Footprint of the Expanded West Antarctic Ice Sheet: Ice Stream History and Behavior

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ABSTRACT

Evaluating the stability of the West Antarctic Ice Sheet and its regulating role in global climate and eustasy hinges on our ability to understand the interaction of ice streams and the bed on which they rest. Rapid streaming of ice is enabled by flow across a deformable till bed produced by the incorporation of basal meltwater into unconsolidated sedimentary material. These ice streams are shown to have flowed across extensive deformable till beds characterized by megascale glacial lineations composed of soft deformation till. The onset of rapid ice discharge occurs at the transition from crystalline bedrock to seaward-dipping sedimentary strata. In most locations, the deformed bed extends tens of kilometers to the outer continental shelf, which implies a thin ice sheet margin. Furthermore, most of the lateral boundaries of these ancestral ice streams were not constrained geologically, and there is evidence that these boundaries migrated a few tens of kilometers.

The extent of the deformable till bed, the nature of the boundaries, and the location of grounding-zone wedges, which record grounding-line positions of individual ice streams, vary from trough to trough, implying unique ice advance and retreat histories. These are all critical parameters in glaciological models and, therefore, predictions of the West Antarctic Ice Sheet's stability.

INTRODUCTION

The configuration of the West Antarctic Ice Sheet has long been considered unstable. The ice sheet typically is grounded (i.e., in direct contact with the underlying rock or sediment) at depths of ≥800 m below sea level. However, it is thin at the margins, so it floats in deep embayments, such as the Ross or Weddell Seas. The potential instability arises from the fact that sea-level rise and/or ice-margin thinning could cause rapid landward shifts in the ice sheet grounding line, with resultant melting (Hollin, 1964; Weertman, 1974; Thomas and Bentley, 1978). The most rapid flow occurs in areas of converging drainage known as ice streams. Ice stream flow velocities are typically a few hundred meters per year versus a few tens of meters per year in nonstreaming portions of the ice sheet. Currently, the dominant ablation of the West Antarctic Ice Sheet occurs through ice streams. The areas of maximum discharge are characterized by low ice sheet profiles that typically terminate in ice shelves (e.g., the Ross and Ronne-Filchner ice shelves). The long-term behavior of these ice streams is considered the most critical factor controlling the stability of the West Antarctic Ice Sheet (Hughes, 1977; Bentley, 1987). Understanding those factors that regulate ice stream behavior over centuries to millennia is crucial to assessing West Antarctic Ice Sheet stability (Bindschadler et al., 1998).

The interaction of ice streams and their subglacial beds is increasingly being recognized as an important control on ice stream behavior (Boulton and Jones, 1979; Alley et al., 1987; Engelhardt et al., 1990; Tulaczyk et al., 1998; Bell et al., 1998; Anandakrishnan et al., 1998; Bindschadler et al., 2001). The working model demonstrates that rapid flow of ice streams is due, at least in part, to flow over a deforming bed that is produced by the mixing of basal meltwater with sedimentary material. Support for this model comes from airborne and over-ice geophysical surveys (Bell et al., 1998; Anandakrishnan et al., 1998) and drilling through the modern ice streams and into the underlying bed (Engelhardt et al., 1990).

Around West Antarctica, the flow of the ice sheet converges as it passes over structural embayments on its journey to the

