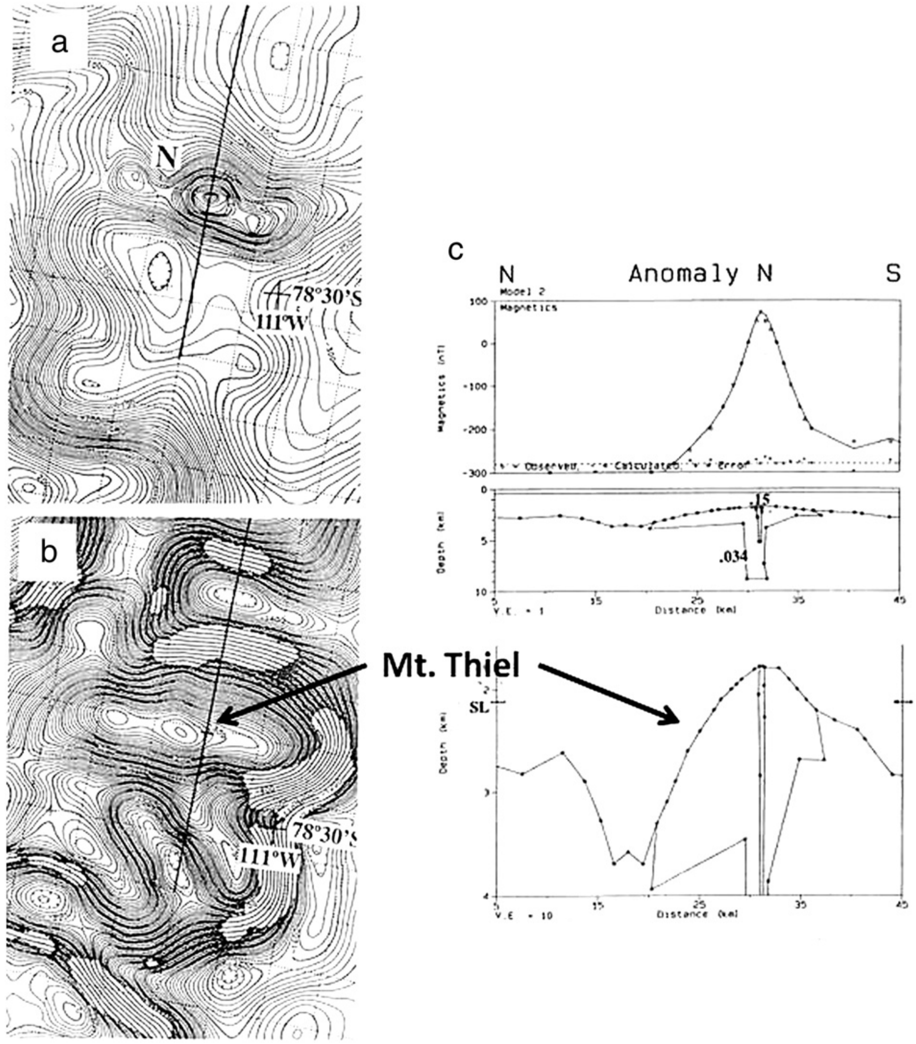


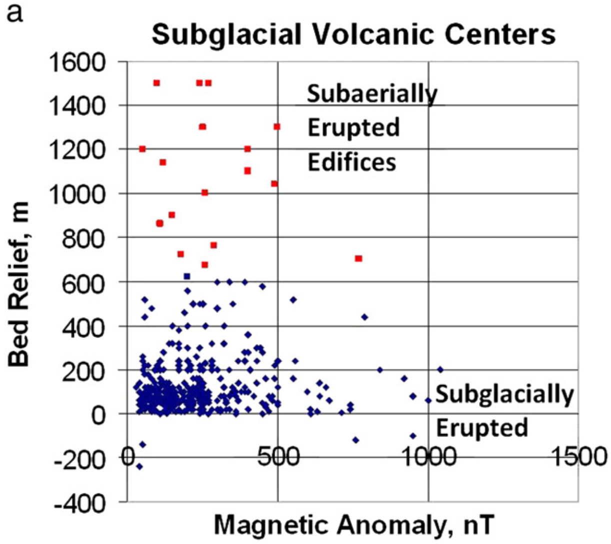
Fig. 7. Aeromagnetic (a) and bedrock elevation (b) maps of area of anomaly N (Mt. Thiel). Note the suggestion of a "moat" bordering the base of Mt. Thiel. (c) Theoretical 2 1/2 D model fit to aeromagnetic profile for anomaly N. Central body has strike length of 2.5 km to west and 2 km to east. Outside body has strike length of 8 km to west and east respectively. Other parameters as in Fig. 5. Note the surrounding magnetic "low" resulting from the inferred shallow Curie isotherm here and in Figs. 2 and 4a.

9. Active subglacial volcanism

Although exposed alkaline volcanic rocks associated with the West Antarctic rift system, surrounding the WAIS extend in age to ~34 Ma., Mt Erebus (<1 Ma), Mt. Melbourne (<0.26 Ma), and Mt. Takahe (<0.1 Ma) are examples of active volcanoes in the WAIS area (LeMasurier, and Thomson 1990). However, most "volcanic centers" are buried beneath the WAIS. If only a very small percentage of these >1000 volcanic, magnetic-anomaly sources are active today, subglacial volcanism may still have a significant effect on the dynamics of the WAIS. Active subglacial volcanism was interpreted from aerogeophysical data reported by Blankenship et al. (1993, Mt. Casertz), and Corr and Vaughan (2008, near Hudson Mts.), who raised the question of possible volcanic effects on the regime of the WAIS. Wingham et al. (2009) reported an increased volume loss from 2.6 to 10.1 km^3/yr from 1995 to 2006 for the Pine Island Glacier in the vicinity of the active subglacial volcano near the Hudson Mts. Behrendt