LETTER

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Inland thinning of West Antarctic Ice Sheet steered along subglacial rifts

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Current ice loss from the West Antarctic Ice Sheet (WAIS) accounts for about ten per cent of observed global sea-level rise[1]. Losses are dominated by dynamic thinning, in which forcings by oceanic or atmospheric perturbations to the ice margin lead to an accelerated thinning of ice along the coastline[2–5]. Although central to improving projections of future ice-sheet contributions to global sea-level rise, the incorporation of dynamic thinning into models has been restricted by lack of knowledge of basal topography and subglacial geology so that the rate and ultimate extent of potential WAIS retreat remains difficult to quantify. Here we report the discovery of a subglacial basin under Ferrigno Ice Stream up to 1.5 kilometres deep that connects the ice-sheet interior to the Bellingshausen Sea margin, and whose existence profoundly affects ice loss. We use a suite of ice-penetrating radar, magnetic and gravity measurements to propose a rift origin for the basin in association with the wider development of the West Antarctic rift system. The Ferrigno rift, overdeepened by glacial erosion, is a conduit which fed a major palaeo-ice stream on the adjacent continental shelf during glacial maxima[6]. The palaeo-ice stream, in turn, eroded the 'Belgica' trough, which today routes warm open-ocean water back to the ice front[7] to reinforce dynamic thinning. We show that dynamic thinning from both the Bellingshausen and Amundsen Sea region is being steered back to the ice-sheet interior along rift basins. We conclude that rift basins that cut across the WAIS margin can rapidly transmit coastally perturbed change inland, thereby promoting ice-sheet instability.

Many independent satellite sensors have been used to gauge the recent mass imbalance of the Antarctic ice sheet, thereby to assess the rate of its contribution to global sea-level rise[2–4,8]. These studies highlight coastal regions of the WAIS as major contributors to current sea-level rise through a process termed "dynamic thinning"[2]. Such a region is Pine Island Glacier in the Amundsen Sea embayment, where gradual ungrounding and thinning of the floating ice shelf, potentially triggered by oceanic forcing, have induced progressive drawdown and thinning of inland ice[3–5]. These observations have reignited concerns that the wider WAIS is progressing towards a predicted collapse within the next few centuries, increasing the need to understand the fundamental influences on its dynamic behaviour.

Theory suggests that the stability of WAIS is controlled by the subglacial topographic configuration, with landward-deepening basins favouring runaway retreat inland[9]. The subglacial geology and crustal structure of the West Antarctic rift system (WARS; Fig. 1a) may also influence ice dynamics[10–12]. Sedimentary basins underlie the onset of some ice streams in the Ross Sea embayment[13,14] and their initiation may be affected by elevated geothermal heat flux linked to inferred recent volcanism[10,15]. Yet, for the Bellingshausen Sea embayment, currently one of the most rapidly thinning parts of the WAIS (Fig. 1b), the subglacial topography and geological setting that may influence ice-sheet behaviour have remained largely unknown. Here we analyse new geophysical data sets from inland of the Bellingshausen Sea and demonstrate that propagation of ice thinning towards the interior is promoted where narrow rift basins associated with a northeasterly extension of the WARS connect to the ocean.

Our data set comprises the first systematic radar survey of Ferrigno Ice Stream (FIS; 85° W, 74° S), a 14,000-km^2 ice-drainage catchment clearly identified by satellite altimetry as the most pronounced 'hotspot' of dynamic thinning along the Bellingshausen Sea margin of the WAIS (Fig. 1b). Data were collected by over-snow survey between November 2009 and February 2010, and supplemented by airborne data collected by the US NASA Operation IceBridge programme in 2009. The only previous measurements of ice thickness across the entire 150 km × 115 km catchment were a sparse set of reconnaissance seismic and gravity spot-depths obtained 50 years previously along exploratory traverses, and a handful of airborne radar measurements collected on the way to other locations (Fig. 1c). Our new view of the bed beneath FIS reveals a narrow subglacial basin with a maximum depth of about 1,500 m below sea level striking northeast–southwest through the catchment. Viewed in the wider context (Fig. 1d), using the most recent compilations of subglacial topography and offshore bathymetry, together with new analyses of magnetic and gravity data, we can see that the basin forms part of a major fault system that connects rift basins in the interior of the WARS to Eltanin Bay[16,17] (Supplementary Fig. 1a–c).

