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ABSTRACT

We analyze Holocene ice flow using global positioning system and radio-echo sounding data acquired near the Amundsen-Weddell ice divide, between Pine Island Glacier and the Institute Ice Stream, West Antarctica. The data show that this part of the West Antarctic Ice Sheet (WAIS) has maintained a stable ice flow regime and ice divide position for ~7000 yr. Independent glacial geological data, in support of this assertion, suggest that the interior of the WAIS west of the Ellsworth Mountains has thinned by only a few hundred meters since the Last Glacial Maximum (LGM) and that the position of the ice divide may be recurrent over longer (more than 20 k.y., perhaps pre-Quaternary) time scales. We suggest that basal topography constrains ice flow in this sector of the WAIS, making the ice divide relatively insensitive to perturbations around the margins of the ice sheet compared with other ice divides. Large-scale forcing measured elsewhere in the WAIS as major reorganizations of the ice sheet surface and flowline pattern may be manifested only in simple vertical changes of the Amundsen-Weddell interior.

INTRODUCTION

Satellite observations show that the Amundsen Sea margin of the West Antarctic Ice Sheet (WAIS) is currently undergoing dynamic thinning and grounding-line retreat (Pritchard et al., 2009; Wingham et al., 2009). The impact of these changes is expected to propagate inland from the ice sheet margin (e.g., Payne et al., 2004), and there is observational evidence that interior parts of the WAIS are already responding to strong dynamic thinning of the Amundsen Sea sector (Conway and Rasmussen, 2009; Pritchard et al., 2009). To fully evaluate the significance of these recent changes with respect to the overall contribution of West Antarctica to global sea level, it is important that the response of the ice sheet to longer term environmental forcing (i.e., since the Last Glacial Maximum, LGM) be determined.

Although post-LGM retreat of the WAIS margin has been broadly defined by marine geological and geophysical surveys (e.g., Lowe and Anderson, 2002), data on the evolution of the interior parts of the ice sheet have proven more difficult to acquire. Maximum LGM thicknesses, rates of Holocene thinning, and ice mass configuration are currently based on only a few "dipstick" measurements from cosmogenic dating of glacial landforms and model-based reconstructions (e.g., Waddington et al., 2005; Bentley et al., 2010). A solution to overcome this data gap is the analysis of internal ice sheet layer stratigraphy in radio-echo sounding (RES) data. Isochronous englacial layers, seen in RES data as reflections from within the ice sheet, can provide information on the behavior and flow of an ice mass because their architecture reflects past variations in the internal strain regime caused by ice flow (Robin and Millar, 1982; Jacobel et al., 1993; Siegert et al., 2003). Assessment of whether changes in the configuration of ice sheet flow have occurred over time scales >1 k.y. can be achieved through the comparison of present-day flow from global positioning system (GPS) or satellite data with paleo-flow orientations derived from structure tracking of englacial layer features. Studies of this kind have shown that Holocene deglaciation (Conway et al., 1999) forced significant flow regime change in the WAIS interior, with rapid and abrupt changes in the configuration and rate of inland ice stream flow in the Ross Sea sector (e.g., Conway et al., 2002; Siegert et al., 2004).

Here we compare flow paths derived from buckled internal layers with GPS surface measurements of ice flow from the upper catchment of Pine Island Glacier, interior WAIS. These are used to establish the long-term flow regime in this hitherto poorly understood part of the ice sheet. The flow pattern is then used to evaluate the stability of the ice divide separating the Amundsen Sea and Weddell Sea sectors of the WAIS (hereafter the Amundsen-Weddell divide) during the Holocene. Our findings regarding flow and ice divide history are compared with observations from glacial geological mapping in the Ellsworth Mountains to form a longer-term perspective on ice flow conditions.

METHODS

A detailed grid of ground-based RES data was acquired around the area of Ellsworth Subglacial Lake (Woodward et al., 2010) and the nearby Amundsen-Weddell divide during the 2007–2008 and 2008–2009 Antarctic field seasons. This major ice divide marks the boundary between the upper catchments of Pine Island Glacier and the Institute Ice Stream (Fig. 1). RES data were acquired using the Deep Look Radio Echo Sounder (DELORES) system operating at a center frequency of ~1.7 MHz. Kinematic differential GPS (DGPS) data, processed using a local base station, were used to determine survey line positions and the elevation of the ice sheet surface.

To supplement the RES survey, the positions of 65 stakes installed on the ice sheet surface were measured with DGPS, processed using a local base station. Conservative estimates of the positional uncertainty of the stakes are ±3 cm in the horizontal and ±5 cm in the vertical. The changes in stake positions between the field seasons were used to establish the rate and direction of ice flow.

