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Key Points:

- Ice-penetrating radar surveys provide ice stream onset zone boundary conditions in central Antarctica
- Subglacial topography restricts hypothesized drawdown of the East Antarctic Ice Sheet through the bottleneck zone with West Antarctica
- Variability of discharge through subglacial troughs could change the form and position of the southernmost West Antarctic ice divide

Supporting Information:

- Supporting Information S1

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Topographic Steering of Enhanced Ice Flow at the Bottleneck Between East and West Antarctica

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Abstract Hypothesized drawdown of the East Antarctic Ice Sheet through the "bottleneck" zone between East and West Antarctica would have significant impacts for a large proportion of the Antarctic Ice Sheet. Earth observation satellite orbits and a sparseness of radio echo sounding data have restricted investigations of basal boundary controls on ice flow in this region until now. New airborne radio echo sounding surveys reveal complex topography of high relief beneath the southernmost Weddell/Ross ice divide, with three subglacial troughs connecting interior Antarctica to the Foundation and Patuxent Ice Streams and Siple Coast ice streams. These troughs route enhanced ice flow through the interior of Antarctica but limit potential drawdown of the East Antarctic Ice Sheet through the bottleneck zone. In a thinning or retreating scenario, these topographically controlled corridors of enhanced flow could however drive ice divide migration and increase mass discharge from interior West Antarctica to the Southern Ocean.

Plain Language Summary The East and West Antarctic Ice Sheets meet at the inland termination of the Transantarctic Mountains. The ice sheets coalesce at a major ice divide, which could migrate and impact ice flow across large parts of Antarctica. A lack of satellite observations of ice flow and ice thickness has previously restricted characterization of this region, its glaciology, and its subglacial landscape. Our ice-penetrating radar surveys reveal three deep subglacial valleys and mountainous subglacial topography beneath the ice divide. New measurements of ice flow evidence faster ice flow within these troughs than in the surrounding thinner ice. Were the ice sheet to shrink in size, an increase in the speed at which ice flows through these troughs could lead to the ice divide moving and increase the rate at which ice flows out from the center of Antarctica to its edges.

1. Introduction

The "bottleneck" zone, where the West and East Antarctic Ice Sheets (hereafter WAIS and EAIS, respectively) meet (Figure 1), is hypothesized to be a critical area where WAIS collapse, as suggested for the Pliocene period (Pollard & DeConto, 2009), could influence the dynamics of the much larger, neighboring EAIS. The bottleneck region contains a major West Antarctic ice divide, separating ice catchments in the Weddell and Ross Sea sectors (Figure 1), which could be susceptible to migration driven by ice dynamics. Although ice flow switching (Conway et al., 2002; Siegert et al., 2013; Winter et al., 2015), complex internal dynamics (Joughin & Alley, 2011), and enhanced "onset" ice flow (Beem et al., 2017; Bingham et al., 2007; Studinger et al., 2001) in the bottleneck region has the potential to impact mass discharge from the Antarctic interior, field site inaccessibility and the orbits of Earth observation satellites have previously restricted our understanding of basal topography and ice flow conditions in this area. This paper uses new aerogeophysical survey data acquired across the bottleneck zone during the 2015/2016 austral summer (PolarGAP survey data: https://earth.esa.int/web/guest/campaigns), complemented by ice thickness data acquired in 2010–2011 (Jeofry et al., 2018; Ross et al., 2012) and recent satellite-derived surface ice velocity measurements (Mouginot et al., 2017; Rignot et al., 2017; Figure 1b) to assess the controls on ice flow at the bottleneck zone. We analyze the aerogeophysical data to characterize the form and relief of major subglacial troughs and evaluate their control on enhanced flow of the tributaries of Foundation, Patuxent (a tributary of the Foundation Ice Stream), Kamb, Whillans, and Mercer Ice Streams, as well as the broader EAIS.

