East Antarctic ice stream tributary underlain by major sedimentary basin

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ABSTRACT

Marine and rift sediments exert a fundamental control on ice stream flow in the West Antarctic Ice Sheet, and hence on its mass balance and stability. In contrast, most ice streams in the much larger East Antarctic Ice Sheet are thought to be relatively stable features resting on till, perhaps underlain by crystalline rock. Any geological controls on East Antarctic Ice Sheet enhanced flow remain largely unknown. We present aerogeophysical evidence indicating that a region of enhanced ice flow in the interior of the East Antarctic Ice Sheet is underlain by subglacial sediments ~3 km thick and that these are influencing the flow regime of the overlying ice. We show that subglacial sediments are important in modulating ice dynamics, not just for the West Antarctic Ice Sheet, but also for its much larger neighbor, and suggest that the sedimentary basin identified here may contain information on the Neogene glacial history of this part of the East Antarctic Ice Sheet.

Keywords: East Antarctica, marine sediments, magnetics, subglacial geology.

INTRODUCTION

Recent measurements of ice velocity from synthetic aperture radar interferometry (InSAR) and estimates of the depth-averaged, steady-state velocity of the Antarctic ice sheet (known as balance velocities) indicate a complex pattern of enhanced ice flow involving ice stream tributaries extending hundreds of kilometers into the interior of both the West and the East Antarctic Ice Sheets (Bamber et al., 2000; Joughin et al., 1999). In several cases structural controls have been suggested for enhanced flow systems in the East Antarctic Ice Sheet (e.g., the Lambert Glacier system and Jutulstraumen, Dronning Maud Land; Hoydal, 1996; Taylor et al., 2004). In general, however, it is unclear what controls the location, temporal stability, extent, and speed of enhanced flow systems in East Antarctica. For parts of the West Antarctic Ice Sheet, the presence of water at the bed combined with deformable subglacial sediments deposited in fault-bounded rift basins and regionally blanketing marine sediments have been shown to be critical (Bell et al., 1998; Studinger et al., 2001; Tulaczyk et al., 1998). As a consequence, considerable effort has focused on understanding and modeling the properties of these subglacial sediments (Tulaczyk et al., 1998, 2000). Despite the fact that the East Antarctic Ice Sheet contains 10 times the volume of ice compared to the West Antarctic Ice Sheet and possesses extensive areas of enhanced flow, the influence of subglacial sediments on the dynamics of the East Antarctic Ice Sheet has not been considered to date. This is largely due to the lack of appropriate geophysical data for the interior of the East Antarctic Ice Sheet, and limited studies addressing the relationship between ice dynamics and geological boundary conditions. Here we analyze a suite of airborne geophysical data from the onset region of Slessor Glacier, Coats Land, and demonstrate that the deepest tributary is underlain by a 3-km-thick sedimentary basin. With the aid of an ice flow model, we suggest that the ice dynamics are influenced by the presence of the sedimentary basin. Finally, by analogy with the Lambert Glacier system in East Antarctica, we hypothesize that the sedimentary basin may imply a dynamic glacial history for this part of the East Antarctic Ice Sheet during the Neogene.