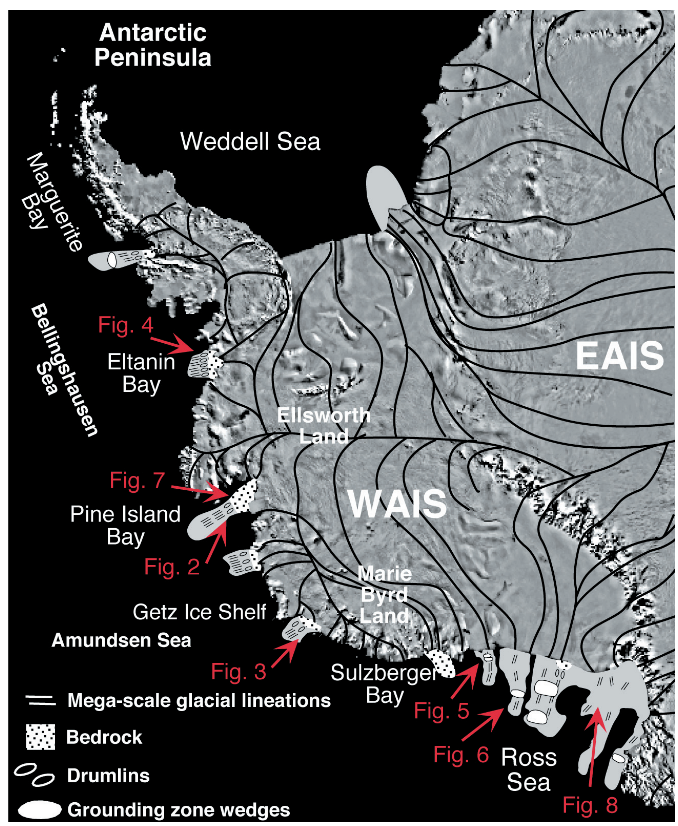

Figure 1. Satellite mosaic showing major drainage outlets of West Antarctica and locations of glacial troughs (light gray), located offshore of drainage outlets. Only larger troughs that extend beyond inner shelf are shown. Marine geophysical surveys were conducted in all of these troughs, except those in the Weddell Sea. Also shown are distribution patterns of large-scale geomorphic features, grounding-zone wedges, and areas where bedrock is present at or near seafloor. WAIS —West Antarctic Ice Sheet. EAIS—East Antarctic Ice Sheet.

coast. Without exception, deep, elongate bathymetric depressions (glacial troughs) occupy the continental shelf offshore of the larger drainage outlets (Fig. 1). This association supports Hughes' (1977) suggestion that glacial troughs mark the locations of former ice streams. There is strong evidence that the West Antarctic Ice Sheet advanced onto the shelf during the Last Glacial Maximum (Anderson, 1999; Anderson and Shipp, 2001). Hence, the troughs should contain a geological record of past ice stream behavior. In this paper, we present results from high-resolution seismic and swath bathymetry surveys and sedimentological examination of cores acquired from many of the large glacial troughs of West Antarctica. The spatial resolution provided by these data allows us to address the following questions about past ice stream behavior, and about the interaction of ice streams and the bed on which they rest.

- Did the expanded West Antarctic Ice Sheet have ice streams and, if so, how extensive were they?
- What geological conditions influenced the onset of paleo–ice streams?
- What geologic conditions control the boundaries of ice streams? Did these boundaries migrate and, if so, over what distances?
- Is there evidence that expansion of ice streams resulted ultimately in rapid retreat of the West Antarctic Ice Sheet?

DATABASE

Geophysical data and sediment cores were acquired within, and in selected areas between, the troughs of the Ross, Amundsen, and Bellingshausen Seas during four separate cruises of the RV/IB *NB Palmer* between 1994 and 1999. Seismic profiles were collected along the axes of the troughs to examine the nature of the bed over which the ice sheet was flowing and image sedimentary deposits formed at and beneath the grounding line (Fig. 2). High-resolution (Chirp) subbottom profiles were acquired to image thin sedimentary units (minimum thickness of ~1 m). Multibeam and deep-tow side-scan sonar images record geomorphic features of various scales and yield information about processes occurring at and within the ice/bed interface. Sediment cores are used to characterize subglacial and glacial-marine deposits; they provide information about subglacial conditions and about the retreat history of the individual ice streams.