and Wold (1963) and Behrendt (1964) show high amplitude magnetic anomalies over exposed volcanic rocks of the Hudson Mountains and adjacent Pine Island Glacier area suggesting that magnetic data coincident with the tight grid of the radar ice sounding lines shown over Pine Island Glacier (Corr and Vaughan, 2008) could define a "volcanic center" beneath the ice there. Behrendt et al. (2004) suggested a volcanic center beneath the Ice Stream D (Fig. 1) grounding line might have influenced melting in this area, if recently active.

I suggested above that Mt. Thiel (the source of anomaly N, Figs. 4 and 7) could be the source of the ash layer observed in the WAISCORE (Fig. 4); it may be another example of a recently active volcano erupted subaerially. Other observations such as (a) half of the high-relief, high-topographic sources in the entire CWA survey area are concentrated in the WAIS divide area; (b) the interpreted shallow Curie isotherm underlies the same area; (c) high heat flow suggested at the base of the WAISCORE (Conway et al., 2011, Fudge, et al., 2011, and G. Clow, personal commun.); and (d) the location of the interpreted caldera beneath the WAIS divide (Fig. 4) all seem consistent with recent to active volcanism beneath this area of the WAIS. Except for isolated Mt. Resnick (Figs. 3 and 11) and the rift shoulder (Figs. 1 and 3), the area of the WAIS divide (Fig. 4) overlies the highest topographic area beneath the WAIS. Drewry (1983) and Jankowski et al. (1983) called this area the "Sinuous Ridge" (Fig. 1) based on widely spaced radar-ice sounding and magnetic profiles.

