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Topographic controls on post-Oligocene changes in ice-sheet dynamics, Prydz Bay region, East Antarctica

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ABSTRACT

Within the general trend of post-Eocene cooling, the largest and oldest outlet of the East Antarctic Ice Sheet underwent a change from ice-cliff to ice-stream and/or ice-shelf dynamics, with an associated switch from line-source to fan sedimentation. Available geological data reveal little about the causes of these changes in ice dynamics during the Miocene Epoch, or the subsequent effects on Pliocene–Pleistocene ice-sheet history. Ice-sheet numerical modeling reveals that bed morphology was probably responsible for driving changes in both ice-sheet extent and dynamics in the Lambert-Amery system at Prydz Bay. The modeling shows how the topography and bathymetry of the Lambert graben and Prydz Bay control ice-sheet extent and flow. The changes in bathymetric volume required for shelf-edge glaciation correlate well with the Prydz Channel fan sedimentation history. This suggests a negative feedback between erosion and glaciation, whereby the current graben is overdeepened to such an extent that shelf-edge glaciation is now not possible, even if a Last Glacial Maximum environment recurs. We conclude that the erosional history of the Lambert graben and Prydz Bay in combination with the uplift histories of the surrounding mountains are responsible for the evolution of this section of the East Antarctic Ice Sheet, once the necessary initial climatic conditions for glaciation were achieved at the start of the Oligocene Epoch.

Keywords: Antarctica, ice sheets, numerical models, Miocene, Pliocene.

INTRODUCTION

The Lambert-Amery system is the largest and probably oldest drainage pathway of the East Antarctic Ice Sheet (~16% by area and older than 33 Ma; Barron et al., 1991; O'Brien et al., 2001) and is a major high-latitude recorder of, and influence on, climate and sea level. A large amount of onshore and offshore geological evidence from the Lambert-Amery system highlights the nature, but not the causes, of major changes in ice dynamics and offshore sedimentation since Eocene time (Stagg, 1985; Mizukoshi et al., 1986; Barron et al., 1991; Cooper et al., 1991; Kuvaas and Leitchenkov, 1992; O'Brien et al., 2001).

Within the broader context of cooling from an ice-proximal fjordal setting to the establishment of today's polar ice shelf (Hambrey et al., 1991; Hambrey and McKelvey, 2000a, 2000b), an ice stream was established in Prydz Bay during late Miocene–early Pliocene time, in association with a major offshore depocenter (O'Brien and Harris, 1996; O'Brien et al., 2001; Fig. 1A). The ice sheet subsequently withdrew to its present position, leaving the Amery Ice Shelf to cover much of the trough. More recently, the East Antarctic Ice Sheet failed to reach the continental shelf break during the Last Glacial Maximum (LGM) (Domack et al., 1998).

The specific reasons for any of these major changes in the Lambert region are unclear, beyond being related to broad-scale changes in tectonics, climate, and oceanography. DeConto and Pollard (2003) demonstrated the importance of atmospheric forcing in establishing glaciation in Antarctica and the use of numerical ice-sheet modeling in testing ideas on ice-sheet evolution. We use a numerical modeling approach to test the hypothesis that changes in East Antarctic Ice Sheet configuration (i.e., its extent and flow pattern) during the past ~20 m.y. have been driven primarily by alteration of tectonic structure or erosional topography rather than variations in climate or ice-sheet mass balance. Our work follows previous well-known investigations of the bed control on ice-sheet extent (e.g., Hughes, 1987).

NUMERICAL MODELING

Experimental Design

Numerical ice-sheet modeling is used to test the role of topographic and mass-balance changes on East Antarctic Ice Sheet configurations (Fig. 2). A horizontally averaged two-dimensional (2D) model is used to undertake reconnaissance studies, to examine changes in