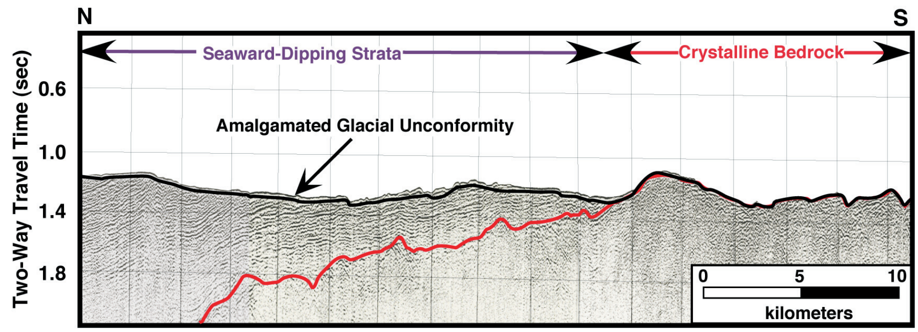

Figure 2. Seismic profile across axis of a large glacial trough, Pine Island Bay, showing rugged crystalline bedrock on inner shelf extending offshore into seaward-dipping sedimentary strata.

RESULTS AND DISCUSSION

Subglacial Conditions

The different troughs of the West Antarctic continental shelf occupy a range of geological settings, based mainly on the extent of bedrock versus sedimentary strata over which the expanded ice sheet flowed. At one end of the spectrum is the crystalline bedrock underlying the continental shelf off western Marie Byrd Land (Fig. 1). In contrast, the Ross Sea continental shelf is underlain by a seaward-dipping succession of incompletely lithified Tertiary and Quaternary age sedimentary strata. Offshore of eastern Marie Byrd Land and Ellsworth Land, the inner shelf is floored by crystalline basement, whereas the outer shelf is underlain by sedimentary strata (Figs. 1 and 2).

Integration of geomorphic information from geophysical data with lithologic data from cores has allowed us to reconstruct the behavior of the ice sheet and characteristics of landforms generated as it moved over different substrates exposed on the continental shelf. The landforms and inferred rate of ice flow/conditions are discussed below and summarized in Table 1.

Shelf areas floored by crystalline bedrock are characterized by narrow, deep troughs that follow the structural grain. Grooves and streamlined spurs on rock surfaces indicate that the ice was in direct contact with the bedrock (Fig. 3).

TABLE 1. GEOMORPHIC EVIDENCE FOR SUBGLACIAL CONDITIONS

Landform	Substrate	Inferred Ice Conditions/Rate of Flow	Example Areas	Figure
Depositional				
Megascale glacial lineations	Sedimentary	Fast	R.S, Getz, PIB, Eltanin Bay	Figures 4, 5, 7
Erosional				
Grooves	Crystalline	Slow	R.S., Pennell, Sulzberger, PIB, Getz	Figures 3, 7
Roches moutonnées	Crystalline	Slow	PIB, Sulzberger	Figure 3
Meltwater channels	Crystalline	Sporadic?	PIB	Figure 6
Gullies	Sedimentary	Meltwater, ice at shelf break	Western R.S., PIB, Pennell, Sulzberger slopes	Figure 5
Intermediate				
Drumlins	Crystalline-sedimentary transition	Accelerating	Central R.S., Getz, PIB, Eltanin, Marguerite	Figures 3, 4

Note: See Anderson (1999) and Wellner et al. (2001) for more detailed descriptions of features. PIB—Pine Island Bay; R.S.—Ross Sea.

In general, the ice traversed younger, less consolidated, increasingly mud-rich sedimentary material more prone to erosion as it advanced seaward across the shelf.