Vogel and Tulaczyk (2006) argued that subglacial volcanism may play a "crucial role" in WAIS stability and showed the results of a model assuming the effect of active Mt. Casertz on the WAIS. Probably wet-based areas of the WAIS would be the most likely to be impacted. Tulaczyk and Hossainzadeh (2011) showed an interpretation, based



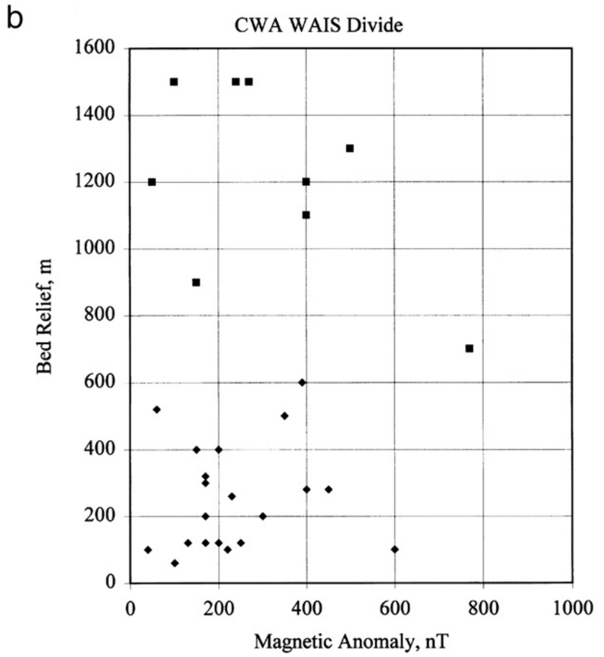
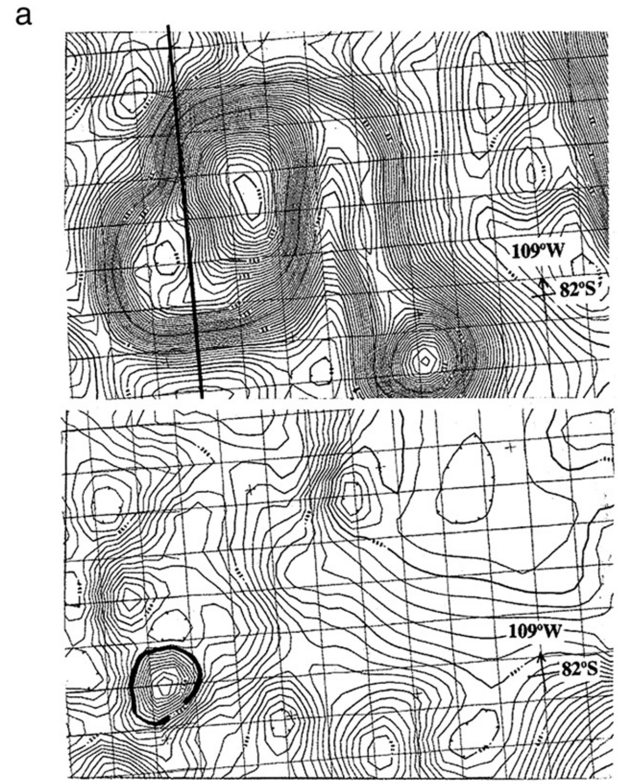


Fig. 8. (a) Comparison of magnetic anomalies correlated with bed relief in area of CWA survey. The great bulk of these >400 (40 –1200-nT) anomaly sources at the base of the ice have low bed relief (60–600 m, with about 80%<200 m). The square symbols indicate high topography as well as high bed relief >600 m (e.g., Figs. 7 and 10); all of these high-topography magnetic sources would be above sea level after ice removal and glacial rebound. Because of their form similar to exposed volcanoes in the WAIS area with edifices primarily comprising subaerially erupted volcanic flows, which have resisted glacial erosion, I infer that these high-topographic, volcanic, highly magnetic sources are also subaerially erupted volcanoes. (b) Subset of (a) indicating 29 anomalies correlated with bed relief in WAIS divide area. Note that 9 of the 18 high topography sources in (a) are in the WAIS dived area which overlies the interpreted caldera.



