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Basement topography and sediment thickness beneath Antarctica's Ross Ice Shelf

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Key Points:

- Aeromagnetic analysis reveals basement surface and evidence of fault-controlled extensional basins beneath Antarctica's Ross Ice Shelf
- Active faults at Siple Coast likely influence ice streams through control of geothermal heat, groundwater, and glacioisostatic adjustments
- A basement high beneath Ross Ice Shelf spatially coincides with a lithospheric boundary, with contrasting sedimentary basins on either side

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Abstract

New geophysical data from Antarctica's Ross Embayment reveal the structure and subglacial geology of extended continental crust beneath the Ross Ice Shelf. We use airborne magnetic data from the ROSETTA-Ice Project to locate the contact between magnetic basement and overlying sediments. We delineate a broad, segmented basement high with thin (0-500m) non-magnetic sedimentary cover which trends northward into the Ross Sea's Central High. Before subsiding in the Oligocene, this feature likely facilitated early glaciation in the region and subsequently acted as a pinning point and ice flow divide. Flanking the high are wide sedimentary basins, up to 3700m deep, which parallel the Ross Sea basins and likely formed during Cretaceous-Neogene intracontinental extension. NWSE basins beneath the Siple Coast grounding zone, by contrast, are narrow, deep, and elongate. They suggest tectonic divergence upon active faults that may localize geothermal heat and/or groundwater flow, both important components of the subglacial system.

Plain Language Summary

The bedrock geology of Antarctica's southern Ross Embayment is concealed by 100s to 1000s of meters of sedimentary deposits, seawater, and the floating Ross Ice Shelf. Our research strips away those layers to discover the shape of the consolidated bedrock below, which we refer to as the basement. To do this, we use the contrast between nonmagnetic sediments and magnetic basement rocks to map out the depth of the basement surface under the Ross Ice Shelf. Our primary data source is airborne measurements of the variation in Earth's magnetic field across the ice shelf, from flight lines spaced 10km apart. We use the resulting basement topography to highlight sites of possible influence upon the Antarctic Ice Sheet and to further understand the tectonic history of the region. We discover contrasting basement characteristics on either side of the ice shelf, separated by a N-S trending basement high. The West Antarctic side displays evidence of active faults, which may localize geothermal heat, accommodate movements of the solid earth caused by changes in the size of the Antarctic Ice Sheet, and control the flow of groundwater between the ice base and aquifers. This work addresses critical interactions between ice and the solid earth.

1 Introduction

The southern sector of Antarctica's Ross Embayment beneath the Ross Ice Shelf (RIS; area ~480,000km^2) is poorly resolved because the region is not accessible to conventional seismic or geophysical surveying. Rock exposures on land suggest that RIS crust consists of early Paleozoic post-orogenic sediments, intruded in places by mid-Paleozoic and Cretaceous granitoids (Luyendyk et al., 2003; Goodge, 2020). ~~Since~~Following the onset of extension in the mid-Cretaceous ~~onset of extension~~, grabens formed and filled with terrestrial and marine deposits, continuing into the Cenozoic (e.g. Sorlien et al., 2007; Coenen et al., 2019), as the Ross Embayment underwent thermal subsidence (Karner et al., 2005; Wilson & Luyendyk, 2009). The physiography of this region then responded to the onset of glaciation in the Oligocene (Paxman et al., 2019), coinciding with localized extension in the western Ross Sea until 11 Ma (Granot & Dyment, 2018). The Oligocene-early-Miocene paleo-landscape of the Ross Sea sector was revealed by marine seismic data (e.g. Brancolini et al., 1995; P´erez et al., 2021) and offshore drilling that penetrated crystalline basement (DSDP Site 270; Ford & Barrett, 1975) (Figure ~~3~~1). Recognition of the role of elevated topography in Oligocene formation of the Antarctic Ice Sheet (DeConto & Pollard, 2003; Wilson et al., 2013) and the likely influence of subglacial topography upon ice sheet processes during some climate states (Austermann et al., 2015; Colleoni et al., 2018) motivated our effort to determine basement topography beneath the Ross Ice Shelf.