Drumlins occur at the contact between bedrock and sedimentary deposits (Fig. 4), marking the zone where ice first encounters a sedimentary bed. Theoretically, this is the location where flow begins to accelerate (Wellner et al., 2001). Seaward of the drumlinized transition zone and above the sedimentary strata, megascale glacial lineations extend tens of kilometers across the shelf (Figs. 4 and 5). They are ridges that are confined to troughs and oriented parallel to trough axes. On average, the lineations are 10–20 m high and have transverse wavelengths of a few hundred meters. High-resolution seismic profiles show that the lineations are part of a homogeneous seismic unit that rests above a glacial unconformity (Shipp et al., 1999). They are identical to lineations observed on previously glaciated landscapes and seascapes that have been attributed to overriding by paleo–ice streams (Clark, 1993; Canals et al., 2000).

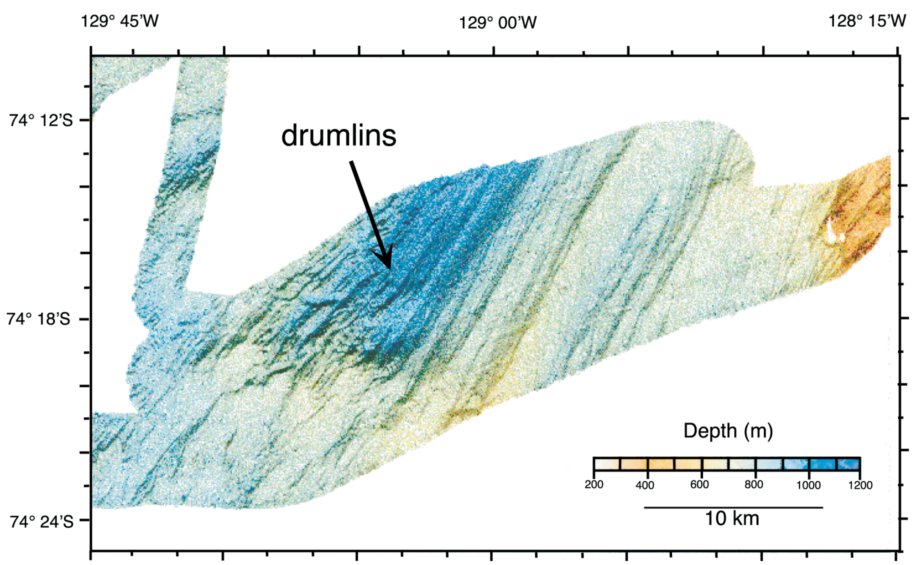

Figure 3. Multibeam mosaic from offshore of Getz Ice Shelf showing grooves and drumlins on crystalline bedrock surface.

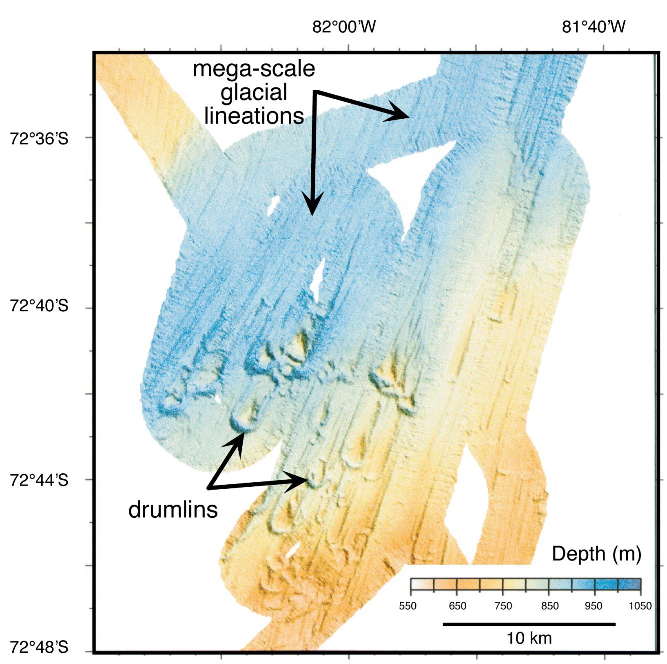

Figure 4. Multibeam mosaic showing drumlins within glacial trough in Eltanin Bay (see Fig. 1). These drumlins occur where the ice sheet first flows from crystalline bedrock across sedimentary strata.