RESULTS

We conducted an airborne geophysical survey of the onset area of an enhanced flow unit, Slessor Glacier, Coats Land, during the Austral summer of 2001–2002 (Fig. 1). Radio-echo sounding (RES) data recorded ice thickness and proxy information on basal roughness (Rippin et al., 2003), and a magnetometer provided total magnetic intensity (TMI) measurements to image subglacial geology. The RES data revealed several subglacial troughs (labeled T1–T4 in Fig. 2) in which the three tributaries of Slessor Glacier lie. The deepest trough, T1, contains Slessor Tributary North, where bed elevations are more than 800 m below sea level. (Note that this was incorrectly described as a tributary of Bailey Ice Stream in our original analyses, but the InSAR velocity data clearly show that this is a tributary of Slessor Glacier.) There is also a trough extending perpendicular to the direction of ice motion (T4) at the eastern end of the area surveyed, that is at a similar depth (Fig. 2) but further inland. After isostatic adjustment and taking into account raised sea levels in the past (Hughes, 1998), parts of T1 would be below sea level if it were ice free now, and most probably was during the last ice-free period. This is a conservative estimate of the submerged area because it does not consider the possibility of partial deglaciation (when isostatic rebound would be less). Estimates of basal roughness, derived from the statistics of the RES bed returns, indicate a particularly smooth ice-bed interface in T1 (Rippin et al., 2004), due most probably to a soft basal layer of till and/or subglacial erosion via basal sliding. Highest roughness was identified in intertributary areas, with low ice flow rates (10 m yr^{-1}). An ice flow model was used to estimate the proportion of ice motion due to internal deformation and basal motion (Rippin et al., 2003). The model provides a conservative estimate of the relative importance of basal motion, as the value of 8 for the ice rheology enhancement factor used is at the upper limit of accepted values (Budd and Jacka, 1989). More than 50% of the total ice speed was found to be due to basal motion in T1 beneath Slessor Tributary North, the contribution of basal motion beneath the other tributaries being insignificant (Fig. 3). This could be due to either

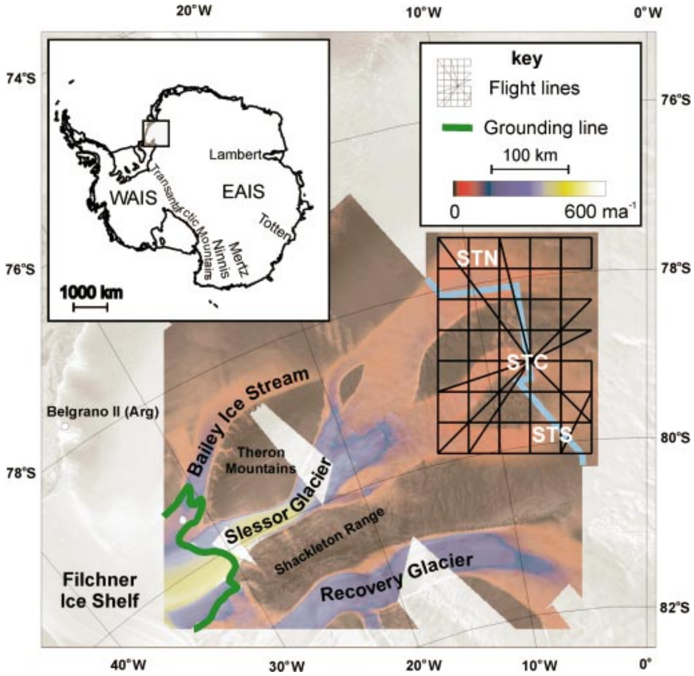

Figure 1. Map showing location of airborne geophysical survey with respect to Bailey ice stream, Recovery Glacier, and Slessor Glacier and its tributaries. STN—Slessor Tributary North, STC—Slessor Tributary Central, STS—Slessor Tributary South; WAIS—West Antarctic Ice Sheet, EAIS—East Antarctic Ice Sheet. Background is from RADARSAT Antarctic Mapping Project (RAMP) mosaic of Antarctica (Jezek et al., 1998). Grounding line is shown by solid green line. Velocities are combination of interferometric synthetic radar aperture data from RADARSAT (Joughin and Bamber, 2005; Joughin and Padman, 2003) west of blue line and balance velocities (Bamber et al., 2000) to east.

basal sliding or subglacial till deformation (Blankenship et al., 2001), both of which require the presence of basal meltwater (i.e., a wet bed).

