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Late Holocene ice-flow reconfiguration in the Weddell Sea sector of West Antarctica☆

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ABSTRACT

Here we report Late Holocene ice sheet and grounding-line changes to the Weddell Sea sector of West Antarctica. Internal radio-echo layering within the Bungenstock Ice Rise, which comprises very slow-flowing ice separating the fast-flowing Institute and Möller ice streams, reveals ice deformed by former enhanced flow, overlain by un-deformed ice. The ice-rise surface is traversed by surface lineations explicable as diffuse ice-flow generated stripes, which thus capture the direction of flow immediately prior to the creation of the ice rise. The arrangement of internal layers can be explained by adjustment to the flow path of the Institute Ice Stream, during either a phase of ice sheet retreat not longer than ∼4000 years ago or by wholesale expansion of the grounding-line from an already retreated situation not sooner than ∼400 years ago. Some combination of these events, involving uplift of the ice rise bed during ice stream retreat and reorganisation, is also possible. Whichever the case, the implication is that the ice sheet upstream of the Bungenstock Ice Rise, which currently grounds over a >1.5 km deep basin has been, and therefore may be, susceptible to significant change.

1. Introduction

Ice within the West Antarctic Ice Sheet (WAIS), which is grounded on a bed predominantly below sea level, flows across a 'grounding line' into the ocean either directly or via peripheral floating ice shelves. The ice sheet is thought to be susceptible to change as a consequence of ocean-induced ice-shelf melting, which leads to inward migration of the grounding line (Pritchard et al., 2012). This process could result in grounded ice loss, which potentially would raise global sea level by >3 m (Bamber et al., 2009a). Critical to assessing the likelihood of future change is an awareness of significant past changes and an identification of regions susceptible to change.

Although the post-LGM retreat of the WAIS is understood broadly, Holocene adjustments are less well known. These changes are more critical to how the ice sheet may change in the immediate future, since the environmental conditions and ice sheet configuration that led to Holocene change are comparable to today. One location where Late Holocene information is absent is the Weddell Sea sector of the WAIS, where airborne radio-echo sounding (RES) has recently revealed the ice sheet grounding line to be positioned at a major steep reverse bed slope (Ross et al., 2012) making it potentially susceptible to mass loss (e.g. Hellmer et al., 2012).

Here we analyse RES and satellite remote sensing data from the Bungenstock Ice Rise (BIR), a small slow-flowing ice dome that currently separates the fast flowing Institute (IIS) and Möller (MIS) ice streams in the Weddell Sea sector of the WAIS. By analysing the englacial layering and surface form of the ice rise we characterise its glacial history. The consequence of this local glacial history to wider ice sheet changes in the Weddell Sea sector is then discussed.

2. RES, internal layers and ice rises

Ice sheet internal layers, measured by RES, occur as a consequence of contrasts in permittivity arising from density changes in the upper few hundred meters of the ice sheet, and in conductivity due to discrete acidic layers of ice that incorporate the aerosol product of volcanic activity deposited on the snow surface (Paren et al., 1975). In slow flowing central regions of ice sheets, and in ice rises that separate ice streams, layering is commonly conformable and continuous over several tens of kilometres (e.g. Siegert, 2003; Siegert and Payne, 2004; Cavitte et al., 2013). Such

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layering, as it has a meteoric origin, is thought to be isochronous (Siegert, 1999). In contrast, in fast flowing ice streams layering becomes buckled due to increased englacial stress gradients caused by differential motion, convergent flow, and flow around subglacial obstacles (Jacobel et al., 1993; Siegert et al., 2003; Leysinger Vieli et al., 2007; Ross et al., 2011). Many ice rises, which by definition possess flow divides, contain only conformable layering. If the flow divide remains in the same position, the layering under the divide will take the form of a stack of Raymond Arches (Raymond, 1983; Conway et al., 1999; Vaughan et al., 1999), which are seen in ice rises in parts of the Weddell Sea sector (Hindmarsh et al., 2011). The englacial layering within an ice rise is therefore of value in assessing whether current regional glaciological conditions have prevailed (Martín et al., 2009).