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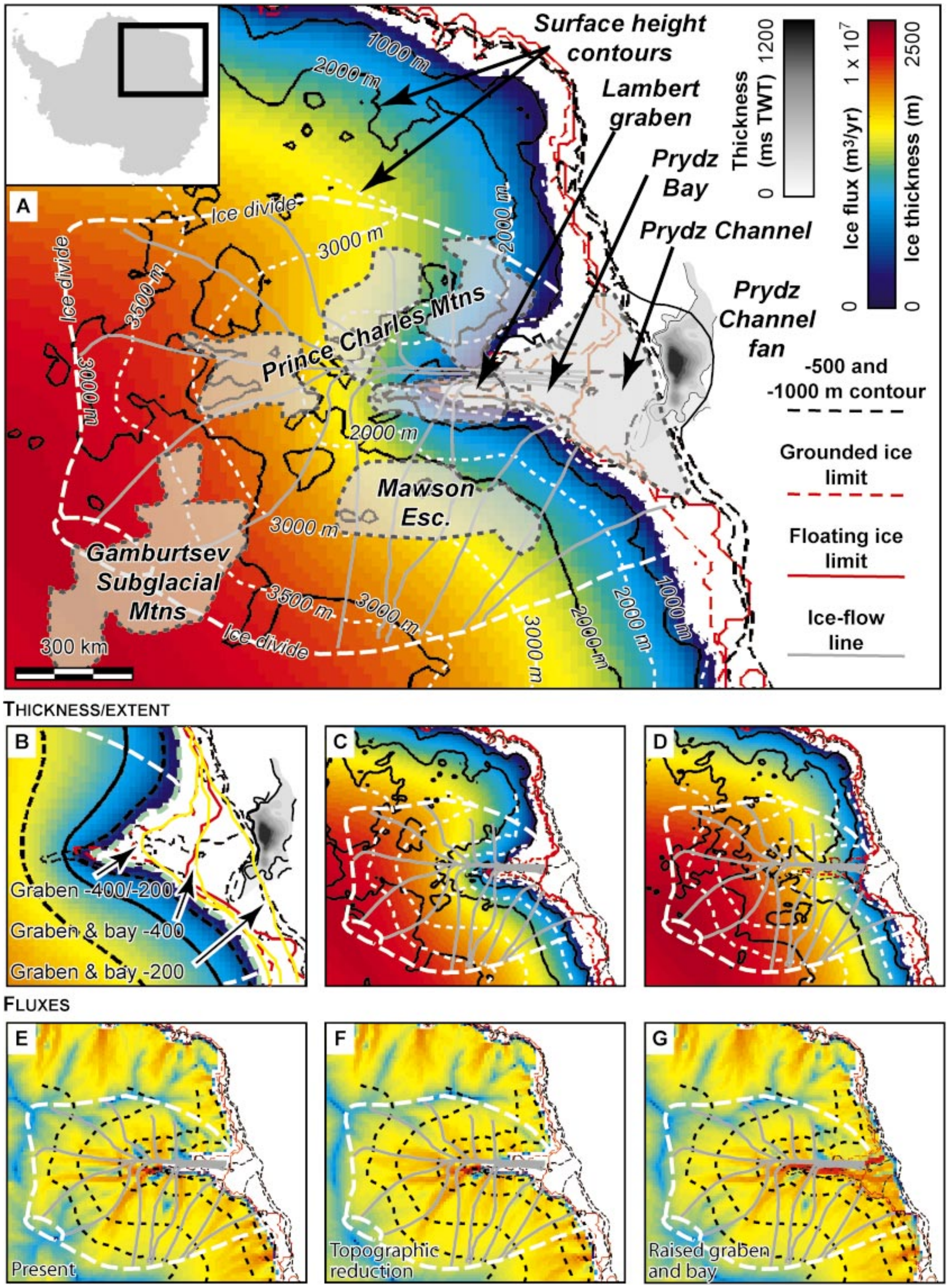
Figure 1. Results from numerical modeling experiments. A: Two-dimensional model representation of present ice extent and thickness. Limits and offshore contours are from Lythe et al. (2000); ice flow lines, ice divide, and white height contours are adapted from Hambrey et al. (1991). Also shown are post–late Miocene isopachs from O'Brien et al. (2001), based on surface A of Mizukoshi et al. (1986). Thickness refers to two-way traveltime of seismic waves through sediment in milliseconds (ms TWT). Inset shows location of study area. B–D: Ice limits from various modeling scenarios. B: Ice-sheet extent calculated under changes to topography and modern environment. Green dashed line denotes maximum position attained when topography was lowered (as detailed in text). Yellow lines denote positions of margin when bathymetry was raised. C: Reduced topographic features. D: Graben and bay raised to 200 m below sea level. E–G: Ice-sheet fluxes calculated by three-dimensional model. E: Present-day run. F: Reduced topographic features. G: Graben and bay raised to 200 m below sea level.