TMI anomaly data provide information about magnetic sources relating to geology at both shallow and deep crustal levels. By high-pass filtering the TMI data with a 9 km cutoff wavelength, we removed the long-wavelength variations that are related to the deep geological structures. The results are expressed in terms of amplitudes of residual (AoR) anomalies that image the near-surface geological features (Blakely, 1995). The AoR values calculated along the flight lines were interpolated to cover the whole region, and the results are shown in Figure 4. The full range of values in the AoR was from 0 to 40 nT (the upper limit plotted in Fig. 4 is 10 nT to highlight low AoR regions) with a noise level of 0.5 nT. An anomalously low ($<$1 nT) AoR area exists in the vicinity of T1, which coincides closely with the region estimated to have been below sea level at some time in the past. The low AoR area is due to a ‘‘nonmagnetic’’ layer, probably sedimentary material (Carmichael, 1989), with its top coinciding with the upper bedrock surface of T1. Forward and inverse modeling of the TMI data both indicate that the thickness of the nonmagnetic layer is $\sim$3 $\pm$ 1 km. This layer is interpreted as delineating a major sedimentary basin underlain by magnetic basement (see Data Repository material[1]). We interpret high-frequency magnetic anomalies over the survey area (i.e., high AoR values) as delineating Jurassic sills and dikes, based upon comparable magnetic signatures over outcrops of these rocks in the

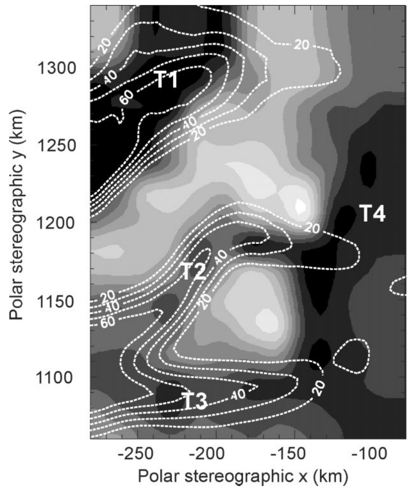

Figure 2. Bed topography with respect to present-day sea level for region derived from radio echo-sounding data. Range shown is from −850 (in black) to 600 m (in white) above sea level. Four basal troughs are marked T1–T4. Combined synthetic aperture radar interferometry and balance velocity contours are plotted in white at 10 m yr⁻¹ intervals.

Shackleton Range and Theron Mountains area (Tessensohn et al., 1999). The low AoR signature over T1 is attributed to post-Jurassic sedimentary infill within a structurally controlled half-graben (Tessensohn et al., 1999) underlying Slessor Tributary North (Fig. DR2; see footnote 1).

DISCUSSION

Four independently derived geophysical variables (bed elevation, basal roughness, magnetic anomalies, and modeled basal motion) strongly support the hypothesis that the basal trough T1 is underlain by a thick ($\sim$3 km) layer of subglacial sediment that is influencing the ice motion overlying it. The thickness, topographic setting, and magnetic signature of the sedimentary basin suggest it is likely of marine

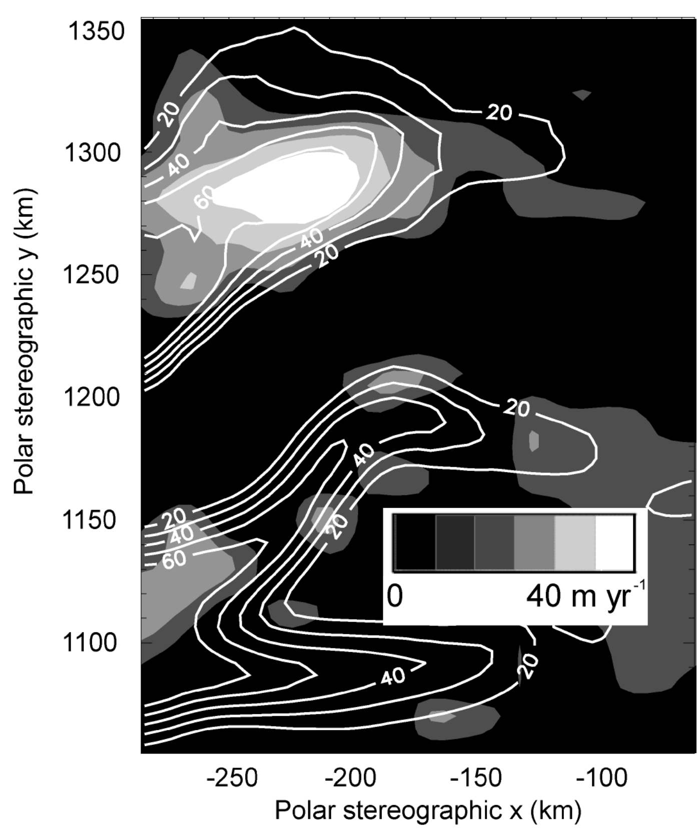

Figure 3. Shaded contour plot of modeled basal motion values. Solid white lines are contours of merged synthetic aperture radar interferometry and balance velocities as in Figure 2.

