New boundary conditions for the West Antarctic ice sheet: Subglacial topography beneath Pine Island Glacier

David G. Vaughan[1], Hugh F. J. Corr[1], Fausto Ferraccioli[1], Nicholas Frearson[1], Aidan O'Hare[1], Dieter Mach[2], John W. Holt[3], Donald D. Blankenship[3], David L. Morse[3], Duncan A. Young[3].

Abstract

Predictions about future changes in the Amundsen Sea sector of the West Antarctic ice sheet (WAIS) have been hampered by poorly known subglacial topography. Extensive airborne survey has allowed us to derive improved subglacial topography for the Pine Island Glacier basin. The trunk of this glacier lies in a narrow, 250-km long, 500-m deep sub-glacial trough, suggesting a long-lived and constrained ice stream. Two tributaries lie in similar troughs, others lie in less defined, shallower troughs. The lower basin of the glacier is surrounded by bedrock, which, after deglaciation and isostatic rebound, could rise above sea level. This feature would impede ice-sheet collapse initiated near the grounding line of this glacier, and prevent its progress into the deepest portions of WAIS. The inland-slope of the bed beneath the trunk of the glacier, however, confirms potential instability of the lower basin, containing sufficient ice to raise global sea by ~24 cm.

1 Introduction

Pine Island Glacier drains around 175 000 km^2 of West Antarctica, and has a complex system of tributaries feeding the main ice stream [*Stenoien and Bentley*, 2000]. Ice flow close to the grounding line is unusually fast (>2.5 km a^{-1}) and its flux is one of the largest in Antarctica. Recent satellite studies have produced the most comprehensive mapping of

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[1] British Antarctic Survey, Natural Environment Research Council, Madingley Road, Cambridge, CB3 0ET, United Kingdom

[2] Optimare Sensorsysteme AG, Am Luneort 15, D-27572 Bremerhaven, Germany.

[3] Institute for Geophysics, University of Texas at Austin, 4412 Spicewood Springs Rd, Bldg 600, Austin, TX 78759, USA.

change for any Antarctic ice stream: between 1992 and 2001 the ice stream and its inland basin thinned [*Shepherd et al.*, 2004]; during the period 1992–98, the grounding line retreated at a rate of almost one kilometre per year [*Rignot*, 1998]; two episodes of acceleration have been observed (1974-87 and 1994-2000) separated by around seven years of steady flow [*Joughin et al.*, 2003; *Rignot et al.*, 2002], and this acceleration of 22 % appears to be responsible for the present imbalance in the Pine Island Glacier basin; the floating portion the ice stream, its ice shelf, has been thinning for almost three decades [*Bindschadler*, 2002], although the position of the ice front has not shown any clear trend over the last 50 years [*Rignot*, 2002].

Although change throughout the Pine Island Glacier basin and the other glaciers of the Amundsen Sea Embayment (ASE) is now established, it has yet to be determined whether these changes are evidence of ongoing deglaciation or simply a fluctuation that does not threaten the equilibrium of the ice sheet. The use of numerical models to make predictions in this regard is, however, significantly hampered by the lack of a good sub-glacial topography on which to base such models. The BEDMAP compilation, for example (Figure 1a) [*Lythe et al.*, 2001], used data from oversnow traverses and a handful of airborne surveys flights, and so gives only a broad picture of the subglacial topography.

During the austral summer of 2004/05 a collaborative US/UK field campaign undertook a systematic geophysical survey of the entire Amundsen Sea embayment using comparable airborne survey systems mounted in Twin Otter aircraft. Here we present the portion of the survey covering the Pine Island Glacier basin led by British Antarctic Survey. A companion paper [*Holt et al.*, in press] provides a description of the survey covering Thwaites, Smith and Kohler glacier basins undertaken by University of Texas.

2 Data acquisition

Operating from a temporary field camp (PNE, S 77° 34’ W 095° 56’) during the 2004/05 austral summer; we collected ~35,000 km of airborne survey data. Our aircraft was equipped with dual-frequency carrier-phase GPS for navigation, radar altimeter for surface mapping, wing-tip magnetometers, gravity meter, and a new ice-sounding radar system (PASIN). In this paper, we describe results arising from the measurement of surface and ice-thickness.