3. Bungenstock ice rise and airborne geophysical data

While most ice rises are crossed by a clear divide ridge, the divide over the BIR is only obvious from satellite data over its 'inland' half (Fig. 1a and b). Bordering the ice shelf, the BIR has a lobate apron-like form with no divide ridge (Fig. 1b). Ice velocities across the BIR are very low, rising from 0 m a^{-1} at its centre to ~5 m a^{-1} at the margin (Rignot et al., 2011) (Fig. 1d).

The BIR has been surveyed on several occasions by airborne RES since the late 1970s (e.g. Janowski and Drewry, 1981; Lambrecht et al., 1999, 2007; Ross et al., 2012), revealing that ice thickness ranges from ~1000 m near the grounding line to >2000 m where it adjoins the MIS. Bed topography is noticeably smooth, with depths of 830–1600 m b.s.l. (Fig. 1c). Loose, unconsolidated basal sediments are likely present beneath the BIR, judging by the very low bed roughness, which is similar to that observed across the Siple Coast region (see supplementary information in Ross et al., 2012).

The most recent two RES surveys of the BIR were undertaken by the British Antarctic Survey (BAS) using a coherent system with a carrier frequency of 150 MHz, a bandwidth of 12 MHz and pulse-coded waveform acquisition at a rate of 312.5 Hz. In these surveys, aircraft position was obtained from differential GPS, and the surface elevation of the ice sheet was derived from radar/laser altimeter terrain-clearance measurements. Doppler processing was used to migrate radar-scattering hyperbola in the along-track direction. The onset of the received bed echo was picked in a semi-automatic manner using PROMAX seismic processing