ice-sheet extent that are invoked by bed morphology. This extent is then used to prescribe the positional limits of the more sophisticated three-dimensional (3D) model to examine the variation in the velocity structure of the ice sheet (Fig. 2).

Boundary conditions are provided by an altered (an erroneous ridge in Prydz Bay was removed), isostatically unloaded BEDMAP subglacial topography (Lythe et al., 2000). Elements of topography that may exert control on East Antarctic Ice Sheet behavior were altered systematically in our experiments. Topographic changes made were as follows. First the elevation of the Prince Charles Mountains and Princess Elizabeth Land–Mawson escarpment was lowered from maximum elevations of 2000 m to 500 m, the average values of the hinterlands. The maximum height of the Gamburtsev Subglacial Mountains was also reduced, from >2900 m to 1200 m, the approximate bed height at Dome Fuji, farther north. Bathymetric changes to the Lambert graben and Prydz Bay involved raising the seafloor to a minimum elevation (maximum water depth) of either 400 or 200 m below sea level from values typically >500 m.

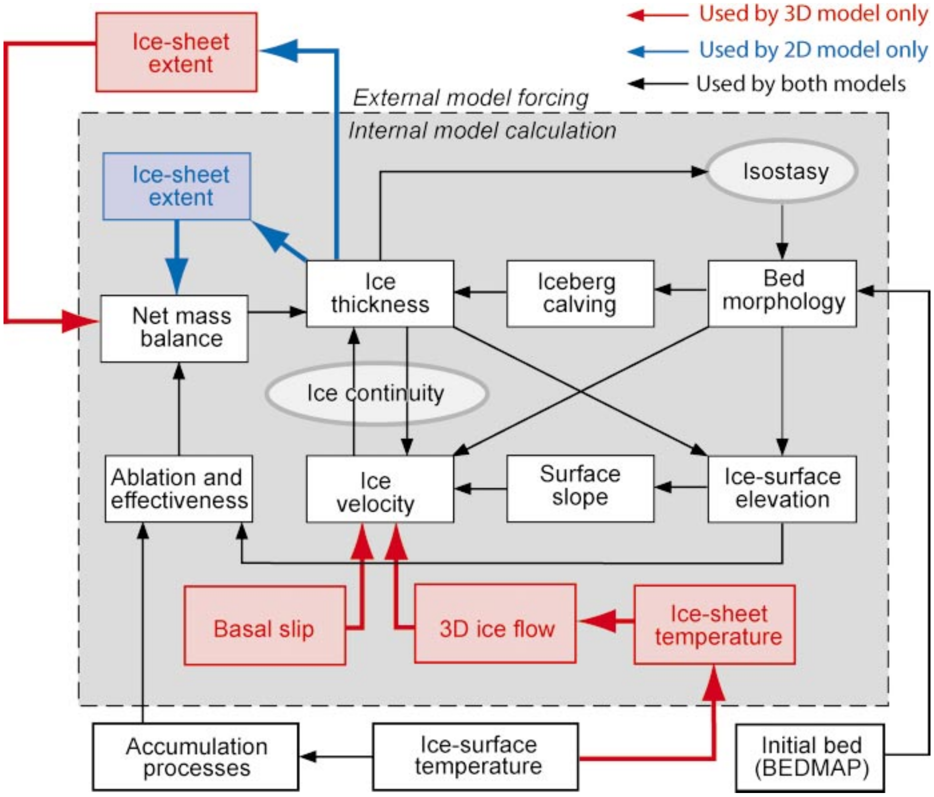


Figure 2. Flow diagram illustrating structure and function of numerical ice-sheet models used in this investigation. Two-dimensional (2D) model (Payne et al., 1989) calculates steady-state ice sheet based on continuity equation for ice and routines for isostasy, and floating and calving ice (depth function is used following Pelto and Warren, 1991). Model runs last 25,000 simulated years, approximately twice as long as required to achieve steady-state solutions. Prescribed modern mass balance results in good match with present ice-sheet extent (see Fig. 1A). Ice-sheet velocity structure is assessed using steady-state, fully three-dimensional (3D) thermo-mechanical model, which calculates ice temperatures and velocity in coupled manner (Payne, 1999). Model includes isostasy and basal slip. Model runs last 100,000 yr and use prescribed ice margin position, derived from 2D model. In this paper, model is used to examine how bed changes affect ice flow and velocity. To this end, interplay between topography and bathymetry, ice-sheet thickness and, where bed is below sea level, transition from grounded to floating ice is important. Grounding-line mechanics are not explicitly treated. Migration of grounding line is related to flux of ice, ice thickness, and depth of water in which floatation can occur.

Model scenarios employ a combination of these topographic changes using a modern mass balance and temperature regime, with further testing using an LGM mass balance and sea level to assess modern East Antarctic Ice Sheet sensitivity (as in Huybrechts, 1990; i.e., a 10 °C reduction in air temperature, a 50% reduction in accumulation, and a 120 m reduction in sea level). Note that the Miocene and Pliocene climates may have been warmer and wetter than today. Such a climate scenario, and its effect on ice flow and extent, is certainly worth investigating, but we restrict ourselves here to analyzing the ice-sheet response to bed morphology.

Model Results

