

Locating subglacial sediments across West Antarctica with isostatic gravity anomalies

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Summary Subglacial sediments are an important control on fast flowing ice in West Antarctica but their spatial distribution over catchment-wide areas is still largely unknown. Previously, airborne gravity anomalies could not clearly image sedimentary basins beneath the ice because broad, crustal-scale gravity signals masked the near-surface anomalies. We show here that it is possible to use additional processing to produce an isostatic gravity anomaly, which is sensitive to the locations of sedimentary basins. Our results reveal that the inferred major basin beneath Thwaites Glacier is confined to the Byrd Subglacial Basin, but that there are also basins underlying the onset of tributary fast flow. In the Ross Sea Embayment, known sedimentary basins coincide with negative isostatic anomalies. The sedimentary basins beneath the Ross Sea Embayment ice streams are more widespread and likely have a greater sediment thickness than the basins beneath Thwaites Glacier in the Amundsen Sea Embayment.

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Introduction

Determining the distribution of subglacial sediments beneath the West Antarctic Ice Sheet's (WAIS') ice catchments is necessary for understanding the dynamic behavior of the WAIS' glaciers and ice streams. We know from the Ross Sea Embayment ice streams that fast flow is controlled by the co-existence of sediment and water (Blankenship et al., 1986; Anandakrishnan et al., 1998; Blankenship et al., 2001; Studinger et al., 2001). Drill sites (Engelhardt and Kamb, 1998), active source seismic experiments (Blankenship et al., 1986), and passive seismic stations (Anandakrishnan and Winberry, 2004) have provided local verification of the existence of sediment below fast flowing ice. However, in order for modelers to have useful estimates for understanding ice sheet response, one must take a broader view and search for sedimentary basins catchment-wide.

The only tool currently able to provide such large-scale subglacial information is airborne geophysics. Much of the airborne work on the WAIS was carried out in the Ross Sea Embayment in the 1990s by the University of Texas at Austin (UT) and various collaborators (eg. Behrendt et al., 1996; Bell et al., 1999; Wilson and Luyendyk, 2006). The British Antarctic Survey (BAS) has also performed aerogeophysical surveys in West Antarctica (eg. Ferraccioli et al., 2006). Most recently, UT and BAS successfully acquired the largest surveys yet attempted in West Antarctica—over the neighboring catchments of the Thwaites and Pine Island Glaciers in the Amundsen Sea Embayment (Holt et al., 2006a; Vaughan et al., 2006). The coverage of the older datasets with the newest Amundsen Sea Embayment data expands the surveyed area of the WAIS to ~516,000 km².

Airborne gravity and magnetic methods have thus far been critical to piecing together a coherent picture of the subglacial environment. The older airborne datasets—hereafter called CASERTZ (Corridor Aerogeophysical Survey of the Southeastern Ross Transect Zone)—cover a significant portion of the Ross Sea Embayment. The CASERTZ potential fields data have been forward modeled for the locations of potential sedimentary basins and thickness of sedimentary infill (eg. Studinger et al., 2001; Bell et al., 2006) but identifying basin boundaries from airborne gravity has been problematic. The well-established technique of using isostatic anomalies to interpret geology has not, up until now, been applied in West Antarctica and using it allows us to re-examine the CASERTZ gravity data for sedimentary basins. Here we present the processing scheme and the free-air, Bouguer, and isostatic gravity results of the Thwaites Glacier survey (called AGASEA). As well, we use published free-air CASERTZ gravity values to calculate new Bouguer and isostatic anomalies for the dataset. We then merged the gravity results of the two surveys and show here a long profile through both the AGASEA and CASERTZ surveys. With this profile, we aim to delineate sedimentary basins on a more regional scale than has been previously attempted.

Methods

The airborne gravity data analysis for the AGASEA survey involved several standard corrections and a few advanced corrections summarized here. The standard reduction for airborne gravity is well-known and we followed the methods of Holt et al. (2006b). We also applied a tilt correction to account for horizontal aircraft accelerations

that tilt the gravity sensor off-level. Lastly, we filtered and upward continued the AGASEA free-air anomalies to 3600m. The resultant free-air anomaly is sensitive to geologic features and resembles subglacial topography (Figure 1, 2a,b). We also upward continued published CASERTZ free-air anomalies (Bell et al., 1999) to the same 3600m level as the AGASEA data and applied a DC shift of -42 mGals to match the absolute level of the AGASEA free-air anomalies.