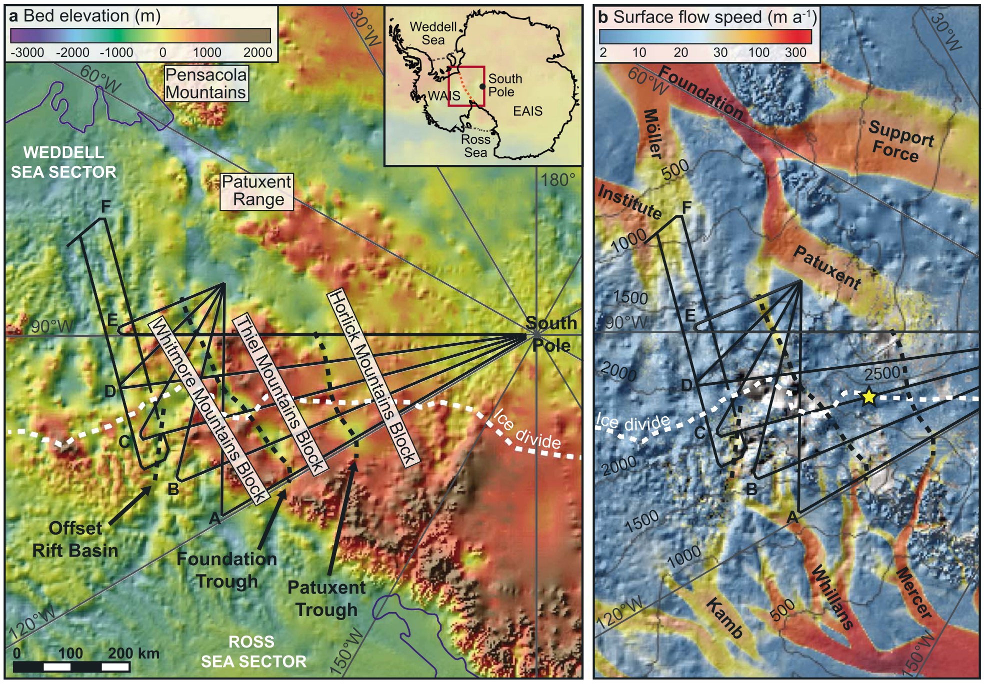

Figure 1. Study area: (a) Subglacial topography, merged with Bedmap2 (Fretwell et al., 2013) and regridded to include ice thickness picks from the PolarGAP RES survey, as well as other preexisting RES surveys (Figure S1) that intermittently cross the ice divide (white dashed line; Rignot et al., 2008). Black lines denote the locations of PolarGAP RES survey flight lines (A–E) and an IMAFI RES flight (F) used in this paper, while dashed black lines denote the location of troughs identified by these RES data. Blue lines indicate the Antarctic Surface Accumulation and Ice Discharge grounding line (Bindschadler et al., 2011). Major mountain ranges are labeled as well as the geographic South Pole, Weddell Sea sector, and Ross Sea sector (these are also marked on the wider Antarctic setting inset map, where the red box highlights the location of panel (a), and the dashed red line denotes the tectonic boundary between East and West Antarctica). (b) Satellite-derived surface ice flow measurements from MEaSUREs version 2 (Rignot et al., 2017), superimposed over a hill shade of bed topography. Regions without data coverage are shown in gray scale. Major ice streams are indicated as well as the Weddell/Ross ice divide (white dashed line), Hercules Dome (yellow star), surface contours at 500 m intervals (gray), and newly identified troughs (black dashed lines). RES = radio echo sounding.

2. Study Area

Our study area extends along the Weddell/Ross ice divide from the Horlick Mountains near the South Pole, to the Thiel and Whitmore Mountains block (Jankowski & Drewry, 1981; Figure 1a), a region described as the bottleneck of East Antarctica by Jacobel et al. (2005) and Pingree et al. (2011). The region encompasses the upper tributaries of Mercer, Whillans, and Kamb Ice Streams, draining to the Ross Sea, and the upper reaches of Institute, Möller, Foundation, and Patuxent Ice Streams (Figure 1), which drain into the Weddell Sea. Rates of surface accumulation at the ice divide range from 0.204 ± 0.035 m_{weq}/year (meters water equivalent per year) to 0.221 ± 0.041 m_{weq}/year (Arthern et al., 2006; Banta et al., 2008), where ice flows out from the divide at just a few centimeters per year (Mouginot et al., 2017; Rignot et al., 2017). In Antarctica, ice flow speeds typically increase from the interior to the coast (Rignot et al., 2011) as ice flow organizes into discrete tributaries of "patterned enhanced flow" (i.e., where velocity $>$ 25 m/year), in areas known as "onset zones." Ice streams are known to have a complex history of stagnations (Retzlaff & Bentley, 1993), reactivations (Hulbe & Fahnestock, 2007), and flow switching (Conway et al., 2002)—often driven by internal dynamics rather than external (e.g., ocean- or atmospheric-driven) forcing (Bingham et al., 2015; Joughin & Alley, 2011).