Deformation of the bed implies high rates of sediment transport at the bed (Alley et al., 1987; Clark, 1993). Typically, megascale lineations extend seaward into wedges of strata that contain seaward-dipping foreset beds. These are referred to as grounding-zone wedges (Anderson, 1999). We believe that these grounding-zone wedges are composed of sediment that was moving seaward within the subglacial conveyer belt. They are equivalent to the "till deltas" of Alley et al. (1987). Grounding-zone wedges that rest above older lineated surfaces are interpreted to have formed during pauses in the retreat of the ice sheet (Shipp et al., 1999).

Where the lineations extend to the shelf break, as in the eastern Ross Sea, they are bounded on the upper slope by gullies that extend downslope into small sediment fans (Fig. 5). Anderson (1999) interpreted these gullies as having been cut by sediment-laden meltwater emanating from the ice sheet–grounding line.

Sediment cores that penetrated megascale glacial lineations produced diamicton samples with relatively low shear strengths and high water content compared to tills deposited by plastering of debris onto the bed (lodgment till) (Anderson, 1999). Otherwise, these diamictons show the same properties as lodgment tills, such as strong homogeneity in composition and grain size (Anderson, 1999). They are similar to the modern deformable till beds that occur beneath Ice Stream B (Engelhardt et al., 1990; Tulaczyk et al., 1998).

In summary, drumlins mark the transition between ice that is resting on bedrock and ice that is flowing across a deformable till bed. Thus, they appear to mark the onset area of former ice streams. But, do ice streams occur only over deformable sedimentary beds? Seismic data from Pine Island Bay show that the inner portions of the bay are floored by crystalline bedrock (Fig. 2). Yet, Pine Island Glacier flows into the bay at velocities between 1.0 and 2.5

km/yr. (Lucchitta and Rosanova, 1997).

The bedrock surface in the Pine Island Bay trough is incised by an anastomosing network of meltwater channels (Fig. 6). These channels occur at water depths of up to 1400 m, so they are interpreted as subglacial features. The channels indicate that significant volumes of subglacial meltwater may have existed beneath Pine Island Glacier when it was grounded on the shelf.

Currently, the floor of Pine Island Bay is blanketed by terrigenous mud that virtually lacks ice-rafted material and increases in thickness toward the glacier terminus. This is interpreted as a meltwater deposit. Radiocarbon ages reveal that accumulation of meltwater deposits is occurring today and, therefore, that meltwater is currently flowing from beneath Pine Island Glacier (Lowe, 2001). Perhaps basal meltwater is present in large enough quantities to support basal sliding of Pine Island Glacier across a crystalline bed.

On the outer shelf of Pine Island Bay, megascale glacial lineations and associated deformation till occur where there are sedimentary strata; meltwater channels are absent. This implies that once the ice advanced onto the sedimentary strata, meltwater was incorporated into the bed. Hence, the mechanism for basal sliding changed. This is consistent with arguments by Tulaczyk et al. (2000) and Raymond et al. (2001) that channelized drainage is unlikely to occur over deformable beds.

In the eastern Ross Sea, megascale glacial lineations extend virtually uninterrupted from the margin of the Ross Ice Shelf to the continental shelf edge (Fig. 5). This implies that once the bed starts to deform, it will continue to deform as long as the ice flows across sedimentary deposits.