RESULTS

RES Data: Internal Ice Sheet Layering

The RES data exhibit buckled englacial layering characterized by a series of clearly discernible peaks and troughs (e.g., Fig. 2A). These originate upstream of Ellsworth Subglacial Lake, in a zone ~10 km from the ice divide where convergent ice flow traverses a series of subglacial mountains (Figs. 2B and 3). Well-developed, buckled englacial layers are clearly draped over a number of these subglacial peaks (e.g., Fig. 2A). Buckles can be tracked for at least 30 km down-ice of the subglacial mountains (Fig. 3), but are not apparent up-ice of the mountains (i.e., in survey lines D22–D28) (Fig. 2B). At the points of origin, the peak-to-trough amplitude of the buckled layers can exceed 150 m with wavelengths of ~1000 m (Fig. 2A). Fold axes (troughs or peaks) were identified and mapped onto the ice sheet surface (Fig. 3). Most fold axes can be tracked throughout the survey grid from their origin to

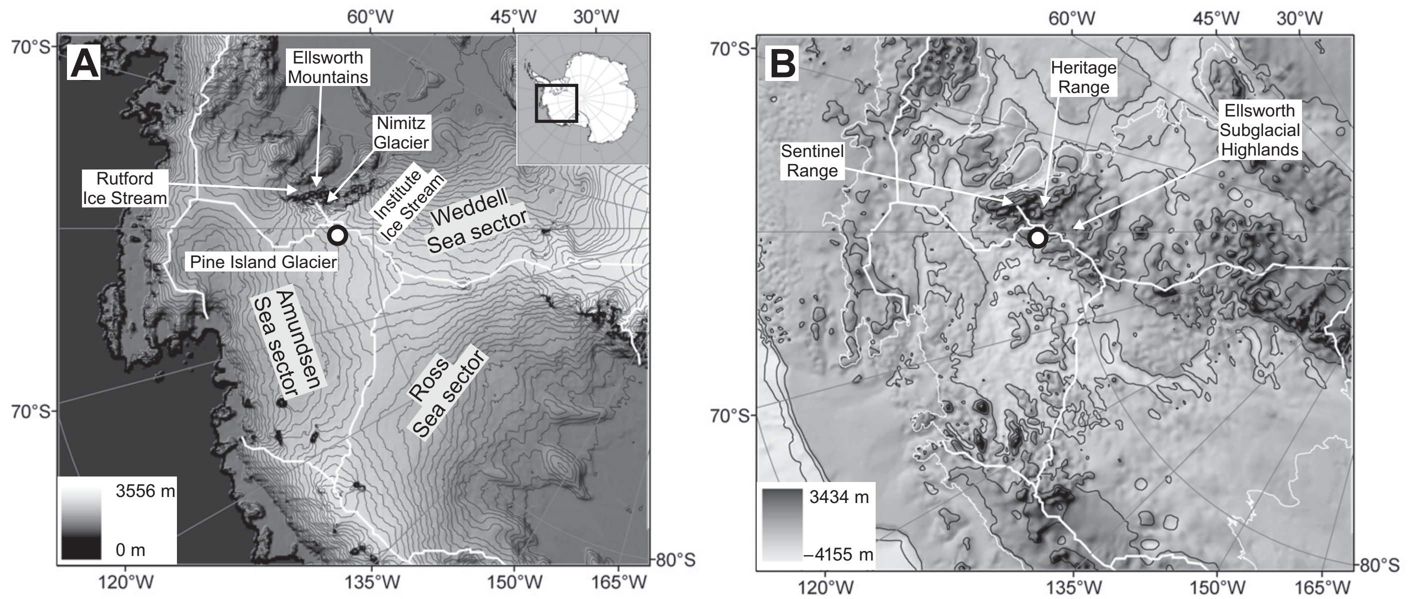

Figure 1. Primary West Antarctic Ice Sheet ice divides. A: Ice surface elevation (Bamber et al., 2009); ice divides (white lines) and ice surface contours (thin black lines at 100 m intervals) are shown. B: Subglacial topography (Le Brocq et al., 2010); ice divides (thick white lines), grounding lines and/or coastline (thin white lines) and bed contours (thin black lines at 500 m intervals) are shown. White circle indicates survey location.