3. Methods

In the austral summer of 2015/2016, over 5,000 km of aerogeophysical data were acquired across the bottleneck region. Aerogeophysical survey flights were undertaken using a Twin Otter platform, with each flight section flown at a constant elevation to optimize the acquisition of gravity data. Aircraft position was obtained with differential Global Positioning System, and the range from aircraft to ice surface was measured by laser altimetry. The aircraft radar altimeter was used to provide an estimate of the surface elevation directly when cloud cover restricted the accuracy of these laser altimetry measurements. Radio echo sounding (RES) data were acquired with the British Antarctic Survey Polarimetric Airborne Survey Instrument radar system (Corr et al., 2007; Jeofry et al., 2018) operating at a center frequency of 150 MHz, a bandwidth of 12 MHz, and an effective pulse repetition frequency of 312.5 Hz. After initial processing, including unfocused Synthetic-Aperture Radar implemented with Doppler beam sharpening to enhance the signal-to-clutter ratio, the data were decimated to 2 Hz (~30 m) sample spacing. A depth-dependent gain was applied logarithmically to enhance weaker deeper reflections, and ice thickness was determined from the RES data using an ice velocity of 0.168 m/ns, with an additional firn correction of 10 m (in accordance with comparable aerogeophysical surveys of Antarctica (e.g., Ross et al., 2012; Vaughan et al., 2006). The bed of the ice sheet was picked in a semiautomatic manner using the first break autopicker function (with subsequent manual editing) in ProMAX seismic processing software.

Our new aerogeophysical data are combined with previously reported ice thickness data from the Institute and Möller Antarctic Funding Initiative (IMAFI) survey (available at https://secure.antarctica.ac.uk/data/aerogeo/) to produce a new digital elevation model of the bottleneck region. Detailed information on the acquisition and processing of those data is available in Ross et al. (2012) and Jeofry et al. (2018). All available point data across the study site (supporting information Figure S1a) were merged into a single database and gridded using a tensioned spline (internal tension 0.25) method with a cell size of 2.5 km. This local raster was subsequently shifted to the same geoid reference as Bedmap2 (Fretwell et al., 2013) and merged with the regional Bedmap2 bed elevation raster to create a new bed topography map of our study site (Figure 1a). Figure S1a shows the difference between our new bed topography map and Bedmap2.

4. Results

4.1. Basal Topographic Features

Radar data extending from 90°S to 83.5°S reveal three subglacial troughs in the bottleneck zone between East and West Antarctica. From south to north we term these Patuxent Trough, Foundation Trough, and the Offset Rift Basin (Figure 1). Patuxent Trough separates the low-elevation Horlick Mountains Block beneath South Pole (where bed elevations close to sea level are overlain by ice ≤2,500 m thick) from the Thiel Mountains Block (Figure 2), where inclined and incised subglacial topography (Figure 2), akin to tilted geological horst and graben structures (cf. Jordan et al., 2017; Paxman et al., 2017) supports ice 800–1,000 m thick. Near the Weddell/Ross ice divide (Figure 3a) the Patuxent Trough is over 15 km wide, with a relief of 600–1,400 m (Figure 3b). On either side of the divide, trough width and relief increase downstream (Figure 2). The ~300 km long Patuxent Trough achieves a maximum width of ~40 km, a relief of 1,000–1,350 m beneath Patuxent Ice Stream in the Weddell Sea sector of Antarctica, and a width of 35 km beneath the upper reaches of the Mercer Ice Stream in the Ross Sea sector of Antarctica (along RES line A), where the trough relief is 1,800 m and the overlying ice is 3,400 m thick (Figure 3c).

With a length of over 350 km, Foundation Trough is the largest subglacial trough, separating the Thiel Mountains Block from the Whitmore Mountains Block (Figure 2). At the Weddell/Ross ice divide (Figure 4a), Foundation Trough is at least 35 km wide, with a relief of over 2,000 m, supporting an ice thickness of 3,200–3,800 m (Figure 4b). Like Patuxent Trough, the width and relief of Foundation Trough varies along its length. Beneath the upper catchment of Foundation Ice Stream, the trough is over 30 km wide, with a relief of 2,000–2,900 m. This width decreases to 18–25 km at the head of the southernmost Whillans Ice Stream tributary (along RES line A), where the valley relief of ~2,000 m supports an overlying ice thickness of ~3,600 m (Figure 4c).