The Bouguer correction removes the effects of known topography, which are constrained accurately by airborne ice-penetrating radar (Holt et al., 2006a), revealing anomalies of smaller magnitude and/or deeper sources. To do so, we remove gravity effects of any materials above sea level and remove effects of any non-rock materials below sea level (von Frese et al., 1981). We re-calculated full 3D, terrain-corrected Bouguer anomalies for the CASERTZ data to include the most up-to-date bedrock and ice thickness maps of West Antarctica and also calculated the Bouguer anomalies for the AGASEA data.

The additional gravity data analysis then separates the deep crustal gravity signals related to Moho variations from the near-surface gravity signals of sedimentary basins. To do so, we employed an Airy isostatic correction to remove the effect of Moho depth variations (Jachens and Griscorn, 1985). The correction calculates the compensation needed at the Moho to support all of the topography (including the ice sheet) assuming Airy isostatic equilibrium. This is a relatively good assumption, based on results indicating low flexural strength of the West Antarctic lithosphere during extension (Karner et al., 2005). The method is sensitive only to changes in the Moho depth, not to absolute Moho depth. Therefore, we pinned our calculated Moho to a 27 km depth, at a passive seismic station (BYRD) where receiver function analyses obtained that crustal thickness (Winberry and Anandakrishnan, 2004). We then calculated the gravity effect of the Moho and applied the corrections to both airborne gravity datasets. We have calculated these three gravity anomalies across the entirety of the AGASEA and CASERTZ data areas and present here a profile across the datasets (Figure 1, red line).

