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Subglacial Sediments: A Regional Geological Template for Ice Flow in West Antarctica

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Abstract. We use aerogeophysical data to estimate the distribution of marine subglacial sediments and fault-bounded sedimentary basins beneath the West Antarctic Ice Sheet (WAIS). We find that significant ice flow occurs exclusively in regions covered by subglacial sediments. The onsets and lateral margins of ice streams coincide with the limit of marine sediments. Lateral margins are also consistently linked with fault-bounded basins. We predict that the inland migration of ice streams B and C_1 towards the ice divide outside the region covered by marine or rift sediments is unlikely. The subglacial geology has the potential to modulate the dynamic evolution of the ice streams and the WAIS.

Introduction

Evidence is emerging that the conditions beneath the West Antartic Ice Sheet provide a template for ice sheet drainage and disintegration by modulating the ice sheet's response to the long term processes of orbital forcing and climate change [e.g. *Bell et al.*, 1998; *Anandakrishnan et al.*, 1998; *Bindschadler et al.*, 2001; *Blankenship et al.*, 2001; and references herein]. Parts of the interior ice sheet reservoir are drained by fast-moving ice streams (> 100 m/year) separated from their catchment areas by onset regions [e.g. *Alley and Whillans*, 1991]. Within the onset area ice flow switches from slow inland flow, dominated by internal deformation, to streaming flow, dominated by basal sliding. Recent studies show that tributaries of ice flow develop at relatively slow velocities (order of 25 m/year) and that a continuous gradation between these flow states is a transitional flow regime which occurs over a spatially extended area [*Joughin et al.*, 1999; *Bamber et al.*, 2000].

The factors controlling basal sliding and the shift from inland flow to streaming flow are under debate [e.g. *Alley and Whillans*, 1991]. It has been proposed that a highly erodable soft sedimentary bed may play an important role by providing the material that forms a lubricating layer of deformable, basal till [e.g. *Alley et al.*, 1986; *Blankenship et al.*, 1986]. Consequently, ice stream onsets may be linked to the distribution of subglacial sediments [e.g. *Bell et al.*, 1998; *Anandakrishnan et al.*, 1998; *Blankenship et al.*, 2001]. Our goal is to use aerogeophysical data to evaluate the influence of the subglacial sediment distribution in the development of the West Antarctic ice streams.

Subglacial Sediment Distribution

We use a set of airborne geophysical data consisting of subglacial topography and gravity data collected on a 5.3 km grid to estimate the distribution of sediments beneath the WAIS (Figure 1). Acquisition parameters and data reduction are described in *Bell et al.* [1999] and *Blankenship et al.* [2001]. In particular, we evaluate two different types of sediment distribution: regionally blanketing marine sediments and linear fault-bounded sedimentary basins.

Distribution of Marine Sediment Drape

To estimate areas of marine sedimentation, we calculate the isostatically adjusted subglacial topography assuming an Airy type compensation with densities of $910\,kg\,m^{-3}$ for ice and $3300\,kg\,m^{-3}$ for asthenosphere (Figure 1a). Marine sediments likely accumulated in areas below the zero-contour of the rebounded topography (paleo-shoreline) prior to the formation of the WAIS and during periods of ice sheet collapse [*Scherer et al.*, 1998]. Possible errors in this estimate of areas with marine sedimentation include uncertainties in paleo sea-level and elevation of the subglacial topography. However, a change in global sea-level during the deglaciated Mesozoic period would not significantly affect the estimate due to the steep topography. Similarly, a 100 m vertical uncertainty in topography from erosion or subsidence would result in less than 10 km of horizontal position. Our estimate of the spatial coverage of marine sediments is not very sensitive to vertical errors in the steep subglacial topography. The thickness of the marine sediment drape remains unconstrained by our estimation, but *Anandakrishnan et al.* [1998] interpret a thin (< 300 m) marine sediment cover from seismic velocities along a short profile in this region (Figure 1a).