Ice sheet dynamics are of high interest in the RIS region because its grounding zone (GZ) and pinning points (Still et al., 2019) buttress Antarctica's second-largest drainage basin (Tinto et al., 2019). Our work in this sensitive region seeks to delimit the extent and geometry of competent basement because the margins of basement highs are sites of strong contrasts in permeability that influence the circulation of subglacial waters. A spectacular example of the confinement of subglacial water between the ice sheet and basement exists in ice radar profiles for the continental interior (Bell et al., 2011), but ~~the hydrologic system~~little is ~~poorly~~ known ~~for~~about the subglacial ~~sediment-filled~~hydrology of deep groundwater reservoirs within sedimentfilled marine basins that receive terrestrial freshwater influx (Siegert et al., 2018; Gustafson et al., 2021). These basins may contain up to 50% of total subglacial freshwater (Christoffersen et al., 2014), where the discharge and recharge along fault-damage zones (Jolie et al., 2021) is controlled by pressure from the overriding ice sheet (Gooch et al., 2016). Possible evidence that RIS basement margins localize ~~geothermal fluids or~~ basinal waters, causing the advection of geothermal heat, comes from elevated values and significant spatial variability of measured geothermal heat flux (GHF) at points around the Ross Embayment (Begeman et al., 2017). Here we present the first map of magnetic basement topography and thickness of overlying non-magnetic sediments for the southern Ross Embayment, developed using ~~ROSETTA-Ice~~ROSETTAIce (2015-2019) airborne magnetic data (Figure 1b, Tinto et al., 2019). Our work reveals three major sedimentary basins and a broad basement ridge that separates crust of contrasting basement characteristics.

2 Data and Methods

We ~~applied Werner deconvolution (Werner, 1953) to estimate the depth to the top of the magnetic crust along~~use ROSETTA-Ice ~~flight lines at 10-km spacing (Figures 1b&S4). The approach assumes that~~ aeromagnetic data to image the shallowest magnetic signals in the crust. Assuming that the overlying sediments and sedimentary rocks produce ~~significantly lower amplitude~~smaller magnetic anomalies than ~~underlying~~the crystalline basement, we treat the resulting solutions as the depth to the magnetic basement (Text ~~S6). Here,~~S1). To do this, we implemented Werner deconvolution ~~is performed~~(Werner, 1953) on 2D moving and expanding windows of ~~aeromagnetic~~ line data ~~by~~, isolating anomalies and solving for their source parameters (~~Birch, 1984~~Text S2, location, depth, susceptibility, body type). The resulting solutions are non-unique; each observed magnetic anomaly can be solved by bodies at multiple locations and depths by varying the source's magnetic susceptibility and width. The result is a depth scatter of solutions (~~black dots in Figure 2), which we filtered based on magnetic susceptibility and binned to produce a basement surface (Text S1).~~Figures 2 & S2), which tend to vertically cluster beneath the true source. This magnetic basement approach has been used to map sedimentary basins throughout Antarctica (i.e. Karner et al., 2005; Bell et al., 2006; Studinger et al., 2004; Frederick et al., 2016) where typically, the tops of solution clusters are manually selected to represent the basement depth. Our approach expands on this method by utilizing a reliable, automated method of draping a surface over these depth-scattered solutions to produce a continuous basement surface (Text S3-4).

We implemented a 2-step tuning process that ties our RIS magnetic basement to well-constrained seismic basement in the Ross Sea, from the Antarctic Offshore Stratigraphy project

(ANTOSTRAT) (Figure 1b, Brancolini et al., 1995). This involved using Operation IceBridge (OIB) airborne magnetic data (Cochran et al., 2014) collected over the RIS and Ross Sea. Minimizing misfits between OIB magnetic basement and ANTOSTRAT basement, as well as between OIB and ROSETTA-Ice magnetic basements, enabled tuning of our method to optimal basement depths (Figures 2, S2, S3e&f, Text ~~S2-3~~S3-4).

Our RIS results (Figure S4) were merged with offshore ANTOSTRAT data (Brancolini et al., 1995) and smoothed with an 80km Gaussian filter to match the characteristic wavelengths of the Ross Sea basement (Text ~~S4~~S5). The combined grid (Figure 3a) was then subtracted from BedMachine bathymetry (Figure 1a, Text ~~S5~~S6, Morlighem et al., 2020), to ~~map basins and~~ obtain the sediment thickness distribution for the Ross Embayment (Figure 3b).