Radar-derived bed echoes across FIS (Fig. 2a, Supplementary Figs 2–4) deviate in form from the U-shaped parabolic profile that represents the 'pure' product of glacial erosion[18]. Instead, the steeply dipping, approximately 1-km-high basin flanks and the flat basin floor resemble classical rift structures[19]. Further supporting evidence for a rift origin is the dip of the bed away from the basin flanks (Fig. 2a, Supplementary Figs 3 and 4), consistent with the tilting of fault blocks and footwall uplift.

Aeromagnetic anomaly data[20] (Fig. 3, Supplementary Figs 5–7) reveal that the Ferrigno rift formed close to the boundary between a highly magnetic magmatic arc province that lies primarily offshore in the FIS region (and that extends from the Antarctic Peninsula to Thurston Island) and a more weakly magnetic province onshore. The latter is interpreted as a back-arc region, where the early WARS developed about 105–90 million years (Myr) ago[21]. This part of the WARS was then reactivated during inferred dextral transtensional motion between 48 Myr ago and 26 Myr ago[17]. Depth to magnetic sources help to constrain our gravity and magnetic models and indicate that the narrow Ferrigno rift contains about 1 km of sedimentary infill (Fig. 3c, d, Supplementary Figs 8 and 9). Three-dimensional inversion of satellite gravity data indicates that the crust is around 25–21 km thick beneath the Ferrigno rift and the adjacent Siple Trough region (Fig. 1d and Supplementary Figs 1c and 10). This is similar to the 22–24-km-thick crust in the western Amundsen Sea embayment[22] and the approximately 20-km-thick crust beneath the Pine Island rift[23] and the Bentley Subglacial Trench[10]. These new findings lead us to conclude that the Ferrigno rift region was affected by crustal thinning associated with the WARS. There is, however, no magnetic evidence in support of widespread Cenozoic magmatism

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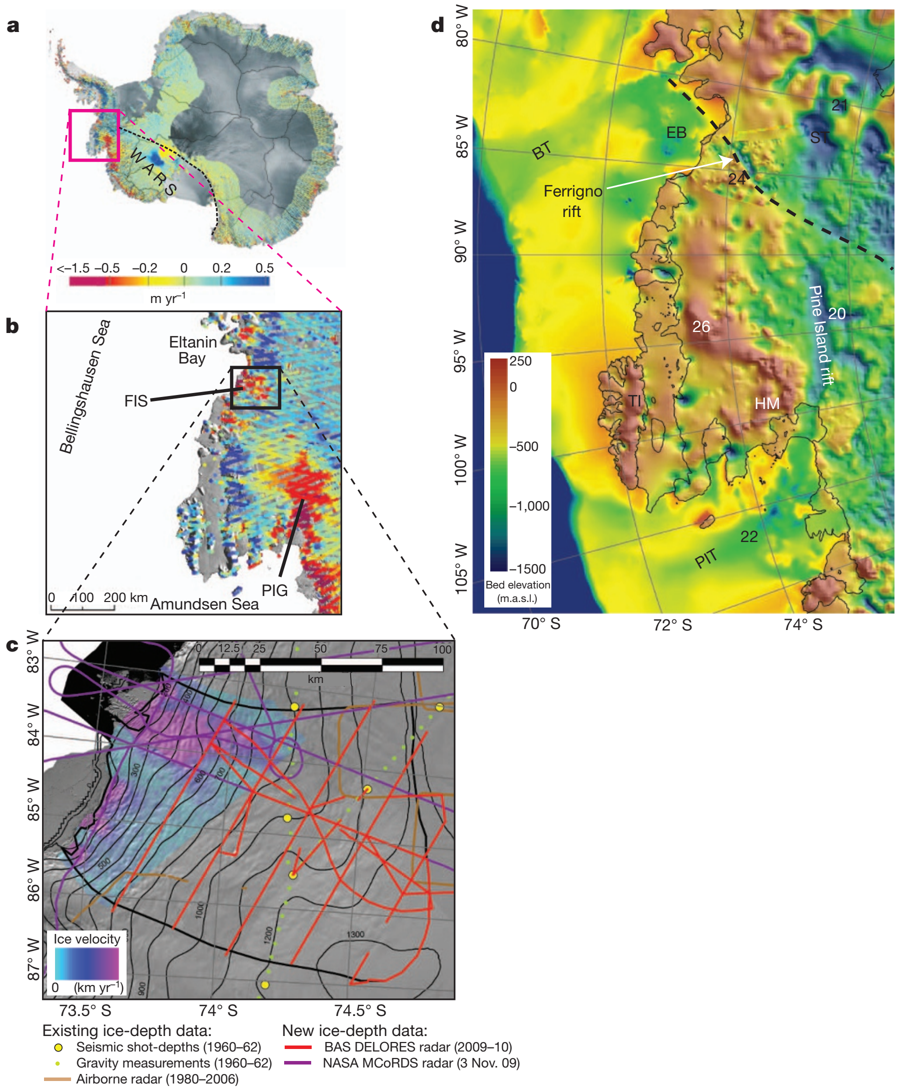