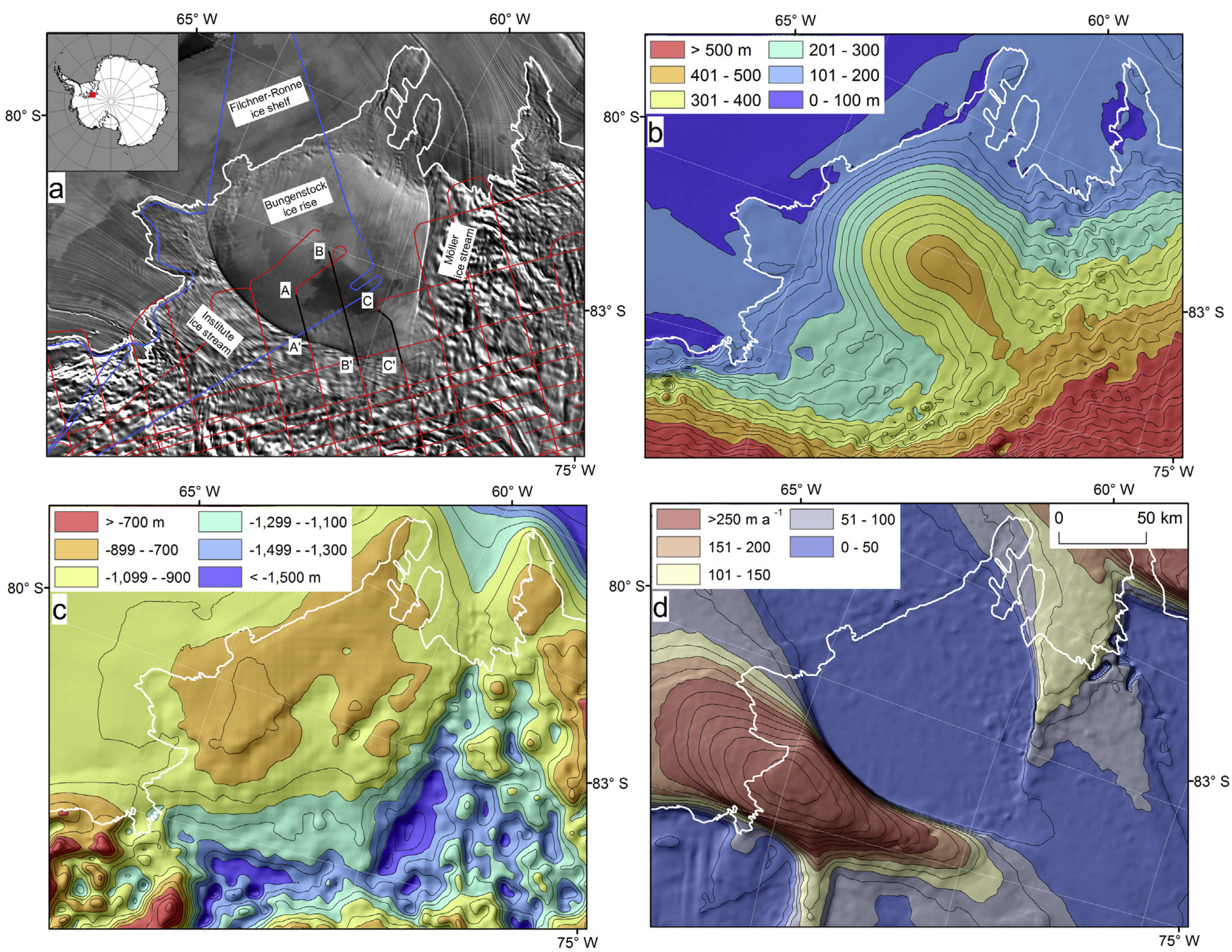

Fig. 1. The Bungenstock Ice Rise (BIR). (a) Location of the BIR, existing BAS RES data and MODIS Mosaic of Antarctica (MOA) ice surface imagery (Haran et al., 2006). White line is the existing ice sheet grounding line from the MODIS MOA, blue lines are RES data collected in 2006/7, red lines are RES data collected in 2010/11. The black sections of RES lines are RES transects given in Fig. 2. (b) Ice surface elevation (data from Bamber et al., 2009b). (c) Subglacial topography (data from Fretwell et al., 2013). (b) and (c) are referenced to the WGS84 geodetic system. (d) Ice surface velocity (data from Rignot et al., 2011).

software. The post-processed data rate was 6.5 Hz, giving a spatial sampling interval of ~10 m. The travel time in the near-surface firn layer is taken as the sum of two components; solid ice and an air gap. When calculating ice thickness we use a nominal value of 10 m to correct for the firn layer. A spatial variation in density affects the equivalent air gap, possibly accounting for variations across the survey area in the order of 3 m. However, this error is small relative to the overall error budget, which is dominated by the uncertainty in the total ice thickness, estimated to be in the order of ±1%.

The BAS BIR RES data reveal a clear difference in englacial stratigraphy between buckled, broken disrupted englacial layers at depth, overlain by near-surface conformable layers. The boundary between these englacial units, in available data, typically occurs at a depth of around 40% of the ice thickness (e.g. 600 m from the surface where the ice is 1400 m thick) (Fig. 2). No evidence