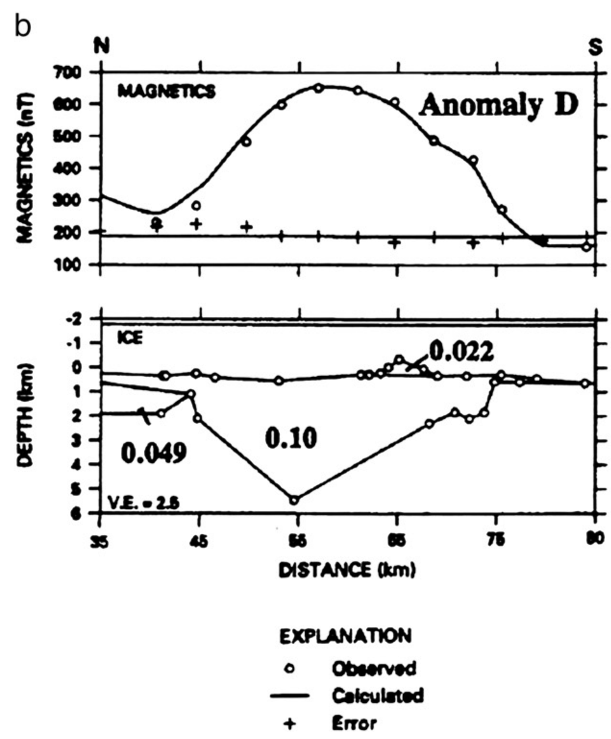


Fig. 9. (a) Detailed aeromagnetic (top) and bed elevation (bottom) maps of area of volcanically active subglacial Mt. Casertz (Behrendt et al. 1995; Blankenship et al., 1993). Contour intervals: 10 nT and 20 m, respectively. Grid survey lines are spaced at 5 km, and north is indicated by arrow. There is no magnetic anomaly caused by the small circular structure (indicated by heavy line on bed elevation map) which comprises the edifice of Mt. Casertz; rather, it is interpreted as a pile of volcanic debris such as pillow breccia or hyaloclastite erupted into the moving ice. (b) Model fit to aeromagnetic profile crossing Mt. Casertz. Susceptibilities indicated in SI. Location of modeled profile is shown (from Behrendt et al., 1995, Fig. 6).

on more recent modeling that indicated that essentially all of the WARS area underlying the WAIS is above the melting temperature. Wright and Siegert (2011) show >60 subglacial lakes beneath the WAIS, which is not inconsistent with Tulaczyk and Hossainzadeh (2011).

Antarctic geological DRILLing (ANDRILL) cores show ~60 cycles of advance and retreat of Ross Ice Shelf over 14 Ma. and extended periods when WAIS was very small if not gone altogether (Naish et al., 2009). Pollard and De Conto (2009) refer to evidence by several authors who show major sea level spikes at 125 Ka, 400 Ka and 1.07 Ma. Their models show rapid fluctuations in the WAIS and several

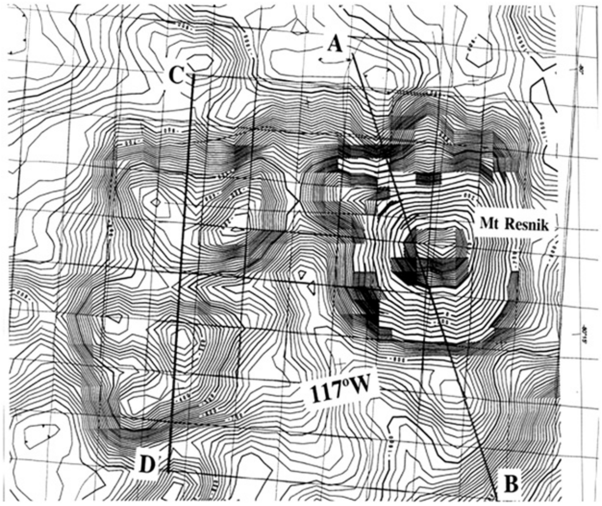


Fig. 10. Bed elevation map of Mt. Resnik area. Orthogonal, 5-km spaced survey lines were flown about 600 m above ice sheet surface in this area Contour interval 20 m. Note that Mt. Resnik has about 1600 m local relief, but the topographic structure interpreted as a glacially modified subvolcanic intrusion extending to the west has only about 400 m relief. Profiles C–D crosses this glacially smoothed edifice of the underlying, highly magnetic "volcanic center".