Figure 1 | Surface change, survey coverage, and subglacial topography for the Bellingshausen Sea sector of West Antarctica. **a**, Rate of surface elevation change along ICESat tracks measured between 2003 and 2007; superimposed over the Landsat Image Mosaic of Antarctica (grey shading). Regions coloured red in the Bellingshausen and Amundsen Sea sectors of West Antarctica exhibit strong ice surface lowering attributable to dynamic thinning. The flank of the WARS is annotated with a black dashed curve. **b**, Enlargement of the boxed area in **a**, with major geographical features labelled. **c**, Enlargement of the boxed area in **b**, showing orientation of new radar tracks obtained across FIS in 2009–10; pre-existing ice-depth measurement locations are also marked. The black line demarcates the Ferrigno catchment. Also shown are satellite-derived ice velocities for the lower portion only of the catchment (ref. 28), 100-m surface contours and background imagery from the Landsat Image Mosaic of Antarctica. **d**, Regional subglacial topography mosaicked from our new data set for FIS (see Fig. 3a and Supplementary Fig. 3 for detail) and refs 29 and 30. The black dashed line highlights a major fault system that we propose connects rift basins in the interior of the WARS to Eltanin Bay (EB). BT, Belgica trough; PIT, Pine Island trough; ST, Siple trough; TI, Thurston Island; HM, Hudson Mountains. Numbers are estimates of crustal thickness (in kilometres) in the WARS derived from inversion of Bouguer gravity anomaly data and seismic data[11,22]. m.a.s.l., metres above sea level.

close to the Ferrigno rift, in contrast to the Ross and Amundsen Sea sectors of the WARS (Supplementary Figs 1b and 11).

A recently suggested middle-Miocene (about 17–13 My ago) change in plate motion between East and West Antarctica[24] has significant implications for how we interpret the Ferrigno rift in relation to inferred Neogene (23–2.5 Myr ago) rifting processes (Fig. 1d and Supplementary Fig. 1). A Neogene rifting stage and glacial overdeepening may account for the deepest basins within the WARS, including the Byrd Subglacial Basin and the Bentley Subglacial Trench[17]. The low effective elastic thickness in the Pine Island rift[23] is similar to values observed over recent rifts[19], supporting the hypothesis of a Neogene rifting phase there. All these features that are inferred to be Neogene rifts may be kinematically linked (Fig. 1d and Supplementary Fig. 10).

We note that the Ferrigno rift broadly aligns with the inland extent and distribution of the dynamic-thinning signal observed at the ice surface with altimetry (Fig. 3a). Modern ice flow also follows the direction of the rift (Fig. 1c). These associations suggest that dynamic thinning of ice towards the West Antarctic interior may be promoted where ice is underlain by glacially overdeepened rift basins associated with development of the WARS.

We propose two factors that can explain the observed correlation of inland dynamic thinning with subglacial rifting. First, the sedimentary infill we identified within the Ferrigno rift (Fig. 3c, d) probably facilitated formation of a deforming bed (see ref. 14 for an example) that would promote enhanced ice flow and thinning. Second, elevated geothermal heat flux has been measured within the Terror rift (Supplementary Fig. 1a), a narrow rift basin that was active in Neogene times[25]. If the Ferrigno rift were similarly active in the Neogene, as we hypothesize, then enhanced geothermal heat flux linked to focused crustal thinning would probably occur beneath FIS. This would lead to excess generation of subglacial meltwater, which in turn would lubricate the bedrock, accelerate ice flow and thereby exacerbate dynamic thinning effects. Although incidences of rifts exploited and overdeepened by ice-stream flow have been noted elsewhere[13,26,27], in none of these cases has an influence on contemporary ice thinning been noted. What seems to be required to promote dynamic thinning inland is a coincidence of a deep rift basin cutting across the ice-sheet margin and inflow of warm ocean water onto the continental shelf.