Fault-Bounded Sedimentary Basins

In addition to a regional marine sediment drape, we consider sedimentation in linear fault-bounded basins formed during periods of crustal extension. These fault-bounded basins may have formed during the Jurassic fragmentation of Gondwana [*Dalziel and Elliot*, 1982] or during proposed Cenozoic extension. Within the survey area, a fault-bounded basin with 1.0 - 2.4 km sediment infill beneath an ice stream has been identified by *Bell et al.* [1998] and *Anandakrishnan et al.* [1998] based on gravity, magnetics, and seismic data (dashed line, Figure 1b,c). We interpret a distinct pattern of negative anomalies in free-air and Bouguer gravity as three other fault-bounded sedimentary basins filled with low-density material (outlined by white line in Figure 1b, c). A pair of linear gravity lows flank the

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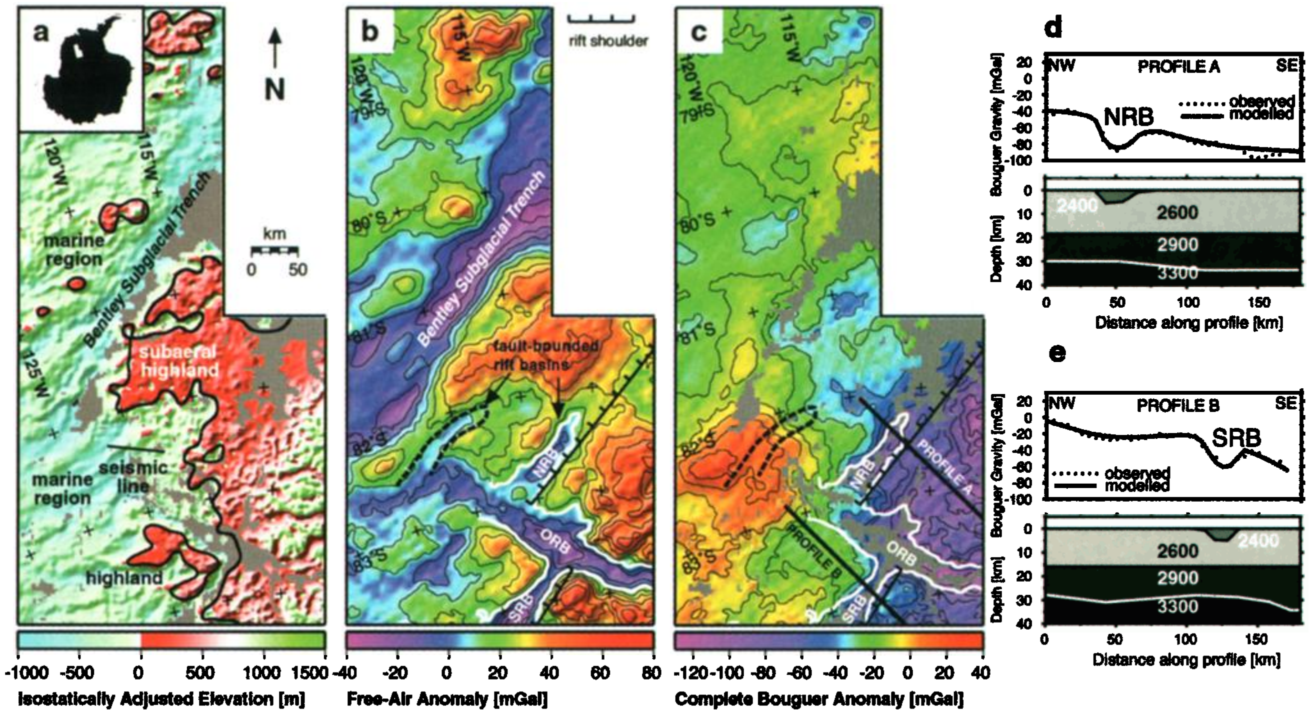

Figure 1. a) Isostatically adjusted subglacial topography map. Grey areas indicate data gaps. b) Free-air gravity anomaly. Contour interval is 10 mGal. Black dashed line outlines sedimentary basin from *Bell et al.* [1998]. Heavy white lines outline fault-bounded sedimentary basins: NRB, northern rift-shoulder basin; ORB, offset rift basin; SRB, southern rift-shoulder basin. c) Complete Bouguer anomaly map. Contour interval is 10 mGal. The Whitmore Mountains crustal block is the region southwest of the rift shoulder. d) and e) Gravity models along Profiles A and B. For locations see c). Densities are given in kg/m^3.

shoulder of the Whitmore Mountains crustal block (northern rift-shoulder basin, NRB, and southern rift-shoulder basin, SRB, Figure 1b, c). These two basins appear to be offset by an elongated gravity low (offset rift basin, ORB, Figure 1b,c).