of obvious, well-formed Raymond Arches is observed in the upper layering. The bed is remarkably smooth beneath the BIR, indicating flow around topography is not responsible for the englacial disruption (Figs. 1c and 2). Instead, the change from buckled to conformable layers (Fig. 2) is best explained by a shift in ice-sheet dynamics from fast to slow flow.

The date of this change can be estimated by calculating the age of the deepest conformable layer, assuming stable conditions. Employing a simple 1-D thinning equation (e.g. Siegert and Payne, 2004) using RES measurements of ice thickness, an accumulation rate of 0.2 m yr^{-1} (Arthern et al., 2006) and assuming negligible basal melting, gives an age of ~4000 years. As substantial basal melt has the potential to reduce this value, and as no obvious Raymond Arches are observed (supporting the idea of recent glaciological change), it should be regarded as an approximate maximum age, however.

4. Satellite imagery and palaeo ice flow

MODIS Mosaic of Antarctica (MOA) satellite imagery reveals parallel surface lineations traversing the BIR (Fig. 3). These features are more diffuse than classic flowstripes as can be seen in the neighbouring IIS and MIS, on the adjacent ice shelf (Fig. 1) and numerous locations around the ice sheet (Scambos et al., 2004; Hulbe and Fahnestock, 2007; Glasser and Gudmundsson, 2012). We have two working hypotheses for their formation: either they are simply decayed remnants of former flowstripes, or they represent a surface expression that post-dates the formation of englacial structures, discussed below. These are not necessarily mutually exclusive hypotheses, however.