periods of deglaciation, particularly "when sub-ice ocean melting increases from 0.1 to 2 myr^{-1} under shelf interiors, and from 5 to 10 m yr^{-1} near exposed shelf edges" such as reported for Pine Island Glacier (Wingham et al., 2009).

Because no geologic samples have yet been acquired from the rock "outcrops" defined by radar ice-sounding at the bed of the ice sheet, there is no direct information about their ages. However, considering volcanically-active Mt. Erebus and the >780-ka Brunhes-Matuyama magnetically reversed flows at Hut Point nearby on Ross Island (Behrendt et al., 1996), the possibility of recent volcanism beneath large areas of the WAIS cannot be ruled out.

There are differing interpretations as to the likelihood of active volcanism beneath the extended crustal lithosphere through which the WAIS flows. Two papers giving somewhat contradictory results (Maule et al. 2005; Winberry and Anandakrishnan, 2004) for late Cenozoic volcanism are examples. Until samples of the inferred volcanic rocks interpreted beneath the WAIS are available for analysis and dating, this question cannot be resolved. Future effects on the stability of the WAIS should not be ignored, as the present rapid changes resulting from global warming, could be accelerated by subglacial volcanism.

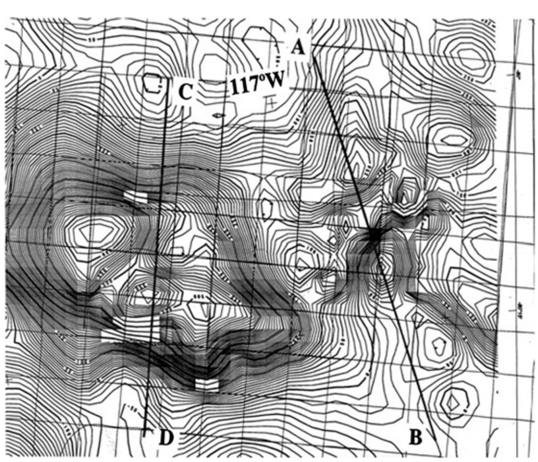


Fig. 11. Aeromagnetic map of Mt. Resnik area. Contour interval 10 nT. Flight lines as indicated in Fig. 10. The complex anomaly over Mt. Resnik requires normal and reversed, high-Q magnetization as shown by model profiles A–B in Fig. 12. We interpret that the former volcanic edifice crossed by profiles C–D (Fig. 13), which may have been erupted beneath the WAIS associated with this structure, have been removed by the moving ice. In contrast, the interpreted volcanic peak of Mt Resnik was probably erupted subaerially at a time when the WAIS was absent, similar to the other exposed volcanic peaks in the West Antarctic rift-WAIS area (Fig. 1).