To constrain the sediment infill, we construct models of the gravity anomalies. Crustal thickness and densities at the northwestern end of Profile A were controlled by the refraction seismic model of *Clarke et al.* [1997] and regression parameters from *Christensen and Mooney* [1995] to convert the velocity model into a density model. Along Profile A, a 5-km-thick low-density body between km 35 and 70 is necessary to match the modeled and observed gravity (Figure 1d). A similar sediment infill of more than 5 km thickness is required along Profile B between km 105 and 135 marking the basin (Figure 1e). The absence of ice thickness measurements along the ORB precludes reliable gravity modeling of the sediment infill. However, the similarity in free-air and Bouguer gravity signatures between the ORB and SRB-NRB basins suggests a significant sediment infill for the ORB.

Linking Ice Stream Tributaries and Sediment Distribution

Marine Sediment Cover

A dentritic pattern of ice stream tributaries in the catchment area of ice streams *B*, *C* and *D* has been mapped by satellite radar interferometry [*Joughin et al.*, 1999] and ground-based GPS measurements [e.g. *Price and Whillans*, 1998] (Figure 2). These measurements suggest that velocities as high as 50 m/year extend over much of the Bentley Subglacial Trench (BST) [*Joughin et al.*, 1999; *Price and*

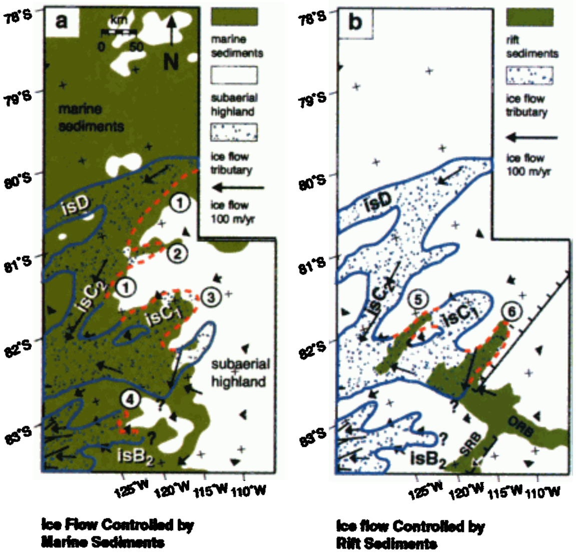

Figure 2. Distribution of marine sediments a) and fault-bounded sedimentary basins b). Ice flow tributaries are outlined by a smoothed 25 m/year velocity contour from *Joughin et al.* [1999] with the exception of the small tributary marked by 2 (10 m/year). Arrows indicate velocities from *Price and Whillans*, 1998. Dashed line marks regions were ice flow appears to be controlled by the distribution of sediments. Question marks indicate data gaps in the interferometric velocity grid. See text for numbers.

Whillans, 1998]. Some of the ice emerging from the BST appears to flow into tributaries of ice stream D (isD) while much of the flow merges into ice stream C_2 (isC_2) at 82°S. Upstream of this convergence, rapid ice flow along ice stream C_1 (isC_1) reaches into the interior of the WAIS. A similar dendritic pattern of flow is imaged in the catchment region of ice stream B_2 (isB_2).

The boundary of marine sediment cover coincides with the onset and the lateral margins of ice flow in several locations (red dashed lines, Figure 2a). In the BST, both the regional flow and the development of a small tributary are linked to the distribution of marine sediments. The southeastern lateral margin of the ice flow coincides well with the estimated paleo-shoreline for over 200 km (No 1, Figure 2a), only interrupted by a narrow embayment. This embayment, which probably contains marine sediments, is occupied by a slow but distinct tributary flowing at < 25 m/year out of a region of slow velocities of < 10 m/year (No 2, Figure 2a). To the south along the isC_1 tributary, the ice flow along the lateral margins and onset of tributary isC_1 coincide well with the location of the paleo-shoreline. (No 3, Figure 2a).