Under the interpretation of decayed flowstripes, the lineations likely demonstrate the approximate direction of former ice flow, which is at a significant angle to the modern flow regime (Fig. 1). Flowstripe preservation time is thought to be normally of the order of centuries (Glasser and Gudmundsson, 2012). Hence, the interpretation of flowstripes preserved over the BIR for up to ~4000 years requires explanation. Certainly there is no known process by which the lineations on the BIR could form *in situ* above stagnant ice.

Flow-orthogonal rheological variations due to e.g. fabric development or internal structures may act to assist flow-parallel lineation preservation, as they may affect local vertical strain rates. There are some indications that such rheological changes may be present in the BIR. On two flightline sections (W–W′ and Y–Y′), >80 km apart on opposite sides of the BIR, 'thrust-like' features are observed extending from the subglacial bed to 400–500 m into the overlying ice (Fig. 3). These features dip towards the interior of the WAIS, with their apparent strike sub-parallel to the Filchner-Ronne Ice Shelf (FRIS) grounding line of the BIR. These features are not aligned with present-day ice flow (Fig. 1d). A similar, although somewhat weaker, near-basal internal reflection is found elsewhere on flightline section X–X′ (Fig. 3). We interpret this reflection as representing the same near-bed thrust-like feature observed elsewhere, but imaged from a flight orientation oblique to the upward sloping plane of the feature. Unusual internal reflections are also observed on flightline section Z–Z′ during a turn in the survey flight (Fig. 3). This feature may also represent the thrust-like feature, but again imaged from an oblique flightline orientation.

The RES data currently available suggest that these thrust-like features may extend across the entirety of the BIR from its shear margin with the IIS, to near the grounding line of the ice shelf offshore from MIS (Fig. 3a). The thrust-like RES reflections identified appear to be contained within a band of flowstripes extending across the BIR (Fig. 3a). We are unsure as to the precise interpretation of these thrust-like features; they could represent glacigenic tectonic features (e.g. Hambrey, 1976) or basal freeze-on of water and/or sediment (Bell et al., 2011). In either case their co-location with flowstripes suggests they may form in line with ice flow (coincident with the strike of the thrusts), and possess a rheology that is different to the surrounding ice.

Alternatively, the preservation age of the BIR flowstripes may be far less than 4000 years. MODIS MOA imagery of flowstripes surrounding the BIR reveals the majority are compatible with modern flow conditions (Fig. 4). In contrast, between the BIR, the Korff and Henry Ice Rises (KIR/HIR) and the Doake Ice Rumples (DIR) to the North, flowstripes appear to fold, indicating possible ice flow direction change (red lines in Fig. 4c), as noted previously by Scambos et al. (2004).

If these flowstripe distortions are related to past changes on the BIR, we can estimate the minimum age of these changes using the Rignot et al. (2011) InSAR-based ice-surface velocity map. Starting at every point on the FRIS margin in turn, we integrate backwards along ice-streamlines to the grounding line to estimate how long ago ice entered the ice shelf. Fig. 4 displays the results. In the region between the BIR, KIR and HIR (Fig. 4c), the orientations of flowstripes are only compatible with the modern flow direction in ice that flowed from the present-day northern edge of the IIS ~400 years ago. This, assuming that ice velocities have not changed significantly over this period, provides an alternative minimum constraint on the age of velocity changes across the BIR.

5. Discussion

The discovery of ice modified by enhanced flow within the BIR can be explained in two ways, leading to two distinct recent (i.e. Late Holocene) glacial histories. In both cases, the enhanced flow originated upstream, and traversed to the BIR across what is now the IIS at a significant angle to modern ice-stream flow. Given that we calculate the switch between enhanced and slow flow in the BIR to be between 400 and 4000 years ago, the formation of the present IIS configuration must also be recent. Prior to this, ice flow would likely have been in the general direction suggested by the BIR surface lineations, assuming they are flowstripes.