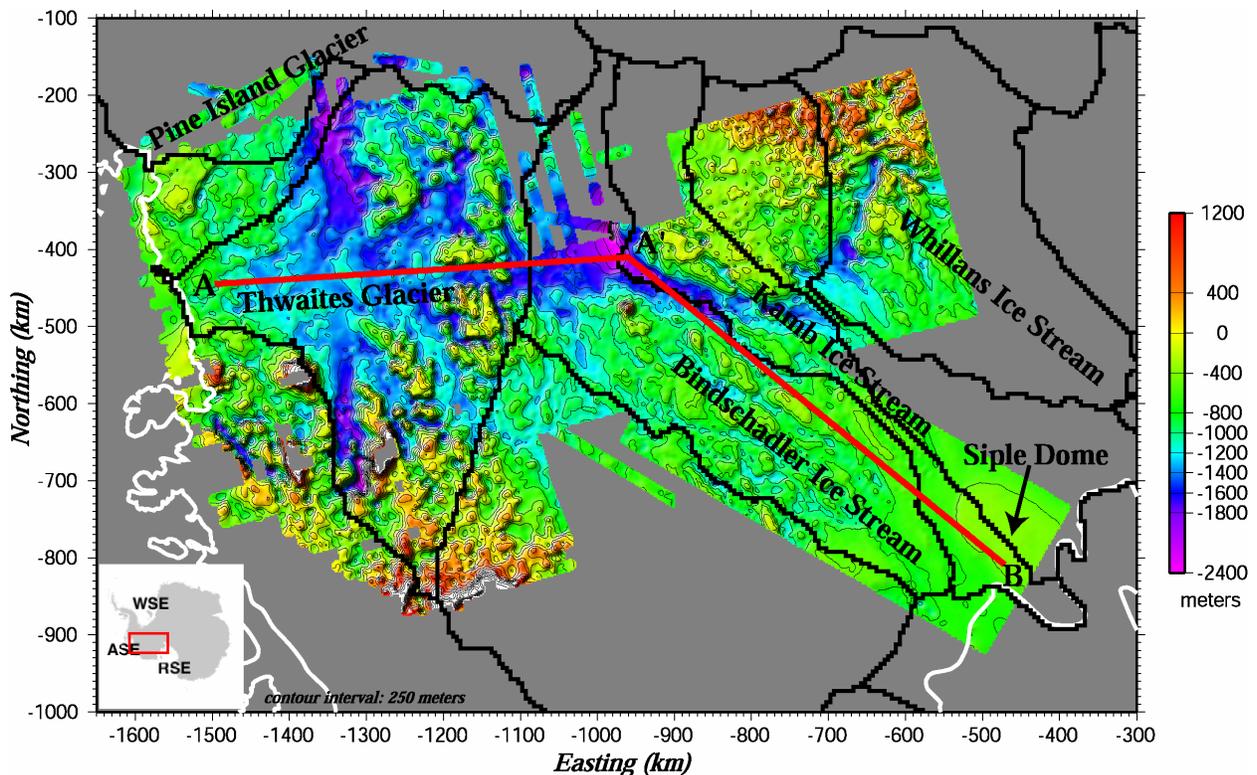


Figure 1. Subglacial topography for AGASEA and CASERTZ from airborne ice-penetrating radar, labeled with glacier and ice stream catchments. Black lines indicate ice catchments in the survey area, derived from ERS-1 data. White lines indicate the West Antarctic coastline. Red line indicates the location of the A-A'-B profile shown in Figure 2. Inset: Antarctic location map- red box is the study area- with major embayments labeled: ASE= Amundsen Sea Embayment, RSE= Ross Sea Embayment, and WSE= Weddell Sea Embayment.

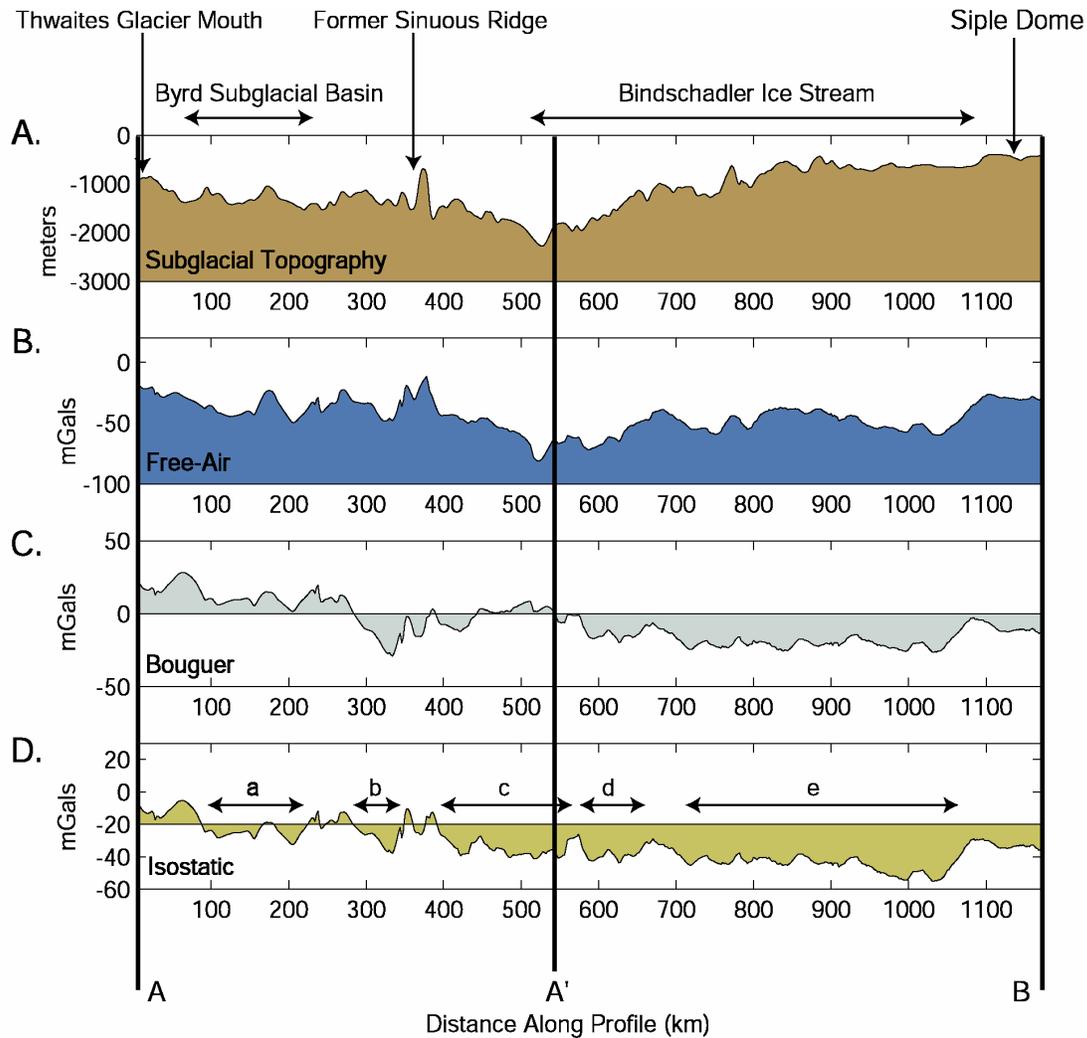


Figure 2. Profiles along A-A'-B, all sampled at 2 km intervals. Heavy vertical black lines are the locations of start (A), midpoint (A'), and end (B) of profile, as marked on Figure 1. Major glaciological and geologic features are labeled. A. Subglacial topography from ice-penetrating radar (Figure 1); B. Free-air gravity anomalies; C. 3D Bouguer gravity anomalies; D. Airy isostatic gravity anomalies with interpreted sedimentary basins.