Throughout the campaign, PASIN was configured to operate with a transmit power of 4 kW around a central frequency of 150 MHz. A 0.1-μsec pulse optimized for imaging the near-surface layering was interleaved with a 4-μsec, 10-MHz chirp that was used to successfully obtain bed-echoes through ice more than 4200 m thick.

Post-processing of GPS data allowed determination of aircraft positions to better than ± 1 m. The network acquired during the 30 flights of the campaign is shown in Figure 1b. Most flights (~25) were in a regular 30-km grid flown at the constant elevation required for the acquisition of gravity data. Five flights over the main trunk and tributaries of Pine Island Glacier, on which gravity data were not acquired, were flown at a constant 150-m terrain clearance to optimize radar data.

Travel-time was converted to ice thickness assuming a wave-velocity of 168 m / µsec, with a uniform addition of 10 m to account for presence of low-density ice in the near surface. Crossover analysis yielded RMS differences of around 23 m in ice thickness. These differences are substantially greater than the wavelength of 150 MHz radio waves in ice (~1 m), and result largely from off-nadir reflections and interpretation/digitizing uncertainty.

3 Topographic analysis

The bed elevation data collected during this campaign were combined with other data (Figure 1b) to produce a new subglacial topography (Figure 1c) using techniques described elsewhere [*Holt et al.*, in press]. Where the ice thickness measurements were not tied to precise GPS measurements of surface elevation, we extracted surface elevation from a digital elevation model derived from satellite altimetry [*Bamber and Gomez-Dans*, 2005]. A digital version of this grid is available from the National Snow and Ice Data Center (www.nsidc.org).

4 Discussion

While it might be argued that the new subglacial topography shows no new regional-scale features, the primary objective of this survey was to provide a subglacial topography on which to build a capacity for predictive ice-sheet modelling, and in this respect, even without sophisticated modelling the topography permits some valuable conclusions to be drawn.

All of the subglacial troughs in this region are narrower and deeper than suggested by the BEDMAP topography. In particular, the Byrd Subglacial Basin (BSB) is, at its narrowest point, only 30 km wide but reaches a depth of 2300 m below sea level, and, in places, is more than 1000 m deeper than the surrounding bed. The confluence of BSB and the Bentley Subglacial Trench (BST) is now clearly delineated.

The northern edge of the Ellsworth Subglacial Highlands (ESH) is more abrupt than previously thought, and we can for the first time resolve a series of sub-glacial valleys that emerge from ESH into the BST. It is probable that these features formed at a time when ice did not fill BST but a small ice cap drained from ESH through small glaciers that shaped these valleys.

In other parts of WAIS the palaeo-shoreline calculated for de-glacial (isostatically-rebounded) topography, provides a good template for the onset of fast ice-flow [*Blankenship et al.*, 2001; *Studinger et al.*, 2001]. This was justified by reasoning that the presence of marine sediments provides the conditions required to initiate streaming flow, and such sediments only accumulate below the de-glacial shoreline. Comparison of ice-flow speeds (Figure 1e) and de-glacial topography (Figure 1f, calculated assuming Airy compensation, allowing for an in-flux of ocean water but neglecting flexural rigidity of the lithosphere) shows no similar correspondence in this area. It is clear that the distribution of fast-ice-flow in Pine Island Glacier basin is strongly controlled by the sub-glacial topography. The trunk of Pine Island Glacier and its two major tributaries [tributaries, 5 and 3, identified by *Stenoien and Bentley*, 2000] occupy deep sub-glacial troughs between 700 and 1000 m lower than adjacent bed. Shallower (<500 m) and much less distinct troughs lie beneath the six other tributaries (1, 2, 4, 6, 7 and 9) now visible in the velocity map. Figure 1f shows, however, that during de-glacial conditions the majority of the Pine Island Glacier basin was far below sea level, and in this area, there is no simple correspondence between fast ice-flow and palaeo-shoreline.

The inland divide of the Pine Island Glacier drainage basin has been delineated by several authors based solely on surface slope [e.g. *Vaughan et al.*, 2001]. Each has suggested the existence of a northern basin comprising the main trunk or the glacier and tributaries, and a more slowly draining southern basin, overlying BST, BSB and part of ESH. A narrow “neck” overlying BSB apparently separates the two portions of the basin. Given the presence of a bed-high (marked H in Figure 1c,f), which is in places <400 m below sea level, it might appear that ice in the southern basin would most easily drain by joining ice flowing west along BSB and into the Thwaites Glacier. The, ice-velocity measured at PNE camp during its occupation (14 m a^{-1}, along 014°T), however confirms ice-flow parallel to the surface slope and that the basin shape drawn by previous authors was broadly correct.