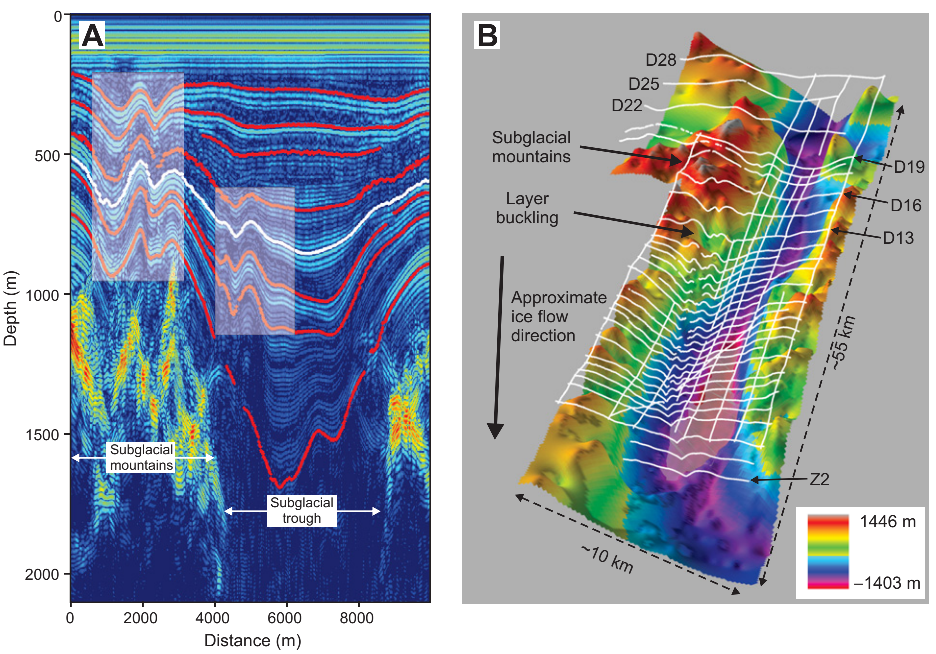

Figure 2. A: Example of radar data (line D16) highlighting buckled internal layering. Layer picks are red with the exception of layer 5 (white). Zones of internal layer buckling are highlighted by white transparent rectangles. Ice flow is approximately out of page. Depth axis assumes radar wave velocity in ice of 0.168 m ns^{-1}. B: Elevation picks for internal layer 5 (white lines) overlying subglacial topography of survey area. Ice divide is between radio-echo sounding lines D22 and D25. Subglacial Lake Ellsworth is delimited by gray shading on bed digital elevation model.

~8 km beyond the down-ice end of Ellsworth Subglacial Lake (Fig. 3), becoming "lost" where the amplitude of the buckles is reduced. The englacial folds reflect the cumulative history of the ice flow regime in the survey area since their formation.

GPS Data: Present Flow Regime

GPS data show that ice flow in the study area has two key characteristics: (1) convergent flow over Ellsworth Subglacial Lake, and (2) pronounced local westward rotation of ice flow in the lower parts of, and immediately down-ice from, the lake (Ross et al., 2011). Flow convergence is greatest at the upstream end of the lake, and decreases down-lake. GPS measurements down-ice of the subglacial lake suggest the emergence of a divergent flow regime (Ross et al., 2011).

Past and Present Flow Regimes: A Comparison of RES and GPS Data

Comparison of GPS measurements with the fold axes reveals a remarkable similarity between modern ice flow and the cumulative history of former flow (Fig. 3). This suggests a stable, persistent flow pattern for at least as long as the age of the oldest englacial folds. Both data sets exhibit flow convergence near the upstream end of Ellsworth Subglacial Lake and the westward rotation in the flow regime down-ice from the lake (Fig. 3). For clarity only the picked buckles from one internal layer (layer 5) are shown in Figure 3, but the same flow paths can be mapped in fold axes from other internal layers (e.g., Fig. 2A).

Although the time at which the buckles formed cannot be dated absolutely (because we do not know the long-term flow velocity), we can estimate an age for their formation. Assuming an ice flow velocity of 5 m yr^{-1} (approximately the mean of our present-day flow measurements) the time it would take for ice to flow the 34 km from the origin of structure ST5-1 (approximately line D19) to the point farthest down-ice where the fold axis of the structure can still be observed (line Z2) is 6800 yr. This figure is subject to uncertainties as it assumes constant ice flow velocities through time and throughout