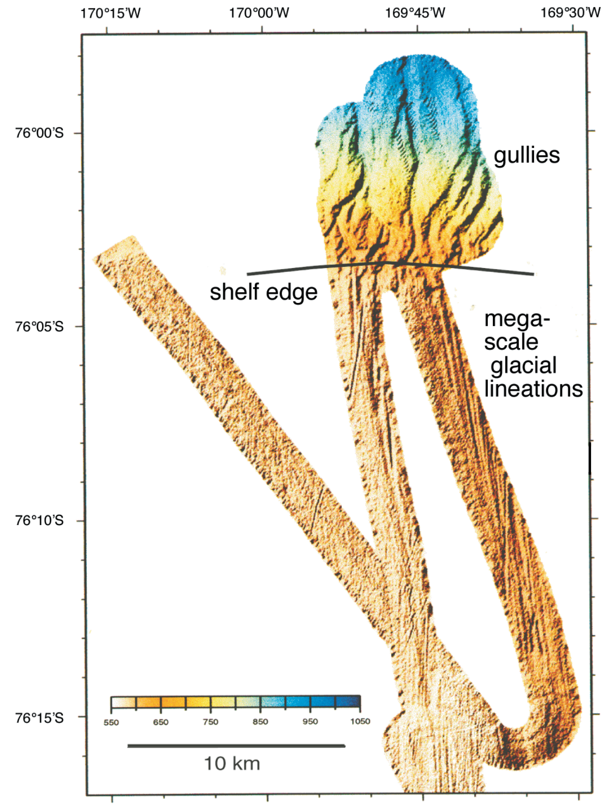

Figure 5. Multibeam mosaic from outer shelf in eastern Ross Sea showing megascale glacial lineations that extend to shelf break. Gullies are present on upper slope, seaward of the lineations. These gullies are believed to have been cut by sediment-laden meltwater emanating from grounding line of expanded ice sheet. Meltwater was no longer being incorporated into a deformable till bed.

Ice Stream Boundaries

The lateral margins of modern ice streams are shear margins between fast-moving and slow-moving ice. These margins are marked by crevasses that typically extend transverse to flow. Raymond et al. (2001) argue that shifting ice stream boundaries would alter the velocity and width of the streaming flow and thus discharge. The issue of ice stream margins is critical to the stability of the ice sheet. One of the important questions raised in recent years concerns the degree to which subglacial geology and topography control the boundaries of ice streams (Shabtaie and Bentley, 1987; Bell et al., 1998; Anandakrishnan et al., 1998; Bentley, 1998). Modern ice stream boundaries are rather broad (typically several kilometers wide).

How distinct are the paleo–ice stream boundaries in West Antarctica, and are they associated with geological boundaries? For the most part, the paleo–ice stream boundaries we have examined are not associated with geological boundaries. The exception to this is on the inner shelf, where the ice first began to encounter deformable sediments and where bedrock highs regulated the movement of the ice. Our geomorphic data demonstrate that megascale glacial lineations, the best geomorphic evidence for paleo–ice streams, are confined to troughs. However, the lateral boundaries of lineated and nonlineated seafloor are diffuse, spanning several kilometers (Figs. 5 and 7).

Seismic records show that depositional features (ice stream boundary ridges) or erosional escarpments mark the lateral margins of some paleo–ice streams (Fig. 8), (Anderson et al., 1992). For the most part, these margins do not correspond to bedrock or stratigraphic boundaries. Indeed, seismic images of some ice stream boundary ridges show evidence of tens of kilometers of lateral migration of ice stream boundaries across relatively uniform Pliocene-Pleistocene strata (Fig. 8).

CONCLUSIONS

The results from this investigation provide strong evidence that ice streams occupied glacial troughs on the West Antarctic continental shelf during past glacial maxima. Our results also corroborate those from previous over-ice and aerial geophysical surveys, which indicate that ice stream onset coincides with the boundary between crystalline bedrock and sedimentary strata.