The Whitmore Mountains Block (Jankowski & Drewry, 1981) hosts the third major trough in our study area, previously referred to by Studinger et al. (2001) as "the Offset Rift Basin". PolarGAP survey data and IMAFI ice thickness measurements (labeled F in Figure 1) increase the inland extent of the Offset Rift Basin, close to the Weddell/Ross ice divide (Figure 5a), where the trough is 30 km wide, with a relief of ~3,500 m. Although the Offset Rift Basin does not appear to cut across the entire Whitmore Mountains Block, the 150-km-long trough provides a conduit for ice flow from deep inland Antarctica to the Siple Coast in the Ross Sea sector of Antarctica, where ice flow discharges through Whillans and Kamb Ice Streams. Further analysis of the basin, in terms of subglacial geometry and its relationship with the surrounding subglacial landscape, is restricted by survey line orientation and location.

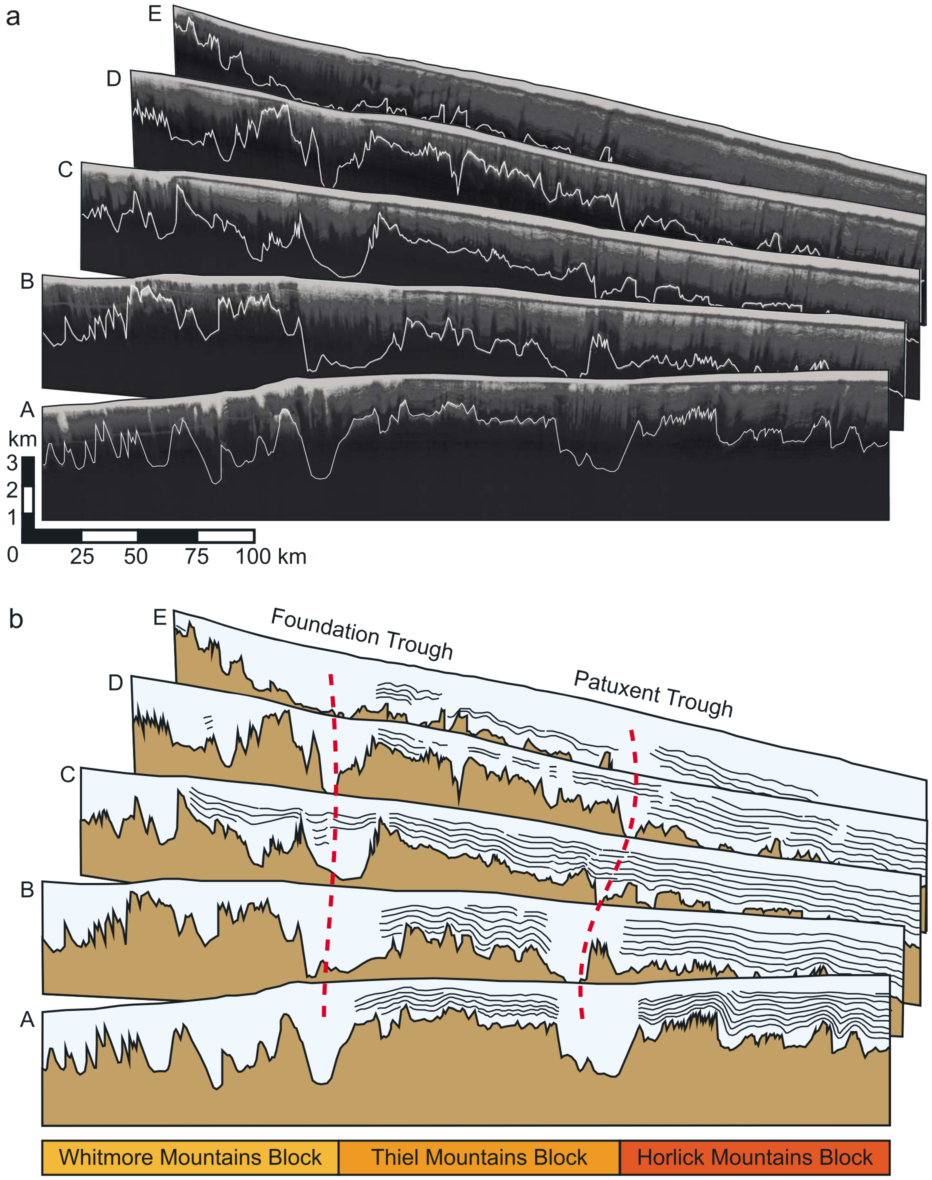

Figure 2. Three-dimensional schematic diagrams placing PolarGAP RES lines A–E (Figure 1) into approximate geographic/spatial context to highlight the morphology of the Patuxent and Foundation troughs, as well as the development of internal stratigraphy down flow within the Patuxent Trough. (a) RES lines A–E, digitized to show the subglacial interface (white). (b) Interpreted gross-scale structure of the two troughs (approximately marked by red dashed lines) that separate the Whitmore, Thiel, and Horlick mountain blocks. Bed topography is highlighted (brown), while black lines denote conformable englacial stratigraphic layers. RES = radio echo sounding.

4.2. Present-Day Ice Flow Configuration