We conclude that the WAIS is most at threat from the inward incursion of dynamic thinning along glacially overdeepened rifts that extend both into the Amundsen and Bellingshausen seas. The Ferrigno rift connects through to Eltanin Bay, where the lack of an ice shelf today and in the observational record implicates the sustained presence of relatively warm air and/or ocean water[7], providing a forcing mechanism for the dynamic thinning of coastal ice. Without favourable subglacial conditions further inland, this dynamic thinning would be limited to the coastal fringes as on other parts of the Antarctic margin; instead, the deep inland reach of the Ferrigno rift facilitates a strong coupling between the oceanic front and the deeper ice-sheet interior (Fig. 3a and Supplementary Fig. 12). The situation at the FIS evokes that of Pine Island Glacier, where, over two decades of observation, the access of warm ocean water has instigated dynamic thinning at the

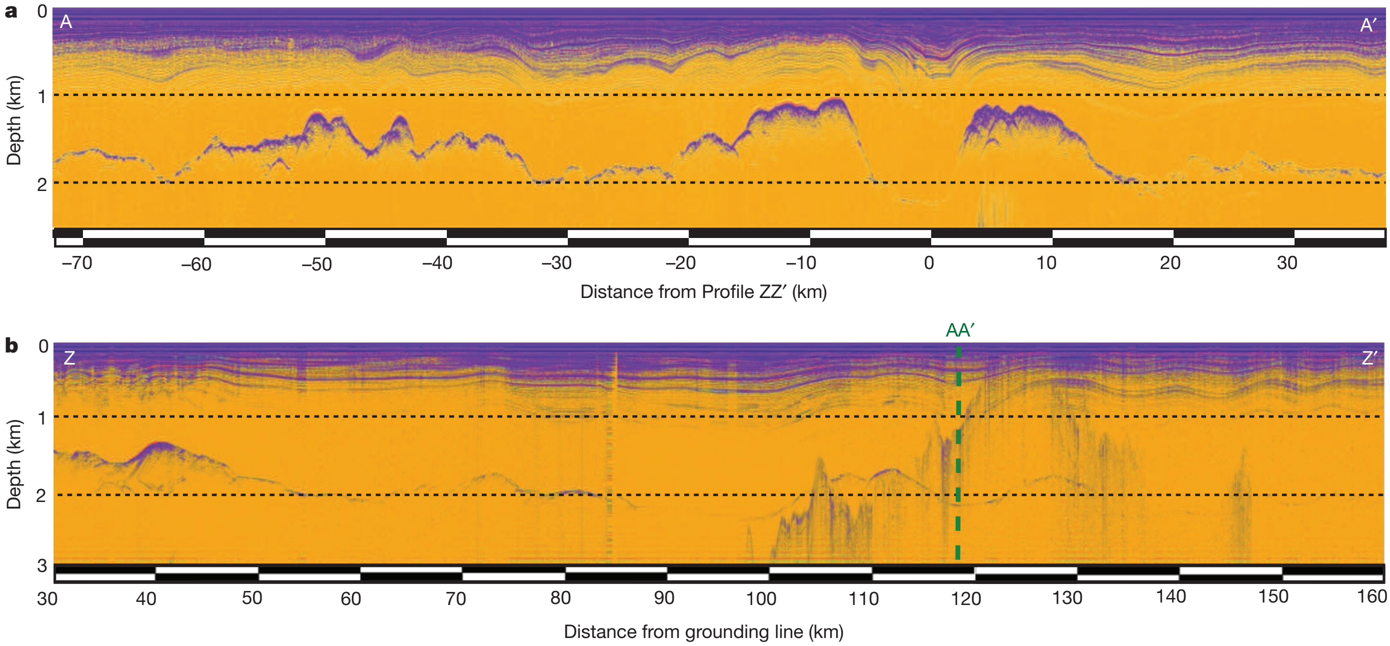

Figure 2 | Radar profiles showing morphology of Ferrigno Ice Stream bed. **a**, 110-km-long radar profile across the Ferrigno catchment transverse to the main axis of ice flow (profile AA′ marked on Fig. 3a). Distance scale is marked relative to the ice-stream (rift) centreline (path followed by profile ZZ′ in **b**). Ice flow is towards the reader. The vertical scales in **a** and **b** show depth below present ice surface. **b**, 130-km-long radar profile collected along the main trench ZZ′ (location marked on Fig. 3a). Distance scale is marked in kilometres from the grounding line; the crossing point of profile AA′ is shown. Sporadic interference patterns between 100 km and 147 km result from 'sideswipe' returns from valley walls as the radar passed over a narrowing in the trench.