5.1. Holocene ice-stream dynamics

At the Last Glacial Maximum ~20,000 years ago, the WAIS was substantially larger than today, with the position of its grounding line shifted seaward relative to its present position to varying degrees across its Ross, Amundsen and Weddell Sea sectors (Conway et al., 1999; Hillenbrand et al., 2012; Larter et al., 2012). Exposure age dating on glacial deposits within the Ellsworth Mountains shows ice thickness up to 480 m greater than today across its Weddell Sea side during the Last Glacial Maximum (LGM) (Bentley

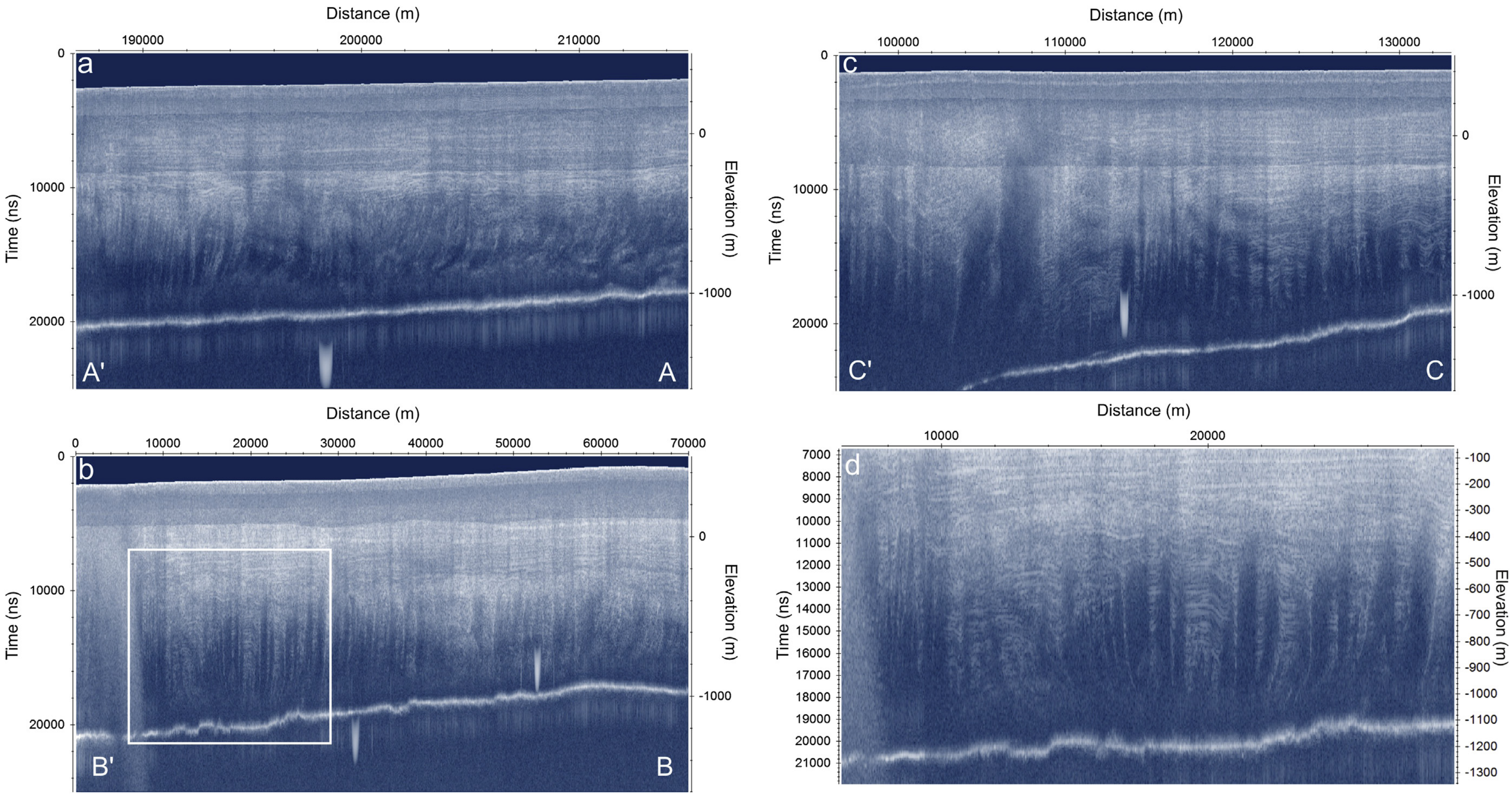

Fig. 2. RES data from the Bungenstock Ice Rise. Three sections showing conformable flat layering overlaying buckled and deformed layering. (a) Section A–A′. (b) Section B–B′. (c) Section C–C′. (d) Expansion of section in B–B′ (indicated by white box in Fig. 2c). The locations of the transects are given in Fig. 1.