The modeled East Antarctic Ice Sheet is relatively insensitive to alterations in the elevations of mountains in the continental interior; such alterations do not result in significant advances of the ice sheet onto the continental shelf (Figs. 1B, 1C). Lower mountain elevations result in broader ice-transport pathways, but the overall velocity structure of the ice sheet is unaffected (Fig. 1F).

Ice-sheet extent can be increased significantly only by altering the bathymetry of the Lambert graben and Prydz Bay (Figs. 1B, 1D). Raising the floor of the Lambert graben by only a small amount (to a maximum 400 m water depth) results in ice-sheet expansion to the outer limits of the graben, i.e., to about the present location of the current Amery Ice Shelf edge. However, this change must be coupled with raising the Prydz Bay floor to a depth of 200 m, or to 400 m combined with an LGM climate and sea level, before shelf-edge glaciation is achieved (Figs. 1B, 1D). Only model runs with changes to the bathymetry of the graben and continental shelf result in shelf-edge glaciation.

DISCUSSION

Prydz Bay Ice-Stream Development

One of the unanswered questions of Prydz Bay glacial history is, how did ice dynamics change during the late Miocene–early Pliocene interval? The late establishment of an ice stream and associated trough-mouth fan sedimentation in an environment dominated by a Paleozoic and younger topographic structure is surprising. What implications do these ice-dynamic changes have for arguments concerning Pliocene East Antarctic Ice Sheet stability? The 3D numerical modeling demonstrates that the effect of raising the bounding mountains is to focus ice flow into the graben, increasing both ice flux and velocity (cf. Figs. 1F and 1E). Ice-sheet extent in terms of grounded ice on the continental shelf is unaffected, however. Such topographic changes may be due to structurally or erosionally driven uplift of the graben's flanks, which is likely to have been significant ($>$500 m) during the Miocene Epoch (cf. Hambrey and McKelvey, 2000a).

We argue, therefore, that at least part of the transition from fjordal ice-proximal sedimentation to focused, continental shelf-edge sedimentation seen at the Miocene-Pliocene transition is probably related to the uplift history of the Lambert graben and coeval changes in ice dynamics. Pliocene evidence at Prydz Bay for a more dynamic ice setting (Hambrey and McKelvey, 2000a) and large-scale ice recession (Hambrey et al., 1991) has been interpreted as consistent with a ‘‘dynamist’’ whole-scale retreat of the East Antarctic Ice Sheet. However, this interpretation may instead be a result of the development of an ice stream within the Lambert graben. Rapid ice velocities and beds below sea level render ice streams very sensitive to alteration in other boundary conditions, such as sea-level and oceanographic change. These two conditions are both likely to have varied significantly in the Prydz Bay region during the Pliocene Epoch. We argue that glacial history within the Lambert system during this epoch is in fact partway between the traditional ‘‘dynamist’’ and ‘‘stabilist’’ contentions.