Ice velocity data from MEaSUREs Version 2 (Mouginot et al., 2017; Rignot et al., 2017) provides important insights into the topographic controls on ice flow for our study area that were not available in Ice velocity data from the NASA Making Earth System Data Records for use in Research Environments (MEaSUREs) Version 1 (Rignot et al., 2011; Figure S1b). The improved spatial coverage of ice velocity data reveals that ice flow of Kamb, Whillans, Mercer, Patuxent, and Foundation Ice Streams onset closer to the southernmost Weddell/Ross ice divide than previously appreciated (Figure 5a). Although satellite coverage is limited in deep inland Antarctica, ice flow observations reveal that ice flows from the Weddell/Ross ice divide, through the troughs, at 1–15 m/year. As ice flows through Patuxent Trough these flow speeds increase to ~30 m/year beneath RES transect lines A and E (Figure 5b), marking the onset of enhanced flow of Mercer and Patuxent Ice Streams.

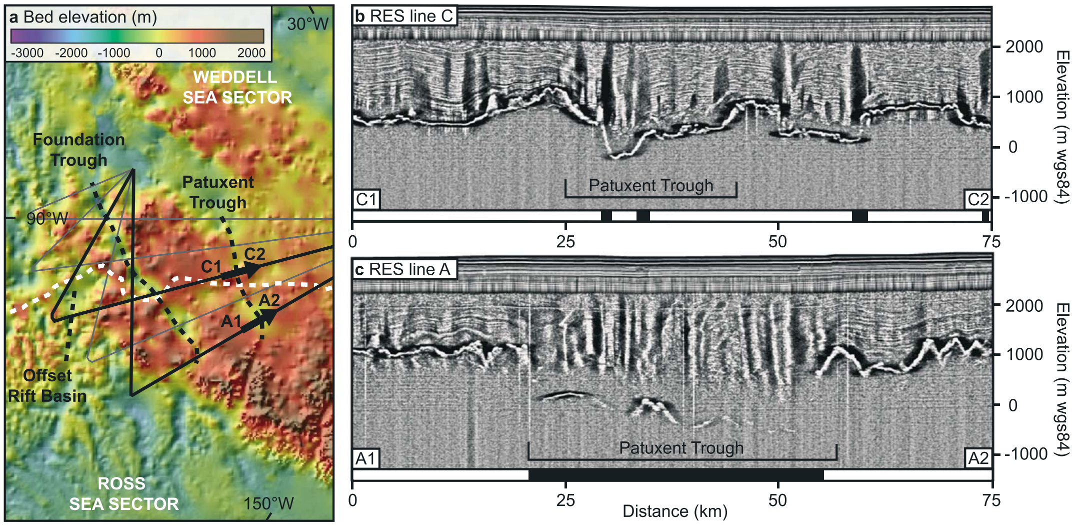

Figure 3. Ice stratigraphy in Patuxent Trough and surrounding area, identified in RES surveys. (a) Subglacial topography map, where arrows show the location of profiles C1-C2 and A1-A2 (in RES lines C and A). (b) Profile C1-C2 from RES line C reveals continuous englacial layering, conformable with subglacial topography in Patuxent Trough and adjacent ice. The white bar below the radargram marks these areas of continuous englacial layering, while regions of disrupted englacial stratigraphy are marked in black. (c) RES line A reveals buckled and disrupted ice within Patuxent Trough, which contrast with the continuous, well-defined englacial layers that drape over the bed in surrounding thinner and slower flowing ice (white bar). RES = radio echo sounding.