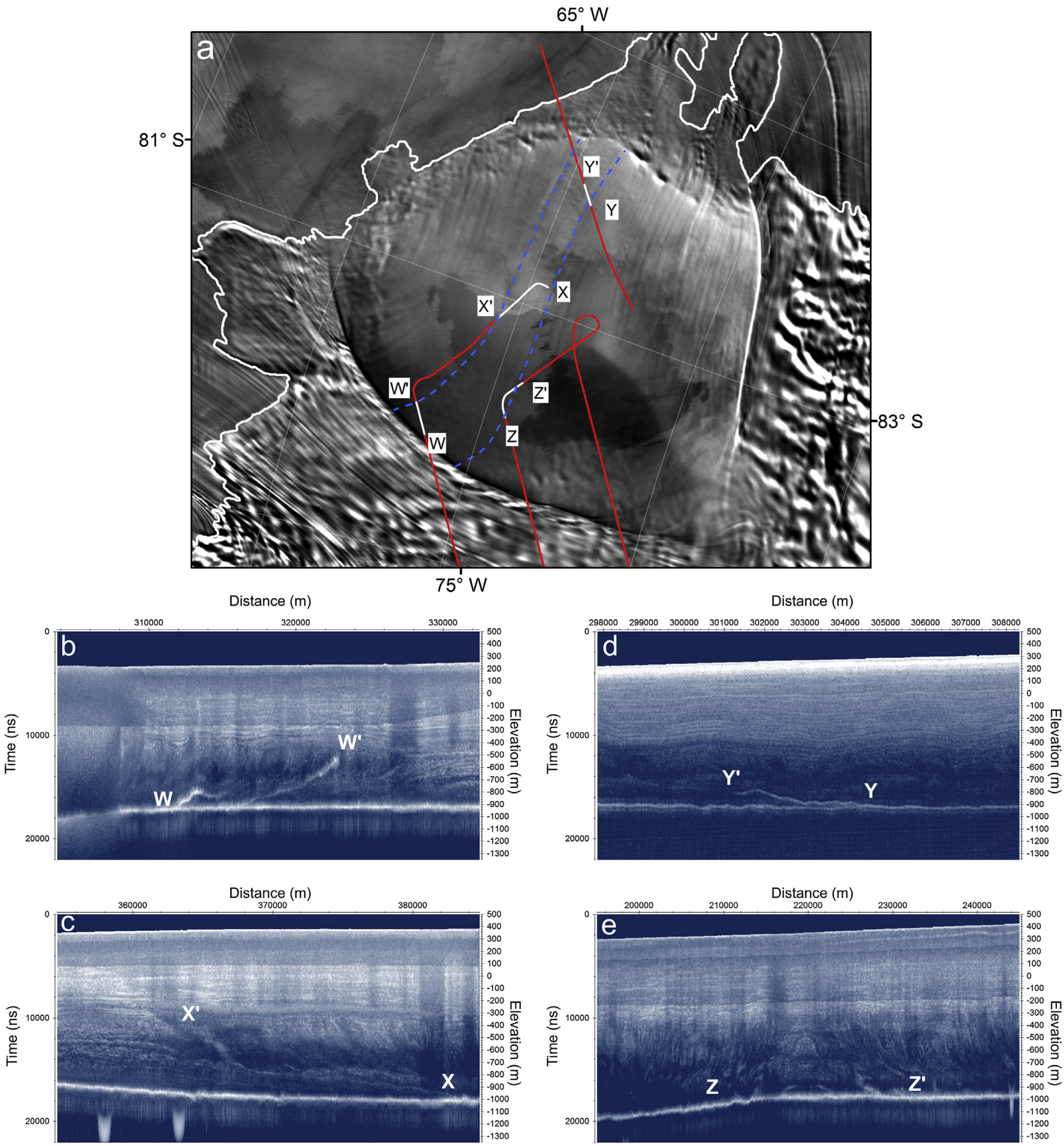

Fig. 3. RES flightlines which image thrust-like features beneath the Bungenstock Ice Rise. (a) Map of flightlines, which are denoted in red. Sections of the RES lines in white show areas where thrust-like and related features are imaged. Backdrop is the MODIS Mosaic of Antarctic (MOA) image map, with the grounding line noted as a white line (Haran et al., 2006); (b) W–W′, showing thrust-like feature imaged along dip axis; (c) X–X′, showing thrust-like feature imaged oblique to dip axis; (d) Y–Y′, showing thrust-like feature imaged along dip axis; (e) Z–Z′, showing 'artichoke-like' feature interpreted as a thrust-like feature imaged during survey flight turn.

et al., 2010). This supports the northern expansion of grounded ice across at least the southern part of what is now the FRIS. While the exact position of the LGM grounding line is uncertain (Hillenbrand et al., 2012), numerical ice-sheet modelling suggests it was positioned several hundred kilometres to the north of its present location (Bentley et al., 2010; Le Brocq et al., 2011), engulfing the IIS/MIS/BIR region with ice ~500 m thicker than today. To the east, ice flow from East Antarctica into the FRIS is likely to have been similar at the LGM to today (Hein et al., 2011). Hence, LGM grounding line change to the Ronne Ice Shelf is thought to be almost exclusively derived from the WAIS.