[1]GSA Data Repository item 2006006, Figures DR1, DR2, and description of airborne magnetic data processing, is available online at http://www.geosociety.org/pubs/ft2006.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

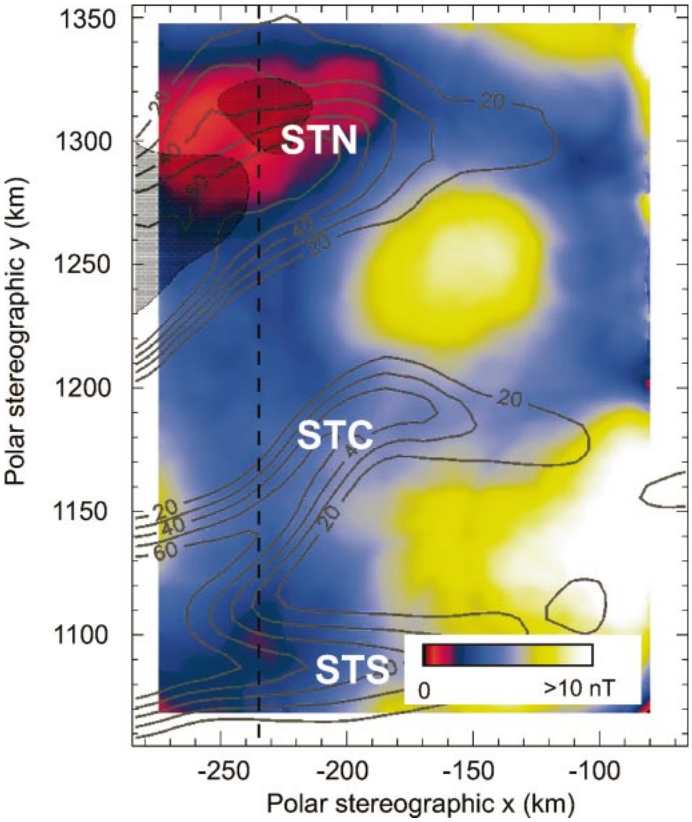

Figure 4. Color-shaded plot of magnetic AoR (amplitudes of residual) anomalies (in nT), interpolated onto 5 km grid. Combined synthetic aperture radar interferometry and balance velocity contours are overlain in black at 10 m yr^{-1} intervals. Region of bedrock calculated as being below sea level after isostatic adjustment is shown by hachured area in upper left corner and is roughly coincident with area of low AoR, shaded red. Flight line discussed in Data Repository material (see footnote 1) is indicated by black dashed line. STN—Slessor Tributary North, STC—Slessor Tributary Central, STS—Slessor Tributary South.

origin. This has two important implications relating to (1) controls on ice dynamics, and (2) the glacial history of this part of the continent. We consider these implications in turn.

First, we note as additional evidence for the influence of the sediment on ice dynamics that the driving stresses in the low AoR area (Fig. 4), which are in the range ~45–50 kPa, are lower than for the other two tributaries and are similar to values for tributaries of the Siple Coast ice streams in West Antarctica (Bindschadler et al., 2001). These ice streams are also known to be underlain by marine and rift sediments (Bell et al., 1998; Blankenship et al., 2001), which are believed to be important in modulating the dynamic behavior of the overlying ice by providing a source of deformable, water-saturated till at the bed (Alley et al., 1986). The fact that basal motion appears to be important only in T1 beneath Slessor Tributary North supports the hypothesis that the sediments are influencing the ice dynamics. It also raises the question of whether ice motion in other parts of the East Antarctic Ice Sheet could be influenced by subglacial sediments. We note, for example, that several enhanced flow features elsewhere in East Antarctica are in areas that could have been submerged at some time in the past. Major regions of enhanced flow (e.g., Totten, Mertz, and Ninnis Glaciers; see Fig. 1 for locations) are associated with basal troughs that are below sea level after isostatic adjustment. The onset region of Totten Glacier appears to coincide with the location of an extensive basal depression ~170 m below sea level. These flow features may or may not have melting at their base at present. If they do not, and a layer of deforming sediment is not currently contributing to the ice motion, then a potential mechanism exists for a rapid increase in ice velocity and hence discharge if melting at the bed occurs in the future. This has important implications for our understanding of the mechanisms controlling the stability of ice flow throughout the continent and for predicting future changes in flow regime via numerical modeling.