The greatest flow speeds in our study area are located within the boundaries of Foundation Trough (Figure 5a), where surface flow speeds exceed 90 m/year along RES transect line A (Figure 5c) as ice enters the complex of dendritic tributaries that define Siple Coast ice streams in the Ross Sea sector of Antarctica. On the Weddell Sea sector surface ice flow speeds of 40–50 m/year are recorded as ice enters the upper catchment of Foundation Ice Stream (Figure 5c). These flow speeds are typically a few times greater than the neighboring, slow-flowing ice (Figure 5a) above the Thiel and Whitmore Mountains Blocks.

Ice flow speeds in the Offset Rift Basin increase from 10–15 m/year near the ice divide, to over 70 m/year, 90 km down valley (Figure 5d). This contrasts with ice flow on either side of the subglacial channel, in which

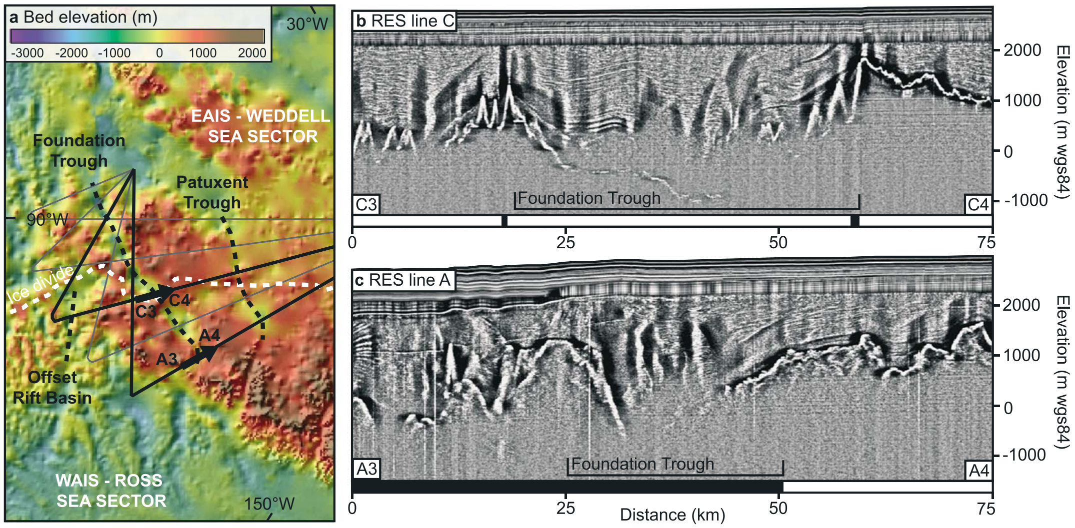

Figure 4. Ice stratigraphy in Foundation Trough and surrounding area, identified with RES surveys. (a) Subglacial topography map, where arrows show the location of profiles C3-C4 and A3-A4 (in RES lines C and A). (b) RES line C, collected close to the Weddell/Ross ice divide (white dashed line in panel a), reveals continuous englacial layering, conformable with subglacial topography, in Foundation Trough and surrounding highlands. The black bar below the radargram highlights short breaks in the otherwise continuous englacial stratigraphy. (c) RES line A, across the southern tributary of Whillans Ice Stream (panel a), reveals disrupted englacial stratigraphy in Foundation Trough (black bar), which contrast with the continuous, well-defined englacial layers draped across the Thiel Mountain Block (white bar). RES = radio echo sounding.