The fact that bed-high H does not currently impede ice-flow from the southern to the northern basins does not, however, mean that this feature is insignificant. Together, the areas of high bed on the northern margins and bed-high H, effectively encircle the northern basin. If the ice sheet in this area were to be lost, the isostatic rebound would bring the highest parts of this bed high H above sea level. So although, there appears to be no substantial bed sill inland of the present grounding line that might halt a future retreat into the northern basin, the inland-rising bed slope around bed-high H (Figure 1d) suggests that a collapse would eventually be constrained to the northern basin and would not reach the deepest parts of WAIS beneath BSB and BST. The volume of ice residing above the floatation limit in the northern basin is equivalent to 24 cm of global sea level rise, while that in the southern basin is equivalent to 28 cm of global sea level rise.

This inference needs to be contrasted with Thwaites Glacier [*Holt et al.*, in press] where, except from short-wavelength roughness, the bed slopes inland monotonically from the grounding line to the deepest part of BSB. Hughes identified Pine Island and Thwaites glaciers as the “weak underbelly of the WAIS” [*Hughes*, 1981], the portion most likely to suffer dynamic collapse. Our sub-glacial topography appears to show that while northern basin of Pine Island Glacier may well be prone to collapse, Hughes’ epithet may now be more appropriate to Thwaites Glacier alone.

5 Conclusions

The new sub-glacial topography derived for Pine Island Glacier basin is a clear improvement on that derived by BEDMAP and will provide the basis for improved predictions of whether recent changes observed in this area are evidence of ongoing deglaciation, or simply fluctuations that do not seriously threaten the long-term equilibrium of the ice sheet.

It is now clear that sub-glacial character of Pine Island Glacier is similar to those in the Weddell Sea sector of WAIS (e.g. Rutford Ice Stream) in that its trunk and main tributaries lie in deep and confined topographic channels that probably represent some pre-glacial geologic features. Thwaites Glacier, on the other hand, more nearly resembles the Siple Coast Ice Streams by lying in a broad but poorly defined trough. It may be reasonable to implicate this difference as the cause of the contrasting ways by which each may have increased its flux in the last decade: it was reported [*Rignot et al.*, 2002] that Pine Island Glacier had maintained its width but accelerated, while Thwaites Glacier maintained its speed but widened. A comprehensive understanding of both styles of drainage will thus be required to fully predict the future stability of Amundsen Sea Embayment of West Antarctica.

The existence of a bed-high surrounding the lower portion of the PIG basin, suggests that a collapse initiated along the trunk of PIG would not progress catastrophically into the southern basin and the deepest parts of WAIS. However, collapse of the northern basin alone would raise sea level by 24 cm and there appears to be no bed topography that might halt a retreat from the present grounding line into the northern part of the basin. This means that the Pine Island Glacier basin still represents a significant threat to sea level over coming centuries.