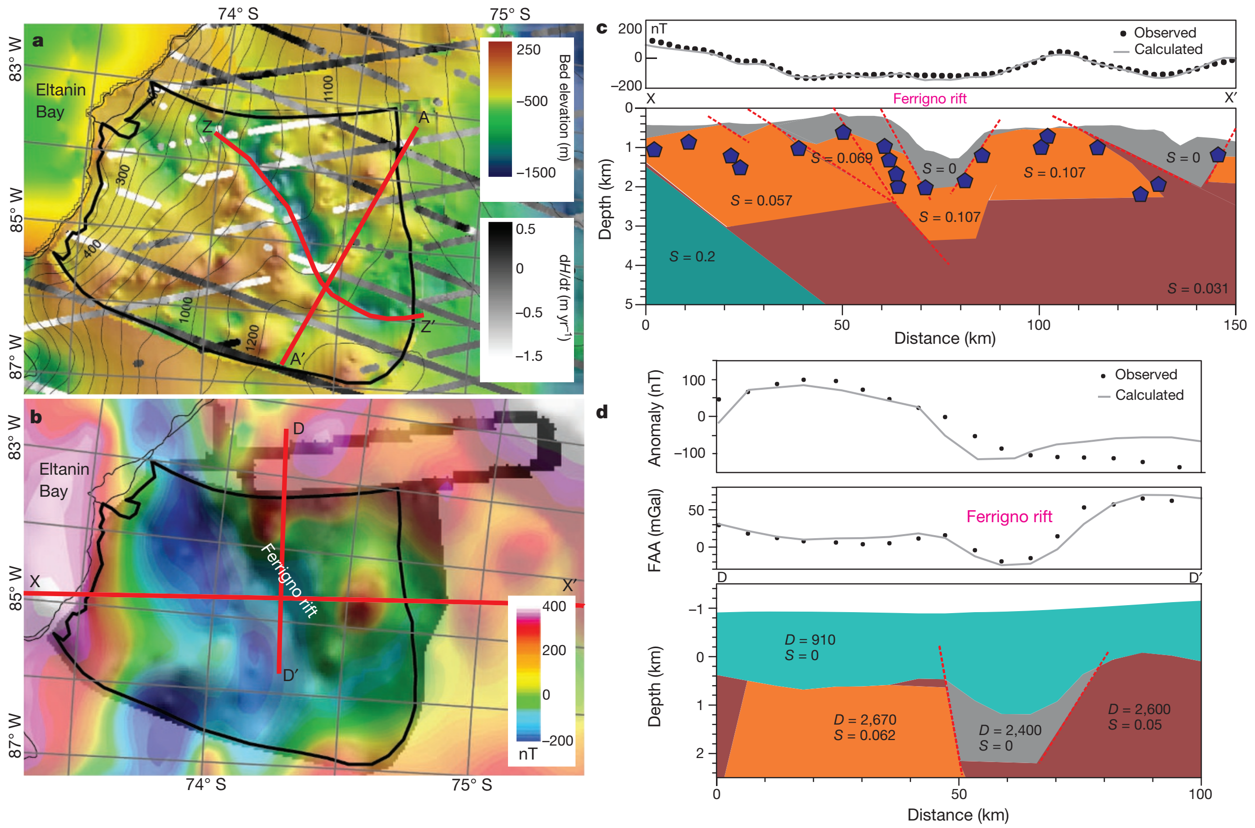

Figure 3 | Dynamic thinning of the ice sheet steered along a subglacial rift. **a**, Rate of surface ice elevation change measured between 2003 and 2007 along ICESat tracks (greyscale) superimposed over subglacial topography, showing enhanced thinning in the interior over the Ferrigno rift region. Black contours with labels show surface topography. Red lines show radar profiles in Fig. 2. **b**, The same area, reduced to the pole aeromagnetic anomaly map (colour scale, partially transparent), with new Ferrigno subglacial topography underneath. Note the northeast–southwest-oriented magnetic low that aligns with the Ferrigno rift. Red lines show the location of our magnetic and gravity models of the Ferrigno rift. **c**, Magnetic model of the Ferrigno rift. Blue symbols show the results of depth to magnetic source calculations that help constrain the model; the numbers denote magnetic susceptibilities. **d**, Combined gravity and magnetic model, indicating an approximately 1-km-thick sedimentary infill in the Ferrigno rift. Magnetic susceptibilities and densities are labelled as S (dimensionless) and D (kg m^{-3}) respectively.

grounding line, followed by propagation of ice drawdown deep along the Pine Island rift[3,23]. A radar profile we collected directly along the main axis of FIS (Fig. 2b) shows the bed deepening inland for about 70 km from the lower reaches. This leaves much of the upper catchment of FIS vulnerable to impending drawdown and retreat analogous to that of Pine Island Glacier, and demonstrates that the risk to the WAIS from dynamic thinning extends beyond the Amundsen Sea embayment.

Overall, the recent changes being witnessed today in West Antarctica represent not simply a short-term ice-sheet response to climate warming, but form part of a wider, sustained and complex system of interactions between tectonic activity, glacial landscape modification, and oceanic and atmospheric change. Over millennia, ice streams such as FIS and Pine Island Glacier have exploited rift structures and, over several glacial maxima, focused flow into palaeo-ice streams that have eroded troughs over the continental shelf such as the Belgica and Pine Island troughs (Fig. 1d). The Pine Island trough itself exploits a tectonic lineament caused by former rifting[22]; the Belgica trough also aligns with a northwest–southeast trending scarp on the inner continental shelf that runs at right angles to FIS and is probably imposed on a major tectonic lineament (Fig. 1d). These 'rift-directed' offshore troughs now form the putative routes through which warm open-ocean waters penetrate back over the continental shelf to attack the ice margin. Overdeepened rift basins onshore are now steering the transmission of this dynamic-thinning perturbation even further back towards the interior of West Antarctica, with likely consequences for ice-sheet stability.