~~We used basement features and geophysical anomaly patterns to infer~~These sub-RIS results together with free-air gravity data allowed us to infer the locations of regional scale faults beneath the RIS. Criteria used to locate faults include 1) high relief on the magnetic basement surface, 2) linear trends that cross zones of shallow basement, 3) high gradient gravity anomalies (Figure S1a, ROSETTA-Ice) and 4) large contrasts in sediment thickness. Narrow, deep, linear basins are likely to be controlled by active faults (e.g. Finn, 2002; Drenth et al., 2019). We display the inferred faults upon a base map of crustal stretching factors (β-factor; the ratio of crustal thickness before and after extension, Figure 4a), using an initial crustal thickness of 38km (Müller et al., 2007), a continent-wide Moho model (An et al., 2015), and our basement surface as the top of the crust (Text ~~S5~~S6).

3 Results

~~An~~We find that an almost continuous drape of sediment covers the RIS region (Figure 3b), with only ∼~~1~~3% of the area having <~~1~~200m of sedimentary cover. Prominent beneath the midline of the RIS is a broad NNW-SSE trending basement ridge (Figure 3a, Mid-Shelf High; MSH), which comprises most of the shallowest (<700 meters below sea level (mbsl~~)~~ ~~subRIS~~)) sub-RIS basement, with several regions ~~having <50m~~with as little as 100m of sedimentary cover. Basement is deeper on the East Antarctic side of the MSH, where it averages ∼2400 mbsl, compared to an average depth of ∼1900 mbsl on the West Antarctic side (Figure 3a histogram). Sedimentary fill is ∼400m greater and more uniformly distributed on the East Antarctic side than the West Antarctic side (Figure 3b histogram).

To estimate our uncertainty~~,~~ (Text S7), we examined the misfit between ~~our basement~~OIB and ANTOSTRAT ~~and OIB~~ basement (Figures 2~~,~~ & S2~~;~~) and between our basement and OIB basement (Figures S3e&f~~, Text S6~~). There is a median misfit of 480m (22% of average RIS depth) for basement~~.~~ (Figure S5, Figure S6). ~~Incorporating the ∼70m uncertainty in the bathymetry model (Tinto et al., 2019), our sediment thickness uncertainty is 550m (37% of average thickness).~~ A similar ~~480m~~470m median basement misfit is estimated by comparing our results to eight active source seismic surveys (Figure 3b, Table S1). Incorporating the ∼70m uncertainty in the bathymetry model (Tinto et al., 2019), our representative sediment thickness uncertainty is 550m (37% of average RIS thickness, Figure S5).

A single broad and deep basin (300 x 600km) separates the MSH and the Transantarctic Mountains (TAM) (Figure 3a, Western Ross Basin). The Western Ross Basin parallels the TAM and has the deepest-observed sub-RIS basement depths of 4500 mbsl, accommodating sediments up to 3800m thick (Figure 3b). It contains a long, narrow NWSE trending ridge with ∼1500m structural relief above the basement sub-basins on either side. Bordering the MSH on the east, an elongate NW-SE trending basin runs from the RIS calving front to the Siple Coast GZ (Figure 3a), where beneath Siple Dome we discover a 100x200km depocenter reaching basement depths up to 4000 mbsl, with sediments up to 3700m thick. We refer to this depocenter as Siple Dome Basin, a feature bounded on the east by a basement high that trends southward from Roosevelt Island. This high rises to its shallowest point at the GZ, where its sedimentary cover is less than 100m. A second deep, narrow basin (50x200km in dimension) is found along the north margin of Crary Ice Rise, separated from the Siple Dome Basin by a NW-SE ridge underlying Kamb Ice Stream. The basin, labeled Crary Trough in Figure 3a, reaches basement depths of 3200 mbsl, with sediments 1800-2700m thick. The southernmost RIS has an additional depocenter with up to 2000m of fill beneath Whillans Ice Stream (location in Figure 1a).