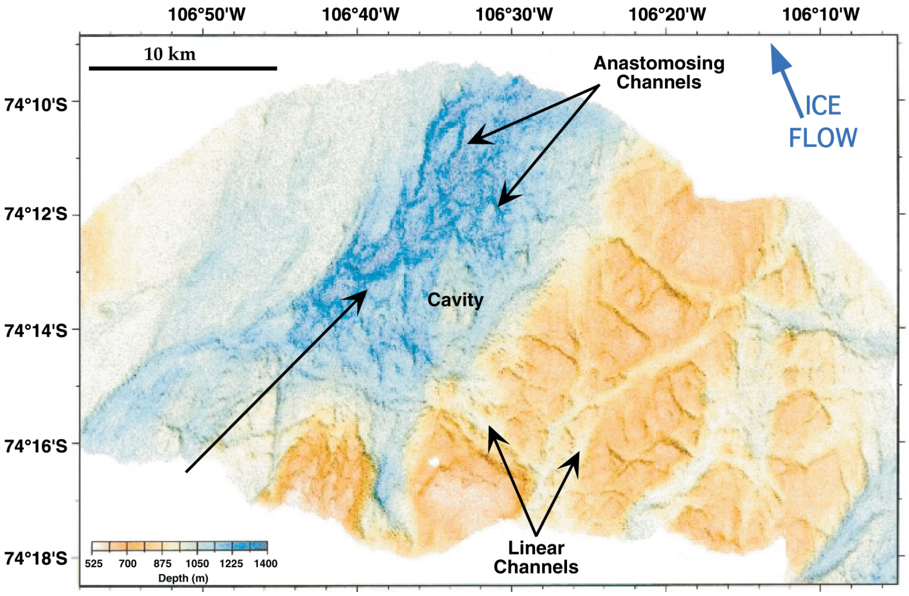

Figure 6. Multibeam mosaic showing anastomosing subglacial meltwater channels in inner part of Pine Island Bay.

However, there is also evidence that channelized basal meltwater may, in some cases, provide the necessary lubricant for subglacial sliding over crystalline bedrock. As the ice sheet advanced across the shelf, it encountered more deformable substrates. In most locations, the deformed bed extends tens of kilometers to the outer continental shelf, which implies greatly extended ice streams. The ice streams in the Ross Sea and Pine Island Bay were 2–4 times more extensive than they are today.

For the most part, the lateral boundaries (shear margins) of ancestral ice streams were not constrained geologically, and there is evidence of a few tens of kilometers migration of these boundaries in unconsolidated sedimentary strata.

Our results suggest that there may be a self-regulating control on West Antarctic Ice Sheet expansion and retreat. The advance of the ice sheet onto the shelf results in more extensive ice streams. This in turn favors a thinner, unstable ice sheet margin that possibly contributes to retreat.

The distribution and extent of megascale glacial lineations, the extent of the drumlinized transition zone, and the distribution of grounding-zone wedges varies from trough to trough, even within the Ross Sea, where several ice streams existed (Fig. 1). These variations indicate that rates of ice stream flow and discharge varied between the different paleo–ice streams and that retreat of some ice streams was episodic. The fact that subglacial features are so well preserved and buried beneath relatively thin recessional glacial-marine deposits implies rapid retreat. The key is to determine which ice streams have a history of rapid retreat, how rapidly they retreated, and what factors led to rapid retreat.