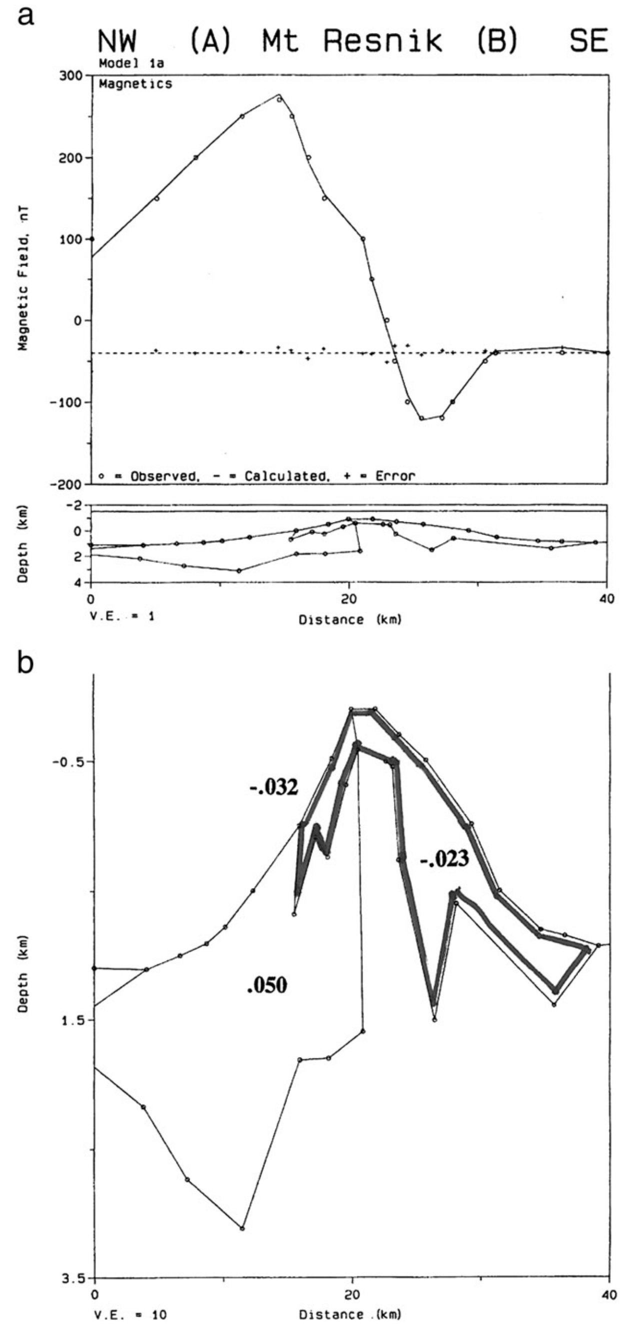


Fig. 12. (a) Theoretical 2 1/2 D model fit to aeromagnetic profiles A–B (location in Fig. 10) for Mt. Resnik. Apparent susceptibilities indicated in SI. Bodies have strike lengths ranging from 4 to 7 km, as appropriate to the magnetic map (Fig. 11) to east and west. Reversed magnetizations (indicated by heavy outline) were required to fit this anomaly as indicated by negative apparent susceptibility contrast at the summit of the peak. An alternate model not shown here (Behrendt, et al., 2006) has normal magnetization overlying reversed. We cannot determine which model is most likely, but interpretation that Mt. Resnik was erupted during a period of magnetic reversal is valid in either case. Note vertical exaggeration (VE) is 1 in the upper profile of the model and 10 in the lower (from Behrendt et al, 2006).

LeMasurier (2008) inferred that because the floor of the WARS is 1000–2000 m lower than the East African and Basin and Range Rifts, even after approximating the mass equivalent of ice as sedimentary basin fill" (as we suggested in Behrendt et al., 1991) the