Results

The Bouguer anomalies calculated for entire AGASEA area range in value from 80 to -180 mGals, though they range from only 25 to -25 mGals along the profile (Figure 2C). The highest value resides within a broad, positive Bouguer anomaly beneath the main flow of Thwaites Glacier (Figure 2C). The CASERTZ Bouguer anomalies are negative along the profile, but less so than the Ellsworth-Whitmore block negative anomaly (Bell et al., 2006). The isostatic anomalies beneath the WAIS produce a more complex spatial pattern. In the profile presented, there are a number of prominent negative isostatic anomalies (Figure 2D), identified by a >10 mGal amplitude drop that stays below the regional isostatic signal of ~ 20 mGals in the AGASEA area and ~ 30 mGals in the CASERTZ area. There is a ~ 120 km wide negative anomaly in the Byrd Subglacial Basin (a) and a ~ 60 km wide negative beneath one of Thwaites Glacier's tributaries (b). There are wider and larger magnitude isostatic negative anomalies in the Ross Sea Embayment (c-e) that coincide well with sedimentary basins revealed from aeromagnetism (Bell et al., 2006). Basin "c" should be interpreted carefully because of poor control on the local subglacial topography.

Discussion

The broad ($> \sim 100$ km) Bouguer anomalies of both the AGASEA data and the CASERTZ data indicate deep sources for the anomalies, likely to be variations in crustal thickness related to differences in tectonic provinces. These regional signals obscure many of the near-surface gravity anomalies, rendering broad sedimentary basins

unidentifiable from the Bouguer anomalies, as was also found by Studinger et al. (2001). The isostatic anomaly, however, removes the overprint of crustal gravity signatures so that near-surface anomalies are more easily identified. The large, negative amplitude isostatic anomalies in both datasets are interpreted here as sedimentary basins, although further work will be required to estimate infill thicknesses and volumes.

There appears to be a minor sedimentary basin (Figure 2D, anomaly b) underlying one of the Thwaites Glacier tributaries, but the most major AGASEA basin is confined to the Byrd Subglacial Basin (anomaly a), ~150 km inland from the grounding line. The isostatic anomaly positives in both datasets can be interpreted as crystalline rocks pending confirmation from the aeromagnetics. There are many major sedimentary basins in the Ross Sea Embayment and they all have negative isostatic anomalies of greater magnitude than those of the Thwaites Glacier catchment. This may indicate a difference in the thickness of sedimentary infill within these basins, where the Ross Sea Embayment basins would be much thicker and cover a larger area.

Conclusions

Subglacial sediments are critical to producing fast flow in the Ross Sea Embayment ice streams and are likely important for Thwaites Glacier as well. Sedimentary basins have been difficult to identify over large areas in the past. However, using airborne gravity-derived isostatic anomalies we have imaged sedimentary basins beneath the Ross Sea Embayment Ice Streams and beneath Thwaites Glacier. The sediments are interpreted as being much more widespread and may be significantly thicker in the Ross Sea Embayment than beneath Thwaites Glacier, though thicknesses cannot be estimated without further modeling of both gravity and magnetic data.