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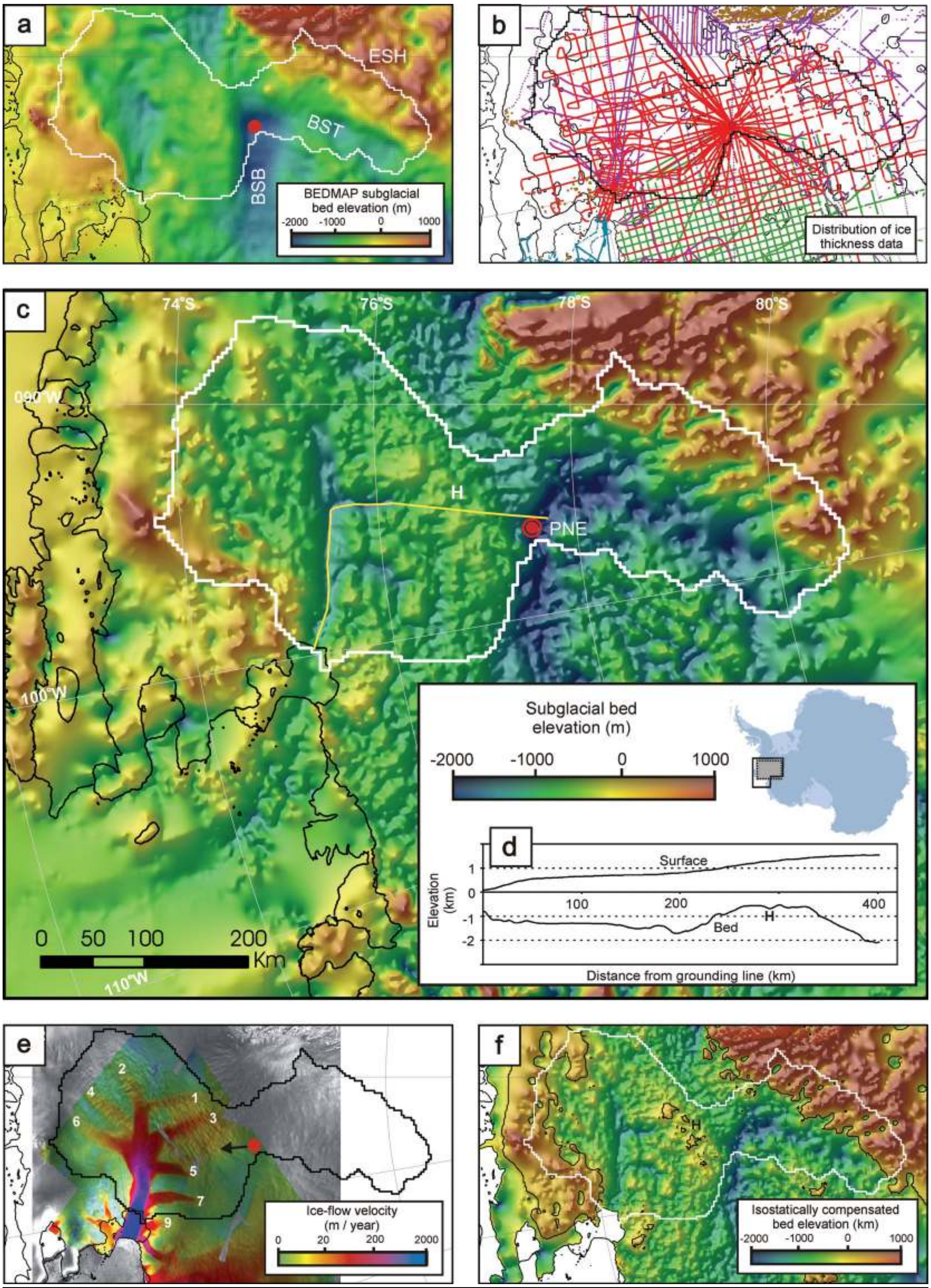

8

Figure Caption

Figure 1 – Subglacial topography of Pine Island Glacier basin. A. BEDMAP subglacial topography [Lythe et al., 2001], on this and other frames grounding lines and icefronts are shown by black lines, PIG drainage basin by white line (black in frames b and e) location of PNE by a red spot, also identified are Byrd Subglacial Basin (BSB), Bentley Subglacial Trench (BST) and Ellsworth Subglacial Highlands (ESH). B. ice-thickness data used to create present subglacial topography including data: acquired by NASA/CECS [Rignot et al., 2004] ITASE [Jacobel and Welch, 2005] and BAS [unpublished] shown in purple; bathymetric data acquired during various US cruises [http://www.ngdc.noaa.gov/] in blue; acquired by BAS (red) and University of Texas (green) during the 2004/05 campaign. C. New subglacial topography, with location of the profile (d) shown by the yellow line, and the location of bedrock high, H, marked. D. a representative profile of ice surface and bed elevation. E. ice-velocity derived from InSAR by Rignot [2004], with tributaries numbered according scheme given by Stenoien and Bentley [2000], the ice-flow direction measured during occupation of PNE is indicated by the arrow. F. subglacial topography allowing for isostatic (Airy) compensation with palaeo-shoreline (0-m contour) shown in black. Inset on legend to c shows locations of areas covered by frames c (full line) and a, b, e and f (dotted line and shading). In each case the range of the colour-scale does not include the extremes of the topographic range.