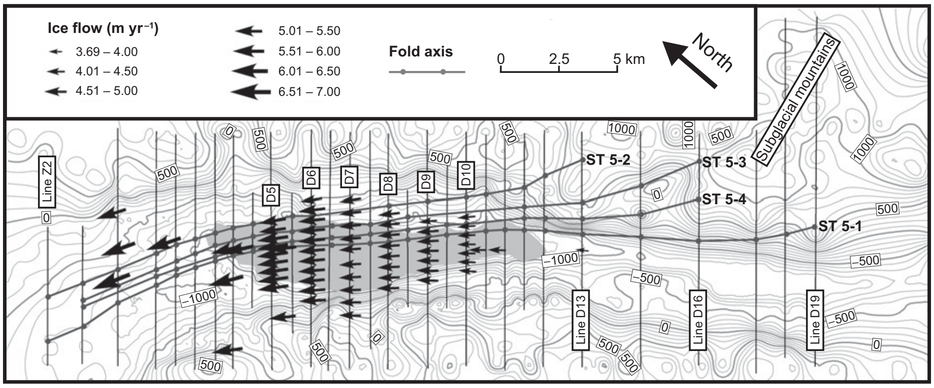

Figure 3. Past and present ice flow. Black arrows represent measurements of current flow rate and direction from global positioning system observations. Gray dots mark locations of prominent internal layer buckles picked from radio-echo sounding (RES) data. Where observed in more than one RES line, these points have been joined (thick gray lines) to indicate flow paths. Data are underlain by subglacial topography represented by contour lines at 100 m intervals. Black lines are those RES lines acquired approximately perpendicular to flow. Lake area is shown by gray shading.

the ice column; however, our method of estimating past ice flow is justified for three reasons. (1) Surface measurements provide a maximum estimate of flow velocity within the ice column. Ice at depth will flow slower than, or at the same rate as, near-surface ice. (2) Our measurements are from an area characterized by relatively high flow rates. An ice velocity of 1.9 ± 0.1 m yr^{-1} (Woodward et al., 2010), measured at a location ~11 km northeast of the lake, is more likely typical of the flow rate up-ice of the lake, closer to the divide, where the ice sheet flows over bedrock. (3) In the area of study, close to an ice divide, rates of ice flow are unlikely to have varied significantly during the past 10 k.y. Our average Holocene ice flow estimate of 5 m yr^{-1} is therefore conservative, because it assumes a rate of ice flow higher than was probably the case. An uncertainty of ±25% in our calculations, and minimum and maximum velocities of 3.75 m yr^{-1} and 6.25 m yr^{-1} (the range of values measured in the survey), suggest a range of calculated transit times of 5440–9066 yr. This suggests stability of ice flow direction for much, if not all, of the Holocene.

DISCUSSION

Implications for Holocene Stability of the Amundsen-Weddell Ice Divide

The internal layering around Ellsworth Subglacial Lake indicates that the configuration of ice flow in this sector of the interior WAIS has been stable for ~7000 yr. Because ice flow occurs parallel to the regional slope of the ice sheet surface, the similarity between the present-day and paleo–ice flow regimes suggests that the overall slope and aspect of the ice surface over and around the subglacial lake has not changed significantly during this period. This does not preclude possible widespread uniform ice sheet thinning during the Holocene. We suggest that the position of the Amundsen-Weddell ice divide ~20–25 km upstream of Ellsworth Subglacial Lake has not migrated significantly and that ice flow toward Pine Island Glacier, over the zone of buckle formation, has persisted for ~7000 yr. If the divide had been located northwest of this zone of prominent subglacial topography (e.g., during the mid-Holocene), however, the buckles would exist in the Institute Ice Stream, and would not be observed in the current data set. We cannot rule out entirely a northwestward migration of the ice divide (i.e., toward Pine Island Glacier, with a reduction in the size of its catchment). However, we believe that migration in this direction is unlikely because it would result in a change to the inflection of the flowpaths recorded in the internal layering, leading to a disparity between past and present trajectories. The data therefore suggest that there has been little, if any, change in the position of a part of one of the primary ice divides of the WAIS throughout most of the Holocene.