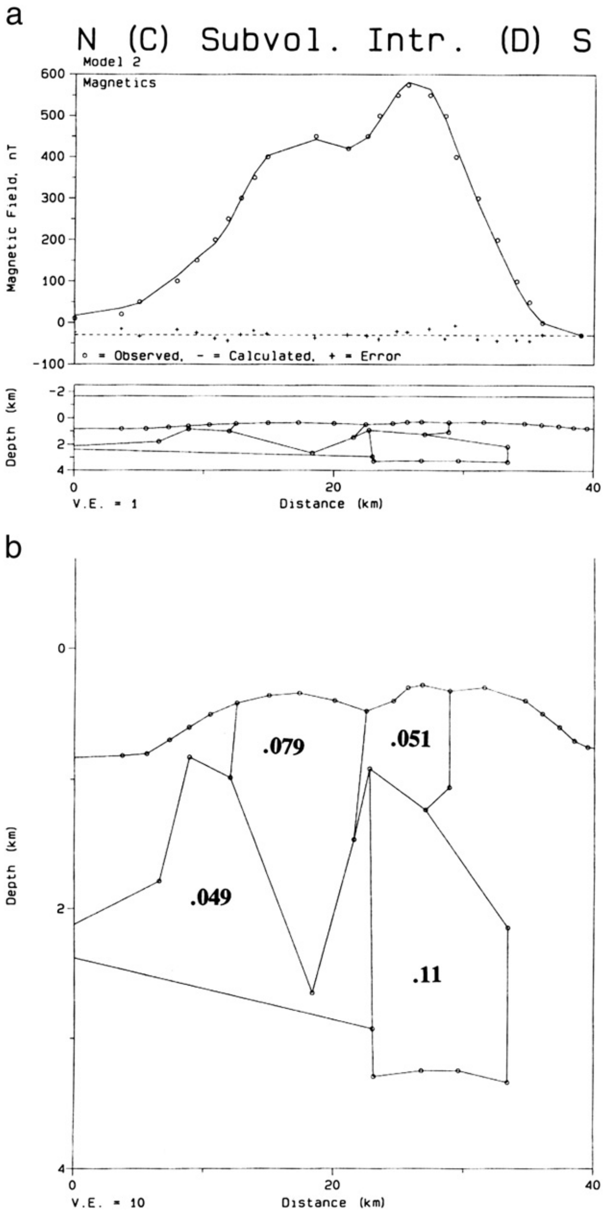


Fig. 13. Theoretical 2 1/2 D model fit to aeromagnetic profiles C–D (location in Figs. 10 and 11) for interpreted glacially smoothed subvolcanic intrusion west of Mt. Resnik. Susceptibilities indicated in SI. Bodies have strike lengths ranging from 2 to 17 km, as appropriate to the magnetic map (Fig. 11) to east and west respectively. Note vertical exaggeration (VE) is 1 in the upper profile of the model and 10 in the lower (from Behrendt et al, 2006).

interior of the WAIS is relatively cool. But, the bed would rise as much as half a kilometer due to isostatic uplift were the ice sheet removed (Drewry, 1983). LeMasurier (2008) suggests low risk of subglacial volcanism destabilizing the ice sheet. I agree that the risk is probably very low, but it still should be considered. Considering the discussion above, there appears to be high heat flow in the caldera area of the WAIS core and Mt Thiel (Fig. 4).

Other rifts, such as the Midcontinent rift system of North America and the rifted Atlantic margin of North America had low elevation and subsidence at the time of rifting accompanied by flood basalts (LIP). Green (1982), based on field geologic mapping, noted that "volcanism in the Lake Superior area began, and apparently continued by the outpouring of large volumes of basaltic lava on a relatively flat surface". Behrendt et al.(1988) reported a 20 km-thickness of basaltic flows deposited in the subsiding Midcontinent Rift based on seismic reflection profiles. Green (1982) reported that "significant doming did not occur as a precursor of rifting". Hutchinson et al. (1991) interpreted the volume of basalts in the Mid Continent Rift as evidence of rifting across a mantle plume, as did Behrendt et al. (1992) for the $>1\times10^6$ km^3 of magmatic rocks in the WARS as discussed here. Keen et al., (2012) discussed the volcanic rifted areas of the Labrador margin of Canada and considered the possibility of a mantle plume as the source of the volcanism there.