The sedimentary basin beneath Slessor Tributary North is ~480 km from the nearest present-day coastline and is 530 km upstream of the present-day grounding line location (Fig. 1). The deposits, if marine in origin, must have formed at a time when this part of East Antarctica was deglaciated. The area of very low AoR suggests that the sedimentary basin likely includes post-Jurassic rocks, but their precise age and origin cannot be directly determined without drilling. Here we present one possible interpretation of the results based on modeled and observed subglacial erosion rates. We stress, however, that this is not the only interpretation that would be consistent with the observations.

A recent modeling study of Ice Stream C, West Antarctica, calculated highest erosion rates for the tributary region (0.6 mm yr^{-1}) in a glaciological setting analogous to Slessor Tributary North (Bougamont and Tulaczyk, 2003). Using this value, it would take only ~1.7 m.y. for Slessor Tributary North to erode a trough to the depth of T1, starting from a flat bedrock. That the sedimentary basin has been preserved suggests that this part of East Antarctica has seen substantial changes in either the pattern of ice flow and/or glaciated extent during the Neogene. If the ice sheet persisted in this region for 25 m.y., for example, then the implied erosion rate beneath the tributary is ~0.04 mm/yr, which is at the lower end of glacial erosion rates observed in nature, and a rate that is more typical for ice frozen to resistant, crystalline bedrock than for temperate ice moving over a sedimentary basin (Hallet et al., 1996). Although it is not possible from the aeromagnetic data alone to determine sediment age, based on the preceding arguments we speculate that the sediments within the graben underlying Slessor Tributary North could potentially contain information on the Neogene history of this part of the East Antarctic Ice Sheet, as is the case for the sediments deposited in the Lambert graben area, Mac Robertson Land (Fig. 1). There, major fluctuations in ice sheet extent involving ice-frontal recessions of several hundred kilometers during the Neogene have been identified (Hambrey and McKelvey, 2000). This may have been due to more temperate climate and glacial conditions in this part of East Antarctica during the Pliocene (Hambrey and McKelvey, 2000; Wilson et al., 2002) or to a structurally controlled ice stream flowing within the Lambert graben (Taylor et al., 2004). Recent ice core results suggest a homogeneous climate variability across the East Antarctic plateau over at least the last three glacial cycles (Watanabe et al., 2003). It seems likely, therefore, that a climate-induced fluctuation in glacial extent within the Lambert basin would also affect the Slessor-Bailey region.

The presence of subglacial sedimentary basins in the interior of the East Antarctic Ice Sheet is important to the debate on the glacial history of the ice sheet (Webb et al., 1984; Wilson et al., 2002) and also for our understanding of the controls on ice dynamics (Alley et al., 1986; Blankenship et al., 2001), yet geophysical evidence for such basins has until now been highly controversial (Drewry, 1976; Ferraccioli et al., 2001; Studinger et al., 2004; tenBrink et al., 1997). This is the first geophysical study to provide evidence for a major sedimentary basin beneath an East Antarctic Ice Stream tributary, suggesting that subglacial sediments may modulate enhanced ice flow in both West (Bell et al., 1998; Studinger et al., 2001) and East Antarctica. The sedimentary basin we identified here is an ideal site for a drilling program that could address both the glaciological properties of the sediments and their depositional history within the largest drainage basin in East Antarctica (Vaughan et al., 1999).

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