METHODS SUMMARY

Our radar survey of FIS represents the only over-snow exploration over the region since two traverses immediately following the International Geophysical Year 50 years previously. It also comprises the first systematic survey (to our knowledge) of any of the WAIS catchments fringing the Bellingshausen Sea. Radar data were collected with the British Antarctic Survey DELORES system, a 2-MHz monopulse 'DEep-LOoking Radio Echo Sounder' with a pulse-repetition rate of 1 kHz and a digitization period of 10 ns. Tying this into dual-frequency global positioning system (GPS) for navigational fixing, we measured ice thickness at 7.5-m intervals along tracks, obtaining a total of 250,970 ice-thickness points. Assuming radar wave speed through ice of 168.5 m μs^{-1}, these were converted to bed elevations with estimated $\pm$3-m vertical resolution (see the file named ferrigno_delores.txt in the Supplementary Information). We also incorporated 17,793 further ice-thickness measurements obtained over parts of FIS on 3 November 2009 by the US NASA Operation IceBridge programme 140–230 MHz Multichannel Coherent Radar Depth Sounder (MCoRDS) (publicly available on http://nsidc.org/icebridge/portal/). We used these measurements, and the small amount of existing earlier ice-thickness measurements (http://www.antarctica.ac.uk//bas_research/data/access/bedmap/), to interpolate bed elevations over a 1-km grid mesh. We provide the final grid file used for this paper, ferrigno_topogrid_1km.txt in the Supplementary Information.

A reconnaissance aeromagnetic survey was made across the region in 1986–1987 (ref. 20), after which no further data were acquired. We reprocessed these data (see the file named mag_Drape3500_redp.XYZ in the Supplementary Information) and analysed them together with land gravity data to derive new models of the Ferrigno rift and estimate the thickness of its sedimentary infill. To assess crustal thickness beneath the WARS we applied three-dimensional inversion to satellite gravity data and airborne gravity data over the adjacent catchment of Pine Island Glacier.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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