10. Conclusions

The aeromagnetic method has been demonstrated as the most useful geophysical tool for studying subglacial volcanic rocks associated with the West Antarctic Rift System (WARS) beneath the WAIS from early surveys in the 1950s and 1960s (particularly when combined with bed topography from radar ice sounding) as in the unique CWA survey. In this paper, I have described and summarized research results of a particularly conspicuous set of magnetic anomalies observed in the over the WAIS. The short-wavelength, high-amplitude (50–>1000 nT) anomalies measured ~1 km above the 2–3-km thick moving WAIS have sources interpreted as "volcanic centers" at the glacier bed, as measured in the CWA survey. The 5-km orthogonal line spacing provided three-dimensional characterization of both the magnetic field and bed topography and allowed detailed modeling of the sources. These models require >1–2 km thickness of highly-magnetic inferred intrusions at the "volcanic centers" having apparent susceptibility contrasts (indicative of high remanent magnetization in the present field direction) to produce the observed amplitudes at the flight elevation. The preponderance of positive anomalies is probably the result to induced magnetization canceling reversed remanent magnetization for many unrecognized "volcanic center anomalies" as only anomalies >100 nT amplitude were carefully examined.

The CWA survey (3.54×10^5 km^2 area) characterizes the much greater area over the WAIS (1.2×10^6 km^2) marked by similar anomalies having inferred "volcanic centers" as sources, observed along widely spaced flight lines collected over several earlier decades (1959–1979). These combined data indicate a minimum volume of 10^6 km^3 for the sources of the magnetic anomalies.

Comparison of a carefully selected subset of ~400 of the >1000 high-amplitude anomalies in the CWA survey having topographic expression at the glacier bed, showed >80% had less than 200-m relief. This low relief could not produce the observed anomalies; a thick subvolcanic intrusion is required. Volcanic edifices consisting of easily erodible hyaloclastites or pillow breccias are interpreted to have been removed by the moving WAIS into which these were "injected". An example from active subglacial volcano, Mt Casertz (Fig. 7), illustrates this process taking place at present.

About 18 high-amplitude subglacial magnetic sources also have high topography and bed relief (>600 m) interpreted as subaerially erupted volcanic peaks when the WAIS was absent, whose competent lava flows protected their edifices from erosion. All of these would have high elevation above sea-level, were the ice removed and glacial rebound to have occurred. Nine of these anomalies are concentrated in the WAIS divide area.

A circular, ~70 km diameter ring of positive anomalies (Fig. 4) in the WAIS divide area, interpreted as evidence of a volcanic caldera (Behrendt et al., 1998), is characterized by high elevation bed topography, and a surrounding regional magnetic "low" interpreted as caused by a shallow Curie isotherm. The WAISCORE in this area, shows evidence of high heat flow and a prominent volcanic ash layer. An interpreted high relief (1.8 km) subaerially erupted volcano, Mt Thiel, has a bed elevation of 400 m, and a 400 nT positive anomaly (Fig. 7). Mt Thiel, about 100 km distance from the WAISCORE, may be the source of the ash layer.

The highest of these subaerially erupted peaks, Mt Resnik (Figs. 3, and 10–12), at 300 m beneath the ice surface about 200 km south of the WAIS divide, has 1.6 km bed-relief. Mt Resnik is marked by a several hundred nT, complex negative anomaly (Figs. 10 and 11) interpreted as resulting from eruption through a magnetic reversal at least 780 Ka (Brunhes-Matuyama). About 100 other negative anomalies (Fig. 2) occur throughout the CWA survey over volcanic centers correlated with bed topography.

Six active volcanoes (two subglacial) have been reported associated with the WARS. Several authors have suggested significant effects on the regime of the WAIS caused by subglacial volcanic activity. Even if there is a low probability, future effects on the stability of the WAIS should not be ignored, as the rapid changes observed in the past 20 years resulting from global warming could be accelerated by subglacial volcanism.

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I thank my many co-authors cited and other colleagues with whom I have worked in Antarctica over the past 55 years. Nelia Dunbar suggested the origin of the ash layer with a subglacial subaerially erupted volcano. Gary Clow shared his preliminary temperature measurements in the WAISCORE. Wesley LeMasurier has contributed many hours discussing our various interpretations. In particular I wish to acknowledge Edward Thiel, who made the first aeromagnetic survey flights over the WAIS in 1959, and who was killed in an Antarctic aeromagnetic survey crash (along with four others) in 1961. The National Science Foundation and the U.S. Geological Survey provided funding and logistic support for this work.

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