~~We inferred the locations of~~Inferred active ~~and inactive~~ sub-RIS faults (Figures 4a & S1~~).~~ ~~Active faults~~) correspond to narrow, linear basement basins with high-gradient gravity anomalies, prevalent on the West Antarctic side (Figure S1a). Inactive normal and ~~strikeslip~~strike-slip faults are inferred along lineaments that segment the shallow MSH into blocks and are oriented parallel to TAM outlet glacier faults. β-factors are indicative of thinned crust and are different on either side of the MSH. The TAM side shows higher β-factors (average 1.99) with low variability. The West Antarctic side has lower β-factors overall (average 1.82), but with some higher values up to 2.1 (Figure 4a).

4 Discussion

Sub-RIS sedimentary basins align with and show lateral continuity with the Ross Sea's Roosevelt Sub-Basin, Eastern Basin, Coulman Trough, and Victoria Land Basin (Figure 3, e.g. Cooper et al., 1995). The MSH passes northward into the Ross Sea's prominent Central High (CH). At the southern RIS margin, the narrow Siple Dome Basin has continuity with the previously identified Trunk D Basin (Figure 3a, Bell et al., 2006). The throughgoing trends imply regional continuity of crustal structure and a common tectonic development of the Ross Sea and RIS regions. Our sediment thicknesses are compatible with those determined by a) eight active-source seismic surveys (Figure 3b), for which the median misfit is 4~~8~~70m (Table S1), and b) surface wave dispersion indicating 2-4km of sediment under the RIS, similar to our range, with the maximum beneath Crary Ice Rise (Zhou et al., 2022). Three additional western RIS seismic profiles report up to several kilometers of sediment, in general accordance with our results (Stern et al., 1991; ten Brink et al., 1993; Beaudoin et al., 1992). Additionally, machine learning applied to geophysical datasets predicts a high likelihood of sedimentary basins at the locations of Siple Dome Basin and Crary Trough (L. Li et al., 2021).

4.1 West Antarctic Rift System extensional basins

The Western Ross Basin has a configuration similar to the western Ross Sea rift basins (e.g. Salvini et al., 1997) with a broad and deep basin, separated into distinct depocenters by a linear, low relief ridge. The deeper of the depocenters, on the TAM side of the ridge, coincides with ~~a narrow~~alternating high and low free-air gravity anomal~~y~~ies (Figure S1a). These similarities suggest the sub-RIS continuations of Coulman Trough and Victoria Land Basin (Figure 3b) likely share a common tectonic origin as fault-controlled basins (Figures 3a & 4a) formed through Cretaceous distributed continental extension across the WARS (Jordan et al., 2020). These sub-RIS basins terminate against the southern segment of the MSH (Figure 3a).

The linear ridge within the Western Ross Basin (Figure 3a) may be an expression of normal or oblique faults linked to the southward-narrowing Terror Rift (Sauli et al., 2021), formed due to Cenozoic oceanic spreading in the Adare Trough (Figure 3b, Granot & Dyment, 2018). The Western Ross Basin, with up to 3800m of fill, terminates along the prominent edge of the MSH that lines up with the fault-controlled trough and crustal boundary that passes southward beneath Shackleton Glacier (Borg et al., 1990). We interpret the basement lineament (Figure 4a) as a transfer fault separating sectors of crust extended to different degrees.

The southeastern RIS margin is distinguished by linear ridges and narrow, deep basins. The prominent NW-SE basement trends coincide with high-gradient gravity anomalies (Figure S1a, Tinto et al., 2019) and thick sediments, suggesting normal fault control and active divergent tectonics beneath the GZ. Our Siple Coast cross-section (Figure 4b) displays dramatic basement relief, exceeding 2km, in the Siple Dome Basin and Crary Trough, which we attribute to displacement upon high angle faults. Portions of basin-bounding faults were previously detected by ground-based gravity surveys upon the Whillans Ice Stream flank (Figure 4a, Muto et al., 2013) and site J9DC (Figure 3b), where large variations in sediment thickness indicate up to 600m of fault throw (Greischar et al., 1992). The continuity between the narrow Siple Dome Basin (this study) and the Trunk D Basin (Figure 3a, Bell et al., 2006) suggests that the active tectonic domain continues southward past the GZ. The fault-controlled tectonic basins may ~~be an expression of~~ reflect a crustal response to the lithospheric foundering hypothesized beneath the South Pole region (Shen, Wiens, Stern, et al., ~~2018~~2018) or be a broader regional expression of Neogene extension that formed the Bentley Subglacial Trench (Lloyd et al., 2015).