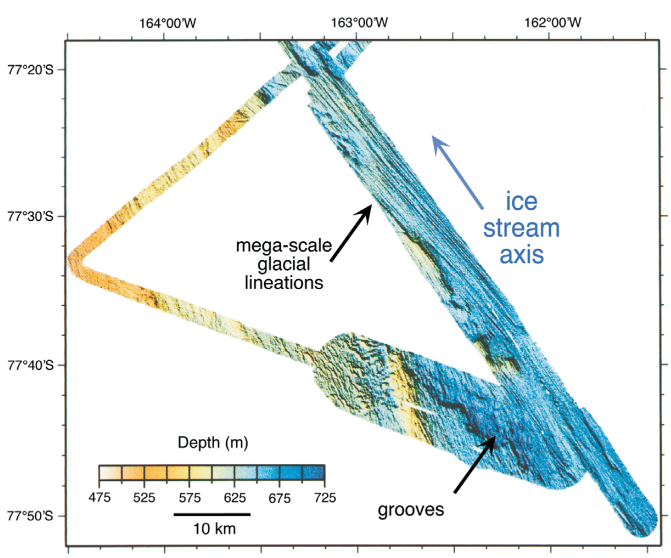

Figure 7. Megascale glacial lineations are the main geomorphic expression of a deformable till bed beneath paleo–ice streams. In this example from the eastern Ross Sea, the boundary between lineated seafloor within trough axis grades into nonlineated seafloor to west of trough.

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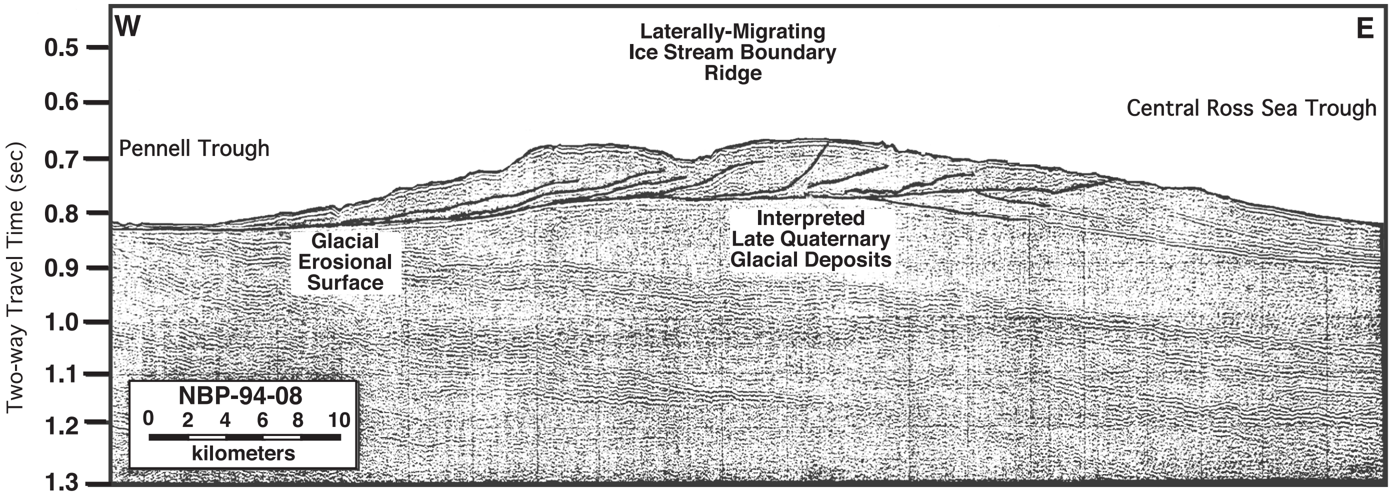

Figure 8. Seismic profile from western Ross Sea showing ice stream boundary ridge. Ridge separates two paleo–ice streams that occupied the Pennell Trough and the Central Ross Sea Trough. Note westward lateral accretion, which indicates significant shifts in ice stream boundary with time. There are no significant differences in substrate conditions across these boundaries.

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On behalf of the Geological Society of America, we would like to express our sympathy and condolences to all GSA members and staff for whom the horrible events on September 11 were a personal tragedy. The hostile actions have affected us all in ways that are hard to describe. GSA has received a number of messages for our members from societies and individuals around the world. We would like to pass them on to you and have posted them at GSA's Web site, www.geosociety.org.

In the days to come, we will go back to our usual business, and air travel will become more secure. We anticipate no changes in our plans for the GSA Annual Meeting in Boston, and we look forward to seeing a great many of you there.

Again, we would like to add our condolences to those from abroad.

Sharon Mosher, President, and **Dave Stephenson,** Acting Executive Director