Among the isB_2 tributaries, several lateral margins appear to be controlled by the distribution of marine sediments. The paleo-shoreline defines a highland (No 4, Figure 2a) with the tributaries developing on either side. Each tributary is developing in a region covered by marine sediments and the lateral margins roughly parallel the paleo-shoreline. Along the southern boundary of our survey area, the southern rift basin is associated with a paleo-shoreline on either side. Although within the survey area, the ice velocities over these marine sediment are slow (28 m/year), fast-moving ice (112 m/year) develops less than 10 km to the southwest outside the survey area (121.4°W, 84.2°S) in the continuation of this basin (not shown in Figure 2).

Fault-Bounded Sedimentary Basins

An acceleration of ice flow and a focus of flow directions occurs within all four fault-bounded rift basins in the catchment area of isB and isC. *Bell et al.* [1998] and *Anandakrishnan et al.* [1998] report a close link between the lateral margins of tributary isC_1 and the TRB in the southwestern portion of the catchment area (No 5, Figure 2b). Over the NRB, the ice has an elevated velocity of about 86 m/year measured at 115°W, 82.5°S and flows at an oblique angle to the regional ice flow but roughly parallel to the strike of the underlying rift basin (No 6, Figure 2b). This sedimentary basin does not have a well defined linear trench but is characterized by isolated deeps (Figure 1a) suggesting that the distribution of sediments is the guide for rapid ice flow and that topographic trenches are not a necessary condition. Above the ORB, the only available ice surface velocity measurements are located at the northwestern end of the basin (121.75°W, 82.75°S, 49 m/year) and at the northeastern boundary (114°W, 83.25°S, 38 m/year). Both velocity vectors parallel the strike of the underlying geologic structure. A fast-moving ice stream develops over the SRB paralleling the long axis of the basin.

Discussion

Transition from Deformation Flow to Sliding

The precise location where basally lubricated motion becomes the dominant process of ice flow is impossible to locate from surface measurements alone. *Joughin et al.* [1999] interpret basal sliding in the northeastern portion of the BST from relatively low velocities (< 50 m/year). Our interpretation of ice flow controlled by distribution of subglacial sediments is based on the assumption that the transition from sheet to ice stream flow takes place continuously over a large area with relatively slow speeds [*Bamber et al.*, 2000].

Influence of Subglacial Topography

Subglacial topography, specifically topographic steps, have been advanced as exerting an influence on ice flow [e.g. *McIntyre*, 1985; *Bentley*, 1987]. Ice flow along the BST, however, seems to develop without the control of a topographic step. The absence of a distinct step in the free-air gravity anomaly within the region of poor radar recovery suggests that no major topographic step is associated with the onset of rapid ice flow in this region.

Similarly, we anticipated rapid ice flow would develop in subglacial channels. In fact, three deep subglacial valleys aligned perpendicular to the southeastern survey boundary (No 1-3, Figure 1a) are not associated with rapid ice flow. *Blankenship et al.* [2001] rule out the possibility of ice streaming in this region based on their interpretation of driving stress. Although we do not exclude the contribution of subglacial topography to the initiation of ice flow, our observations suggest that subglacial sediments are a necessary condition for the development of significant ice flow.

Conclusions

Significant ice flow occurs exclusively in regions covered by subglacial sediments. The boundaries of ice flow and subglacial sediment coincide closely. The correlation is evident for both linear sedimentary basins and for the widespread marine sedimentation, suggesting that sediments can provide a template for ice flow. Subglacial sediments appear to be a vital condition for the development of significant ice flow and consequently have the potential to influence location and migration of ice stream onsets. We predict the onsets of ice streams B and C_1 will not migrate inland towards the ice divide outside the region covered by marine or rift sediments. The subglacial geology plays an important role in the dynamic behavior of the West Antarctic ice streams and it can modulate the dynamic evolution of the ice sheet.

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