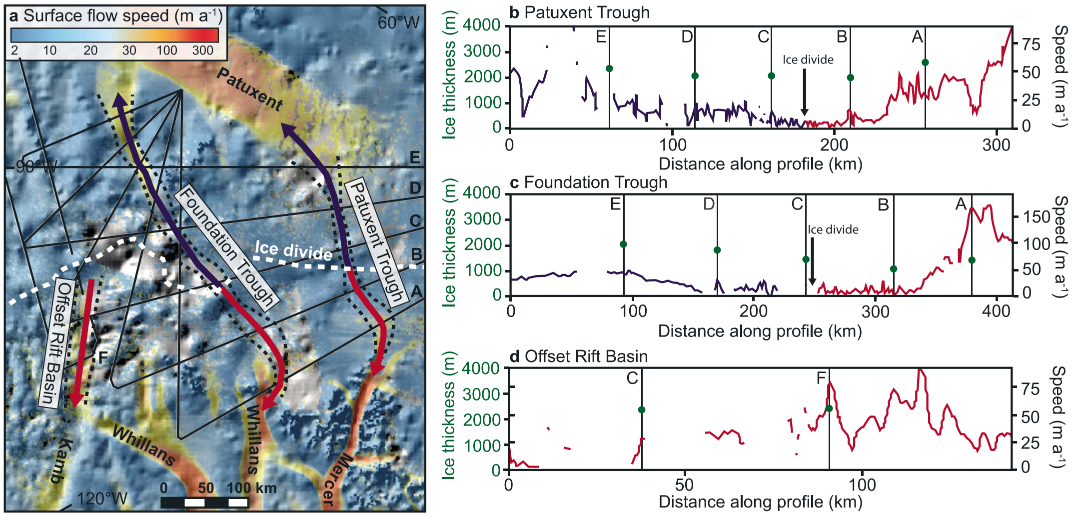

Figure 5. Satellite-derived surface ice flow measurements from MEaSUREs version 2 (Rignot et al., 2017), superimposed over bed topography and highlighted in (a) to show the extent of profiles along Patuxent Trough (b), Foundation Trough (c), and the Offset Rift Basin (d), where approximate trough boundaries are marked by a black dashed line in panel (a). The local ice divide is marked in panels (a)–(c) to show the point of separation between ice flowing toward the Weddell Sea (dark blue) and ice flowing toward the Ross Sea (red). The intersections between along-trough profiles and RES flight lines (A–F) are also marked on panels (b)–(d), where green dots reflect RES-derived ice thickness measurements. RES = radio echo sounding.

ice flows at 10–20 m/year above the elevated Whitmore Mountains Block. Tributaries of Kamb and Whillans Ice Streams capture ice flow from the Offset Rift Basin; the uppermost tributary of Kamb Ice Stream follows the straight trajectory of the Offset Rift Basin, while ice flow from the Offset Rift Basin to Whillans Ice Stream diverges 120°. This southern tributary of Whillans Ice Stream has surface flow speeds in the region of 60–180 m/year, contrasting with the uppermost tributary of the Kamb Ice Stream, where ice flows at 20–70 m/year, even though the main trunk of the Kamb Ice Stream is almost stagnant (Ng & Conway, 2004).

5. Discussion

5.1. Subglacial Topography

Our RES data reveal complex high-relief topography beneath the southernmost Weddell/Ross ice divide, in the bottleneck zone between East and West Antarctica. Three subglacial troughs provide a series of low-elevation conduits that channelize ice flow from interior Antarctica to Foundation Ice Stream and ice streams of the Siple Coast. While the pattern of this topography is presumably tectonic in origin (Rose, 1979; Studinger et al., 2001; Jordan, Ferraccioli, Armadillo, & Bozzo, 2013), the current over-deepened geometry of the troughs is also attributed here to fluvial and glacial modification during more restricted paleo ice sheet configurations (e.g., in Oligocene and Miocene times; Young et al., 2011).

As deforming sediments at the base of ice sheets can alter frictional stress and modify ice flow speeds (Bell et al., 1998; Peters et al., 2006; Stokes, 2018) it is important to assess the possibility of marine sediments at the base of Patuxent Trough, Foundation Trough, and the Offset Rift Basin. In these deep troughs RES returns are often weak or intermittent, so we explore the potential for marine sediments in our study area with the use of an isostatically rebounded elevation map (Figure S2), calculated using a simple Airy isostatic compensation of the current ice load (assuming an ice density of 915 kg/m^3 and mantle density of 3.33 kg/m^3; Jordan, Ferraccioli, Ross, et al., 2013). The resultant rebounded bedrock topography map (Figure S2) demonstrates that the valley floors of Patuxent Trough, Foundation Trough, and the Offset Rift Basin would be located above sea level along PolarGAP RES survey flight lines if the ice sheet were to be removed. While we recognize that erosion, flexural isostatic effects, and faulting will generate different paleotopographies compared to the simple predictions of an Airy isostatic model (Paxman et al., 2016, 2017), major recent erosion and faulting is not known to have occurred in this region. As a result, these findings provide no evidence for extensive, recent marine sedimentary drapes in Patuxent Trough, Foundation Trough, or the Offset Rift Basin. However, our analysis does not exclude the possibility of terrestrial sedimentation by geological, glaciological, and fluvial processes. Any terrestrial sediment accumulations could therefore extend the inland extent of subglacial sediments, recorded by Studinger et al. (2001), and impact ice flow dynamics (Bell et al., 1998; Peters et al., 2006; Stokes, 2018).