Ice Divide Position Over Longer Time Scales

A pre-Holocene, regional-scale context for the Amundsen-Weddell divide is provided by the glacial geology of the Ellsworth Mountains. A pronounced glacial trimline has long been recognized on the western side of the Sentinel Range of the Ellsworth Mountains at elevations of between ~2500 and 3010 m (Denton et al., 1992). The paleo–ice surface suggested by this trimline has a morphology subparallel to the current ice surface: the highest mapped elevation of the trimline (3010 m) is above the position where a present-day ice divide between the Rutford Ice Stream and the Nimitz Glacier intersects the mountains, and implies as much as 650 m of thickening. Trimline elevations dip both north and south from this central point (Denton et al., 1992). We suggest that the Sentinel Range trimline, formed when a previous incarnation of the WAIS inundated the western side of the Ellsworth Mountains, represents the position of a major ice divide aligned along the long axis of the Ellsworth Subglacial Highlands. Based on the shape of the trimline, the position and orientation of this reconstructed ice divide imply that the position of the Amundsen-Weddell ice divide may have varied little over long (more than 20 k.y., perhaps pre-Quaternary) time scales. Denton et al. (1992) presented two alternative hypotheses for the age of this trimline: an LGM age, or an older (possibly pre-Quaternary) one. Recent data (Bentley et al., 2010) have shown that the prominent Sentinel Range trimline is older than the LGM, and that a pre-Quaternary model may be more appropriate. Dates on a drift deposit in the adjacent Heritage Range show that the distinctive upper limit (trimline) of this deposit, ~230–480 m above present-day ice, marks the upper elevation of the WAIS surface at the LGM (Bentley et al., 2010). Preliminary mapping suggests that an equivalent limit may be recognized in the Sentinel Range as a weathering break at ~350–400 m above present-day ice, well below the Denton et al. (1992) trimline. The data in Bentley et al. (2010) show only a few hundred meters of ice sheet thinning since the LGM, and that the Denton et al. (1992) Sentinel Range trimline represents a pre-LGM ice sheet surface. This trimline may mark a recurrent ice divide configuration, possibly since prior to the Quaternary. Because trimlines record only thicker ice sheet configurations, we cannot rule out WAIS collapse in this interval, merely that when the ice sheet is present the position of the ice divide appears to be a recurrent, stable feature.

Implications for Dynamic Thinning of the Amundsen Sea Sector

Recent ground-based observations from the Western Divide of the WAIS (between the Amundsen and Ross Sea sectors) suggest current thinning rates of ~0.08 m yr^{-1}, and divide migration toward the Ross Sea of 10 m yr^{-1} (Conway and Rasmussen, 2009). Modeling suggests that this trend may have occurred throughout the Holocene (Neumann et al., 2008), although it is difficult to disentangle whether this is a response to long-term (millennial) or short-term (centennial) forcing (Conway and Rasmussen, 2009). Our ice flow analysis shows that migration rates of this magnitude cannot have affected the Amundsen-Weddell divide for at least the past ~7000 yr, although it should be noted that there are no data on present-day, short-term divide behavior.

The contrasting behavior of the two ice divides may be a function of their underlying basal topography (Fig. 1B): the Amundsen-Weddell divide is underlain by the rugged topography of the Ellsworth Subglacial Highlands (Vaughan et al., 2006), while the topography beneath the Amundsen-Ross divide is far more subdued (Holt et al., 2006). The stability of the Amundsen-Weddell divide in the past ~7000 yr is in marked contrast to large-scale changes elsewhere in the WAIS. As a consequence, we believe that the Amundsen-Weddell ice divide may be insensitive to changes elsewhere in the ice sheet (cf. Scambos et al., 2004). This has important implications for our understanding of the future evolution of the WAIS. The pronounced morphology of the Ellsworth Subglacial Highlands and Ellsworth Mountains, compared with other regions beneath the WAIS (Fig. 1B), could lead to the ice sheet interior around the Amundsen-Weddell divide being resistant to even the most pronounced alterations to the ice sheet margin, including the dynamic changes currently taking place around the margin of the Amundsen Sea sector. Independent support for the topographic control on the Amundsen-Weddell ice divide comes from large-scale ice sheet modeling, which simulates a large ice dome positioned over the Ellsworth Subglacial Highlands even under super-interglacial conditions (Pollard and DeConto, 2009).

CONCLUSIONS

From observations of ice flow and englacial layering near the Amundsen-Weddell ice divide in the vicinity of Ellsworth Subglacial Lake, and from the Ellsworth Mountains, the following can be concluded. (1) For most of the Holocene, the ice divide between the Amundsen Sea and Weddell Sea embayments, one of the primary WAIS divides, did not undergo significant migration toward the Institute Ice Stream. Northwestward migration toward Pine Island Glacier is also unlikely. (2) Glacial geological evidence suggests that this divide position may be a long-term, recurrent, stable feature of the Amundsen-Weddell ice divide. (3) The long-term stability of the Amundsen-Weddell divide contrasts directly with the Amundsen-Ross ice divide, where observations reveal current ice divide migration at a rate of ~10 m yr^{-1} (Conway and Rasmussen, 2009). Our results indicate that similar migration (with expansion of the Amundsen Sea sector) cannot have occurred to the Amundsen-Weddell divide during the past several millennia. (4) The resilience of the Amundsen-Weddell divide is probably the result of the geometry of the underlying Ellsworth Subglacial Highlands and adjacent Ellsworth Mountains. These conclusions provide a long-term context to the recent changes documented in the Amundsen Sea sector of West Antarctica and contribute to our understanding of the long-term development of the WAIS.

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