Some constraint may also be placed on the probable age of Prydz Channel. Although it is a relatively shallow feature in the shelf ($\sim$200 m relief), the channel focuses ice flux at the shelf edge (Fig. 1G). Assuming that the massive volume of sediment deposited in the Prydz Channel fan since late Miocene time (Figs. 1A, 1B) is a result of glacial processes alone, then the channel, however small, must have existed at the same time in order to focus flow from the Lambert graben to this one point. Because shelf progradation was approximately equal everywhere along the shelf edge until late Miocene time (Cooper et al., 1991), we believe the Prydz Channel is unlikely to significantly predate late Miocene time.

Erosional Controls on Ice-Sheet Extent?

The failure of the Lambert-Amery system to reach the outer shelf during the LGM (Domack et al., 1998) is replicated in our modeling experiments. The minimum requirement to induce shelf-edge glaciation with an LGM climate and sea level is the raising of the floor of the Lambert graben to a maximum water depth of 400 m. In the model domain, this equates to the reemplacement of a minimum of 1.39×10^6 km^3 of sediment in the graben (unadjusted for compaction or isostasy). The volume of late Miocene sediment required to raise the graben floor for shelf-edge glaciation requires a time span of $\sim$1 m.y. on the basis of the long-term post–late Miocene depositional rate of the Prydz Channel fan, as calculated from seismic mapping in O'Brien et al. (2001) (Fig. 1A). The suggestion that the ice sheet has not advanced to the shelf edge since at least the Bruhnes-Matuyama boundary (0.73 Ma), first interpreted on the basis of the geology of the fan (O'Brien et al., 2001), has strong support in the modeling results.

The extent of this sector of the East Antarctic Ice Sheet is currently limited strongly by the erosionally determined depth of the Lambert graben. Prydz Bay was probably a site of sediment transfer in the Quaternary Period. The reported seismic character and sediment distribution in Prydz Bay (O'Brien et al., 2001) replicate the appearance of other ice-streaming areas, such as the North Sea off Scandinavia, where sediment transport has been inferred (Sejrup et al., 1996). The removal of sediment from the relatively soft floor of the Lambert graben has overdeepened the fjord to such a degree that it is almost impossible to ground ice through it at a flux sufficient to drive the ice sheet fully across the shelf.

Additional Controls on Ice-Sheet Extent

While this paper is not concerned directly with testing the hypothesis that increased accumulation rates affect the glaciation of Prydz Bay, it is appropriate to mention it. This hypothesis can certainly be tested in future modeling experiments, where an ice-sheet model is linked to a climate model, in a manner similar to that of DeConto and Pollard (2003). The results presented here depend greatly on the depth-related iceberg-calving model. While changing the model alters the position of the ice margin, it does not affect adversely the main conclusions of the paper.

CONCLUSIONS

The value of predictive, geologically controlled, regional studies is in the ability to tease out individual factors that may be important in inducing large-scale and significant ice-sheet change. The results presented here indicate that understanding the structural and erosional history of the Lambert graben and Prydz Bay are probably the most critical elements in understanding more fully the glacial history of the East Antarctic Ice Sheet and, in particular, changes in its behavior during the Miocene-Pliocene transition.

Uplift of the bounding Prince Charles Mountains and Mawson escarpment focused ice flow into the Lambert graben, thickened the ice sheet, and increased ice flux. These changes led to a reorganization of ice flow and the establishment of fast-flowing ice in the graben and on the continental shelf, as reflected in the sedimentary record. During the Pleistocene Epoch, erosion of the graben floor limited ice flux and extent of the ice sheet on the continental shelf, resulting in the current East Antarctic Ice Sheet climatic insensitivity and configuration. While climatic changes form the overall framework for Antarctic history, we suggest that this sector of the East Antarctic Ice Sheet is at least equally strongly controlled by topographic forcing.

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