~~1.1 Cryosphere-groundwater implications~~

~~Fault juxtaposition of low-permeability basement next to permeable basin fill, in a subglacial setting, is likely to affect groundwater reservoir capacity and promote fluid overpressure of the ice sheet-confined aquifer (e.g. Ravier & Buoncristiani, 2018), with consequences for ice sheet processes (Christoffersen et al., 2014). The effects of deep voluminous groundwater within the sub-Whillans fault-controlled basin, discerned using magnetotellurics, are thought to influence ice streaming (Gustafson et al., 2021). Groundwater discharge and recharge along fault damage zones (Jolie et al., 2021) may influence the distribution of heat in the subglacial environment (Burton-Johnson et al., 2020). Modulated by pressure from the overriding ice sheet (Gooch et al., 2016), upward movement and discharge of waters may deliver heat that induces basal melting. Alternatively, basin recharge can sequester heat at lower depths within permeable basin fill. Regionally elevated GHF modeled along the Siple Coast (Shen et al., 2020) and anomalously high GHF (285 mW/m²) at Subglacial Lake Whillans (Figure 4a, Fisher et al., 2015) are likely the result of the active extensional setting and strong GHF localization upon faults bounding sedimentary basins. If this localization persists beneath the Siple Coast ice streams, it is likely to influence ice flow.~~

~~At a more regional scale, active graben-bounding faults likely accommodate relative motion in response to changes in ice sheet volume along the Siple Coast, a region underlain by low-viscosity mantle (Whitehouse et al., 2019; Shen, Wiens, Anandakrishnan, et al., 2018). In this region, Kingslake et al. (2018) found evidence of swift glacioisostatic rebound following Holocene deglaciation, with changes in bed elevation and geometry producing a negative feedback (cf. Lowry et al., 2020; Coulon et al., 2021) that drove ice sheet re-advance and re-stabilized the ice sheet. The matter is receiving considerable debate (Neuhaus et al., 2021).~~

~~Central High -~~

4.2 Consequences for ice sheet dynamics

Our basement topography and suggested crustal faults likely exert a strong influence on the overriding ice, especially along the Siple Coast. Here, we show deep and thick sedimentary basins which likely contain voluminous basinal aquifers (Figure 4b; cf. Gustafson et al., 2021). Where these aquifers discharge along fault-damage zones, they can enhance GHF and promote basal melting (Gooch et al., 2016), as depicted in Figure 4a. The elevated GHF seen at Subglacial Lake Whillans (285 mW/m^2, Fisher et al., 2015) may arise from fault localization (Figure 4a). Confinement of the aquifers between the ice bed and low-permeability basement may promote fluid overpressure, enabling ice streaming (e.g. Ravier & Buoncristiani, 2018). Additionally, the Siple Coast faults likely accommodate the solid Earth's response to fluctuating ice volume. A matter receiving considerable debate (Neuhaus et al., 2021; Venturelli et al., 2020; Lowry et al., 2019), is Kingslake et al.'s (2018) finding of rapid re-advance of the Siple Coast grounding zone following Holocene deglaciation. The re-advance was in part due to swift glacioisostatic rebound (cf. Lowry et al., 2020; Coulon et al., 2021), a process aided by the region's low-viscosity mantle (Whitehouse et al., 2019) and likely to be accommodated upon pre-existing crustal faults, as observed in the Lambert Graben (Phillips & L¨aufer, 2009). Our proposed grabenbounding faults would provide a tectonic control on the glacioisostatic adjustment of the Siple Coast region.