5.2. Ice Flow Configuration

Our data show that the newly identified Patuxent Trough, Foundation Trough, and previously identified Offset Rift Basin control the ice flow regime in the bottleneck zone, by steering ice flow and limiting its ability to modify its position by lateral migration (Figure 2). While satellite-derived ice flow measurements extend the recognized onset zone of Patuxent, Mercer, Whillans, and Kamb Ice Streams farther inland, radar data also reveal highly variable ice structure within and outside the troughs and in the upstream and downstream sectors of the troughs. Figure 3b reveals continuous englacial layering, conformable with subglacial topography in Patuxent Trough, and adjacent thinner ice flows near the Weddell/Ross ice divide in RES transect line C. However, as this ice streams into the upper catchment of Mercer Ice Stream, RES transect line A reveals disrupted englacial stratigraphy in Patuxent Trough (Figure 3c). This contrasts with bed conformable englacial layers in surrounding highland areas. Similar englacial stratigraphic features are also recorded in Foundation Trough (Figure 4b), where continuous englacial layering, conformable with basal topography, is visible in RES transect C (near the Weddell/Ross ice divide), within and outside the deep subglacial trough. As this ice flows into the southern tributary of Whillans Ice Stream, RES transect line A reveals disrupted englacial stratigraphy in Foundation Trough (Figure 4c). Again, this contrasts with continuous, bed conformable englacial stratigraphic layers that drape across the neighboring Thiel Mountains Block.

The presence of undisturbed englacial stratigraphy extending to depth beneath the Weddell/Ross ice divide suggests relative stability of the ice sheet at the bottleneck and at Hercules Dome (marked in Figure 1b) for several millennia (cf. Jacobel et al., 2005). However, should the ice sheet thin or retreat in the future, in response to internal dynamic processes (e.g., thermal or hydrological changes) or external forcing (potentially from ocean-driven melting of buttressing ice shelves and/or increased areal extent of surface melting and summer rainfall; DeConto & Pollard, 2016), ice flow would be routed through the topographically defined Patuxent and Foundation troughs, thereby retaining a distinction between East and West Antarctica. Modifications to mass balance in interior West Antarctica could also impact ice flow through the Offset Rift Basin. Mass balance changes could enhance ice flow through the Offset Rift Basin, potentially reactivating enhanced flow along the main trunk of Kamb Ice Stream (which abruptly stopped in the nineteenth century; Retzlaff & Bentley, 1993; van der Wel et al., 2013) and/or slow down or stagnate the presently fast-flowing Whillans Ice Stream (Figure S3; Joughin et al., 2005; Scheuchl et al., 2012).

5.3. East Antarctic Ice Sheet Drainage Through the Bottleneck Zone

Pingree et al. (2011) hypothesize that a WAIS collapse, akin to the extreme model scenario of DeConto and Pollard (2016), could lead to drawdown of the EAIS through the bottleneck zone at the southernmost WAIS divide. The occurrence of several high relief linear mountain ranges and subparallel subglacial valleys, with no regional scale transverse troughs for East Antarctic ice to flow through (Figure 1a), limits the potential for this hypothesized ice discharge. While this ancient topography anchors the WAIS (Ross et al., 2014), deep subglacial troughs beneath the ice divide could facilitate drawdown of local parts of the EAIS and/or enable westward movement of the ice divide. This scenario could be forced by retreat of Foundation Ice Stream, in response to collapse of the WAIS in the Weddell Sea sector, or through changes in buttressing by the Filchner-Ronne Ice Shelf (Hellmer et al., 2012).

6. Conclusions

PolarGAP RES transects refine ice stream onset zone boundary conditions in central Antarctica at the inland termination of the Transantarctic Mountains. Linear mountain ranges and deep subglacial troughs in the bottleneck region between East and West Antarctica separate flow of the EAIS from West Antarctica, limiting hypothesized drawdown of the EAIS through the WAIS. Undisturbed englacial stratigraphy in Patuxent and Foundation Troughs suggest relative stability of the ice sheet at the Weddell/Ross ice divide beneath Hercules Dome for several millennia. However, in a thinning or retreating scenario, these topographic corridors could facilitate enhanced flow farther inland, with the potential to drive ice divide migration, and discharge mass rapidly from the central interior of West Antarctica. The differential mass flux to Weddell and Ross Seas depends on the migration of this divide.

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