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References

- Anandkrishnan, S., D. D. Blankenship, R. B. Alley and P. L. Stoffa (1998), Influence of Subglacial Geology on the Position of a West Antarctic Ice Stream from Seismic Observations, *Nature*, 394, 62-65.
- Anandkrishnan, S. and J. P. Winberry (2004), Antarctic subglacial sedimentary layer thickness from receiver function analysis, *Global Planet Change*, 42, 167-176.
- Behrendt, J. C., R. Saltus, D. Damaske, A. McCafferty, C. A. Finn, D. D. Blankenship and R. E. Bell (1996), Patterns of Late Cenozoic Volcanic and Tectonic Activity in the West Antarctic Rift System Revealed by Aeromagnetic Surveys, *Tectonics*, 15, 660-676.
- Bell, R. E., V. A. Childers, R. A. Arko, D. D. Blankenship and J. M. Brozena (1999), Airborne Gravity and Precise Positioning for Geologic Applications, *J Geophys Res*, 104, 15281-15292.
- Bell, R. E., M. Studinger, G. D. Karner, C. A. Finn and D. D. Blankenship (2006). Identifying Major Sedimentary Basins Beneath the West Antarctic Ice Sheet from Aeromagnetic Data Analysis. *Antarctica: Contributions to Global Earth Sciences*. D. K. Fütterer, D. Damaske, G. Kleinschmidt, H. Miller and F. Tessensohn. Berlin, Springer, 117-121.
- Blankenship, D. D., C. R. Bentley, S. T. Rooney and R. B. Alley (1986), Seismic Measurements Reveal a Saturated Porous Layer beneath an Active Antarctic Ice Stream, *Nature*, 322, 54-57.
- Blankenship, D. D., D. L. Morse, C. A. Finn, R. E. Bell, M. E. Peters, S. D. Kempf, S. M. Hodge, M. Studinger, J. C. Behrendt and J. M. Brozena (2001). Geologic Controls on the Initiation of Rapid Basal Motion for West Antarctic Ice Streams: A Geophysical Perspective Including New Airborne Radar Sounding and Laser Altimetry Results. *Antarctic Research Series. The West Antarctic Ice Sheet: Behavior and Environment*. R. B. Alley and R. A. Bindschadler. Washington, D.C., American Geophysical Union, 77, 105-121.
- Engelhardt, H. and B. Kamb (1998), Basal sliding of Ice Stream B, West Antarctica, *J Glaciol*, 44, 223-230.
- Ferraccioli, F. F., P. C. Jones, A. P. M. Vaughan and P. T. Leat (2006), New aerogeophysical view of the Antarctic Peninsula: More pieces, less puzzle, *Geophys Res Lett*, 33, L05310.
- Holt, J. W., D. D. Blankenship, D. L. Morse, D. A. Young, M. E. Peters, S. D. Kempf, T. G. Richter, D. G. Vaughan and H. F. J. Corr (2006a), New boundary conditions for the West Antarctic ice sheet: subglacial topography of the Thwaites and Smith Glacier catchments, *Geophys Res Lett*, 33, 4pp.
- Holt, J. W., T. G. Richter, S. D. Kempf, D. L. Morse and D. D. Blankenship (2006b), Airborne Gravity Over Lake Vostok and Adjacent Highlands of East Antarctica, *G-cubed*, 7, Q11012.
- Jachens, R. C. and J. Griscom, Eds. (1985). *An Isostatic Residual Gravity Map of California, The Utility of Regional Gravity and Magnetic Anomaly Maps*, SEG Press.
- Karner, G. D., M. Studinger and R. E. Bell (2005), Gravity anomalies of sedimentary basins and their mechanical implications: Application to the Ross Sea basins, *West Antarctica, Earth Planet Sci Lett*, 235, 577-596.
- Studinger, M., R. E. Bell, D. D. Blankenship, C. A. Finn, R. A. Arko, D. L. Morse and I. Joughin (2001), Subglacial sediments: A regional geological template for ice flow in West Antarctica, *Geophys Res Lett*, 28, 3493-3496.
- Vaughan, D. G., H. F. J. Corr, F. F. Ferraccioli, N. Frearson, A. O'Hare, D. Mach, J. W. Holt, D. D. Blankenship, D. L. Morse and D. A. Young (2006), New boundary conditions for the West Antarctic ice sheet; subglacial topography beneath Pine Island Glacier, *Geophys Res Lett*, 33, L09501.
- von Frese, R. R. B., W. J. Hinze, L. W. Braile and A. J. Luca (1981), Spherical earth gravity and magnetic anomaly modelling by Gauss-Legendre quadrature integration, *J Geophys*, 49, 234-242.
- Wilson, D. S. and B. P. Luyendyk (2006), Bedrock platforms within the Ross Embayment, West Antarctica: Hypotheses for ice sheet history, wave erosion, Cenozoic extension, and thermal subsidence, *G-cubed*, 7, Q12011.
- Winberry, J. P. and S. Anandkrishnan (2004), Crustal Structure of the West Antarctic rift system and Marie Bird Land hotspot, *Geology*, 32, 977-980.