~~4.2~~4.3 Mid-Shelf High - Central High

~~Using contrasts in crustal characteristics, including magnetic and gravity anomalies, Tinto et al. (2019) identified a mid-Ross Embayment north-south trending geologic boundary separating crust of East and West Antarctic affinity. Geological substantiation comes from basement rock samples recovered from the CH at DSDP 270 (Ford & Barrett, 1975), and at Iselin Bank (Figure 3, Mortimer et al., 2011), which have lithologic affinities to the TAM. The MSH in the magnetic basement coincides with this boundary, as does the Ross Sea's CH, an association that is borne out by passive-seismic studies that show the boundary to be present at lithospheric scale (Cheng et al., 2021; WhiteGaynor~~The 650-km-long Mid-Shelf High features three shallow, blocky segments >150 km in breadth, which have only thin sediment cover (<200m). At their shallowest points, the top of basement lies within ~300m of the ice shelf base, at a depth comparable to the basement high at Roosevelt Island. Roosevelt Island is a modern pinning point (Still et al., 2019) owing to the thicker sediment, there (Figure 3b). We introduce the MSH as a prominent pinning point at times of advance and greater extent of the Antarctic Ice Sheet, in keeping with evidence from subglacial sediment records that indicate a major ice flow divide between East and West Antarctic ice during and since Last Glacial Maximum (X. Li et al., 2020; Licht et al., 2014; Coenen et al., 2019).~~). The distinct~~

The prominence of the MSH is due in part to the contrasting geologic properties ~~on either side~~ of the ~~MSH related to West~~East versus ~~Ea~~West Antarctic type crust ~~(Tinto et al., 2019) appear to have controlled the~~and their respective responses to WARS extension. We ~~determined high and homogeneous~~ ~~βfactors~~distinguished β-factors on the TAM-side that are high and uniform, indicating distributed crustal extension. The West Antarctic ~~side's~~side displays lower β-factors ~~indicate lesser extension~~overall, but with ~~specific sites of more~~localized extreme thinning beneath Siple Coast (Figure 4a). The greater amount of extension on the East Antarctic side coincides with the deeper bathymetry (Figure 1a), deeper basement, and thicker sediments (Figure 3).

~~The CH-MSH basement feature trends southward~~ The contrasting properties are also evident in ROSETTA-Ice magnetic and gravity anomalies, used by Tinto et al. (2019) to identify a north-south trending tectonic boundary along the midline of Ross Embayment. The MSH in the magnetic basement coincides with and spans this boundary, which has been further substantiated by passive-seismic studies that show a lithosphericscale boundary (Cheng et al., 2021; White-Gaynor et al., 2019). To the north, the features continue into the Ross Sea's Central High. Southward, the MSH basement feature trends into the TAM, where its western edge aligns with Shackleton Glacier, occupying a major fault separating the distinct geologic domains of the central and southern TAM (Borg et al., 1990; Paulsen et al., 2004~~). Previous authors noted the alignment of the Shackleton Glacier Fault, a 250-km long fault on the south side of the TAM (Drewry, 1972), and~~), which also parallels a prominent magnetic lineament at the South Pole (Studinger et al., 2006). ~~This N-S sequence of structures~~The structure may be an expression of the East Antarctic craton margin or a major intracontinental transform (Figure 4a, Studinger et al., ~~2006). The spatial correspondence of the East-West Antarctic geologic boundary, the N-S series of linear features, and the prominent basement highs suggest the CH-MSH is a major tectonic feature that, through tectonic inheritance (Corti et al., 2007), has influenced the rift architecture and development of Ross Embayment.~~2006).

~~Paleotopographic~~At the time of Oligocene initiation of the Antarctic Ice sheet, paleotopographic reconstructions of the ~~early Oligocene depict a~~ proto-Ross Embayment ~~divided by~~depict a long, ~~narrow mountain~~broad range ~~(the MSH-CH),~~, emergent above sea level (Paxman et al., 2019; Wilson et al., 2012), that we equate to the MSH-CH that divides the Embayment. The CH hosted small ice caps with alpine glaciers ~~and small ice caps (De Santis et al., 1995). These ice caps represent~~formed during the initial glacial stage in the region ~~and once established, were the centers from which~~(De Santis et al., 1995), and continental ice expanded to the outer Ross Sea continental shelf from those centers (Bart & De Santis, 2012). Between the late Oligocene and mid-Miocene, the CH subsided by up to 500m ~~of subsidence and sedimentation occurred~~ (Leckie, 1983; Kulhanek et al., 2019~~) and the CH became covered in~~), receiving 100's of meters of sediment ~~(~~cover (~400m at DSDP 270; De Santis et al., 1995).

The geophysical similarities and continuity between the Ross Sea's CH and the RIS's MSH imply a similar glaciation and subsidence history for the ~~RIS region as for the Ross Sea.~~MSH. A terrestrial/alpine stage for the MSH helps to explain the region's potential to hold the late Oligocene's larger-than-modern ice volumes (Wilson et al., 2013; Pekar et al., 2006~~). Analysis of subglacial sediment identified a major ice flow divide between East and West Antarctic ice since~~), with the ~~Last Glacial Maximum (X. Li et al., 2020; Licht et al., 2014; Coenen et al., 2019). These findings highlight the CH-~~MSH ~~as important features for both~~-CH having a central role in Oligocene ice sheet development and the subsequent evolution of the ice sheet and ice shelf, as is documented in the Ross Sea (Halberstadt et al., 2016).

~~4.3~~4.4 Thermal subsidence and sedimentation

Incorporating the updated basement basin extents and geometries into post-rift thermal subsidence modeling will enable better constrained paleotopographic reconstructions. For the sub-RIS, these reconstructions (Wilson et al., 2012; Paxman et al., 2019) use a post-Eocene subsidence model based on gravity-derived basin geometries and uniform β-factors (Wilson & Luyendyk, 2009). This model predicts uniform stretching of the eastern sub-RIS from the ice front to the Siple Coast, while our β-factors show increasing stretching from the ice front to the Siple Coast. This observed additional thinning likely has resulted in more subsidence for Siple Dome and the north flank of Crary Ice Rise, which can now be accounted for in reconstructions. Our sediment thickness comparison with past models (Text ~~S5~~S6, Wilson & Luyendyk, 2009) shows the majority of the subRIS, especially the Siple Coast, contains more total sediment than previously estimated (Figure S1f). Depending on the age of this sediment, reconstructions may need to account for the additional sediment deposition and loading.

5 Conclusions

Here we present a depth to magnetic basement map for the Ross Ice Shelf (RIS) from Werner deconvolution of airborne magnetic~~s~~ data. The RIS magnetic basement is tied to Ross Sea seismic basement, providing the first synthetic view of Ross Embayment crustal structure. ~~Subtracting~~Using a bathymetry model, we obtain the sediment thickness distribution and calculate crustal extension factors for the sub-RIS. The extensional features we image, resulting from West Antarctic Rift System extension, have continuity with Ross Sea basement structures to the north, and the prominent Mid-Shelf High trends northward into the Ross Sea's Central High. This combined high separates East and West Antarctic type crust, affected by different degrees of continental extension. The Mid-Shelf High was likely subaerial in the Oligocene, able to support alpine ice caps in early Antarctic glaciation~~, and subsequently to form an~~. Subsequently it formed a prominent pinning point and ice flow divide between the East and West Antarctic Ice Sheets.

Newly identified narrow, linear, deep sedimentary basins provide evidence of active faults beneath the Siple Coast grounding zone, where thinned crust overlying anomalous mantle (Shen, Wiens, Anandakrishnan, et al., 2018) likely experiences elevated geothermal heat flow promoting the formation of subglacial water. Faults that control basement margins may accommodate motion caused by the glacioisostatic response to ice sheet volume changes. Subglacial sedimentary basins in this setting likely contain confined aquifers within permeable basin fill. Here, ice overburden pressure would control flow both between and within the subglacial and groundwater systems, possibly localizing geothermal heat. Updated sediment thickness and basin extents should be incorporated into new paleotopographic reconstructions of time intervals of interest for ~~paleoice~~paleo-ice sheet modeling. Our work contributes critical information about Ross Embayment basement topography and subglacial boundary conditions that arise from an interplay of geology, tectonics, and glaciation.

6 Open Research

ROSETTA-Ice and OIB magnetics data are available ~~from~~through https://~~pgg.ldeo.columbia.edu/data.~~ www.usapdc.org/view/project/p0010035. Results from this study are available to download from ~~https://doi.pangaea.de/10.1594/PANGAEA.941238.~~ ~~A~~https://doi.pangaea.de/10.1594/PANGAEA.941238 and a Jupyter notebook documenting our workflow and figure creation is available at https://zenodo.org/badge/latestdoi/470814953.

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Figure 1. **(a)** Bathymetry and sub-ice bed elevations (Morlighem et al., 2020) including ROSETTA-Ice gravity-derived bathymetry (Tinto et al., 2019) beneath the Ross Ice Shelf (RIS). Labels include ice streams and outlet glaciers. **(b)** Basement ~~depths~~elevation from ANTOSTRAT marine seismic compilation in the Ross Sea (Brancolini et al., 1995) and airborne magnetic data from ROSETTA-Ice (over RIS) and Operation IceBridge (~~over Ross Sea).~~black dashed lines). Inset map shows figure location, West Antarctic Rift System (hatched red),~~ and~~ Transantarctic Mountains (dark blue), and ice shelves (light blue). Shelf edge, grounding line, and coastlines in black (Rignot et al., 2013). MODIS imagery from Scambos et al. (2007).
~~MODIS imagery from Scambos et al. (2007).~~

Figure 2. Ross Sea magnetic and seismic basement comparison. Operation IceBridge airborne magnetic data (lower panel) from segment 403~~-1 (Figure 1b).~~1 used in Werner deconvolution to produce magnetic anomaly source solutions (black dots). Filtering removed shallow solutions, and remaining solutions (circles scaled to magnetic susceptibility) were binned and interpolated to produce the magnetic basement (orange line with uncertainty band).~~ Bathymetry from Fretwell et al. (2013). Seismic basement from ANTOSTRAT (Brancolini et al., 1995). See Text S2-S3 for a description of symbols.~~

Figure 3. **(a)** ~~Depth to basement~~Basement elevation (magnetic for Ross Ice Shelf (RIS), seismic elsewhere) contoured at 1km intervals. Pink lines are onshore mapped and inferred faults (Goodge, 2020; Siddoway, 2008; Ferraccioli et al., 2002). White lines are offshore faults (Salvini et al., 1997; Luyendyk et al., 2001; Chiappini et al., 2002; Sauli et al., 2021). Dashed white lines show Mid Shelf High and Western Ross Basin extents. **(b)** Sediment thickness contoured at 1km intervals. Previous basement-imaging RIS seismic surveys (Table S1) are plotted on same color scale, with upper and lower uncertainty ranges as circle halves, where reported. Trunk D Basin outlined in West Antarctica (Bell et al., 2006). Color scales for both a) and b) are set to sub-RIS data range. Colorbar histograms show data distribution for East vs West Antarctic sides of the sub-RIS, separated by the Mid-Shelf High. Inset map shows East vs West divide. Vertical lines on histograms denote average values of each side.

Figure 4. Tectonic interpretation of the sub-Ross Ice Shelf (RIS). **(a)** β stretching factors (Text ~~S5), with sediments removed.~~S6). Colorbar histogram shows data distribution of West vs. East Antarctic sides, same as Figure 3. Black and grey lines indicate inferred active and inactive faults, respectively, with kinematics shown with half-arrows (strike or oblique-slip) and hachures (normal-sense). White lines show previously reported faults, same as Figure 3a. Dashed-white outline is Trunk D Basin (Bell et al., 2006). Black and blue dots show Subglacial Lake Whillans and sedimentary basin from
Gustafson et al. (2021), respectively. Cross-section A-B in red. **(b)** Siple Coast cross-section from A-B, showing basin sediments bounded by faults, with geothermal heat flux (GHF) through the crust (lower panel from Burton-Johnson et al. (2020), upper panel interpreted~~) with implications for subglacial hydrology.~~). Ice surface, ice base, and bathymetry from Morlighem et al. (2020). Ice streams colored by velocity (Mouginot et al., 2019~~).~~; Venturelli et al., 2020). Moho is from Shen, Wiens, Anandakrishnan, et al. (2018).
Lower panel shows ROSETTA-Ice gravity. Named features are labeled on top.

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