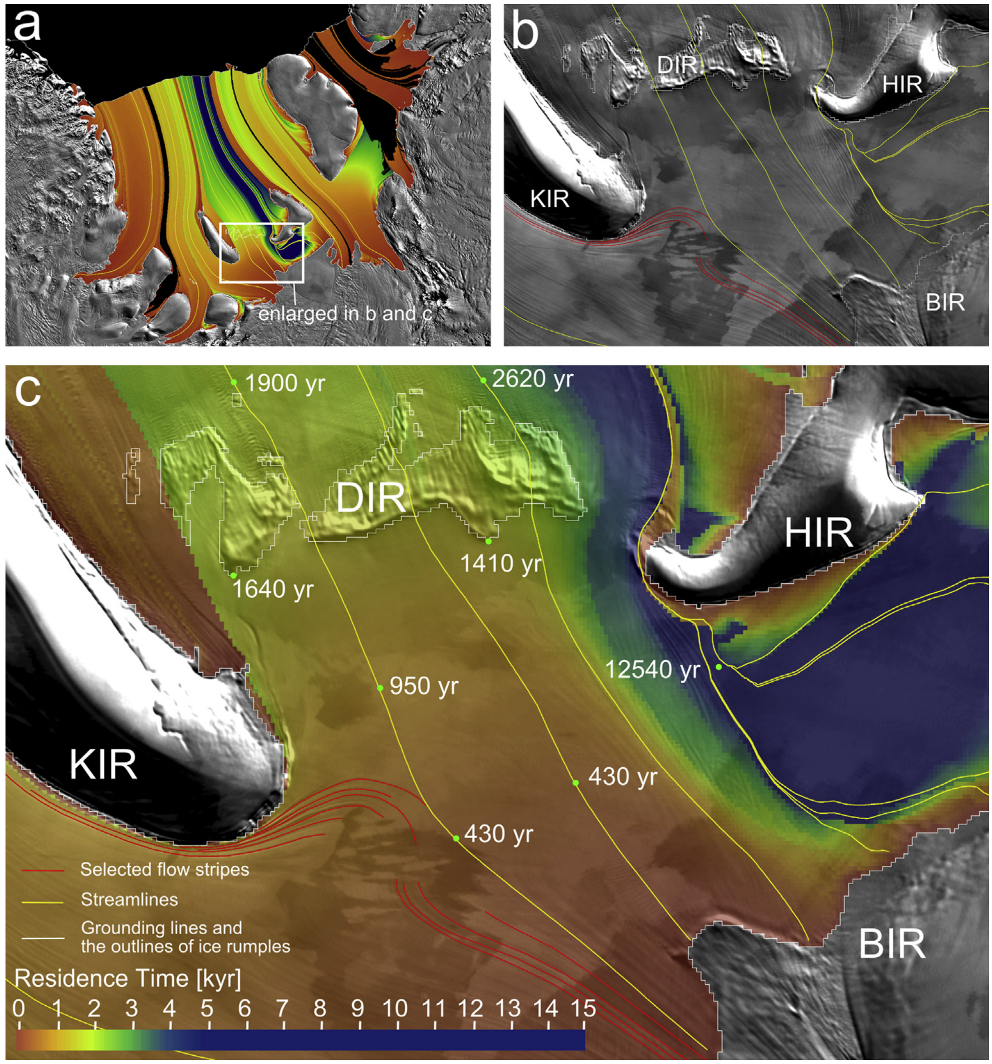

Fig. 4. Ice surface residence time within the FRIS, calculated using Rignot et al.'s (2011) InSAR-derived surface velocity map. The results are overlain on MODIS Mosaic of Antarctic (MOA) imagery (Haran et al., 2006). (a) Residence time for the whole FRIS. The area of the ice shelf in black indicates areas affected by gaps in the velocity data and the white box denotes the region expanded in (b) and (c). (b) Modern ice flowlines (in yellow) superimposed on flowstripes between the BIR, KIR and HIR. Selected mapped flowstripes are displayed in red. (c) Residence time for ice displayed as a colour map and labelled at specific locations north of the BIR.

If this LGM scenario is correct, the ice flow direction of the IIS and MIS, and the BIR could have been substantially changed from that at present, involving broad northeast-ward flow of thick ice into an ice stream within the Filchner (Thiel) Trough (Bentley et al., 2010; Hillenbrand et al., 2012; Larter et al., 2012). According to cosmogenic exposure dating, ice sheet thinning (and southerly migration of the grounding line) has been taking place progressively since ~15 ka, meaning the final retreat to the present glacial configuration at the IIS/MIS/BIR region was recent (i.e. Late Holocene) (Bentley et al., 2010).

Like the FRIS, the majority of grounding line retreat (and ice stream retreat) across the Ross Ice Shelf took place during the Holocene (Conway et al., 1999). The result was the relatively recent formation of the current fast flowing outlets across the Siple Coast, which themselves have experienced recent (last few centuries/ millennial) changes to flow directions and ice dynamics, especially adjacent to the Siple Dome separating the Whillans and Kamb ice streams (Conway et al., 2002; Hulbe and Fahnestock, 2007; Catania et al., 2012). This model, of grounded ice retreat and ice dynamic change, is a first way of explaining the features observed in the BIR (Fig. 5). A northwards-lying grounding line, implying a grounded ice sheet over the southern FRIS might permit grounded ice flow from the inland IIS, currently strongly influenced by basal topography (Ross et al., 2012), to have been directed across what is now the BIR (Le Brocq et al., 2011). Grounding line retreat would lead to ice thickness being reduced (Bentley et al., 2010). Under these circumstances an increasing influence of bed topography could lead to ice flow being directed around the ice-rise location, perhaps in association with a change to the routing of basal water (e.g. Anandakrishnan and Alley, 1997), leaving stagnant, formerly dynamic ice (i.e. the BIR). This shut-down would likely leave the ice of the BIR underlain by water-saturated sediment. The absence of well-developed Raymond Arches, whose formation time-scale would be several thousand years, can then be explained by divide movement induced by changes in nearby ice-stream flow (Nereson et al., 1998) and (low levels of) basal sliding.

5.2. Post-retreat uplift-induced ice advance

While the ice stream change model is conceptually simple, and is based on comparable glaciological observations in similar situations elsewhere in Antarctica, it is not definitive. A steady post-

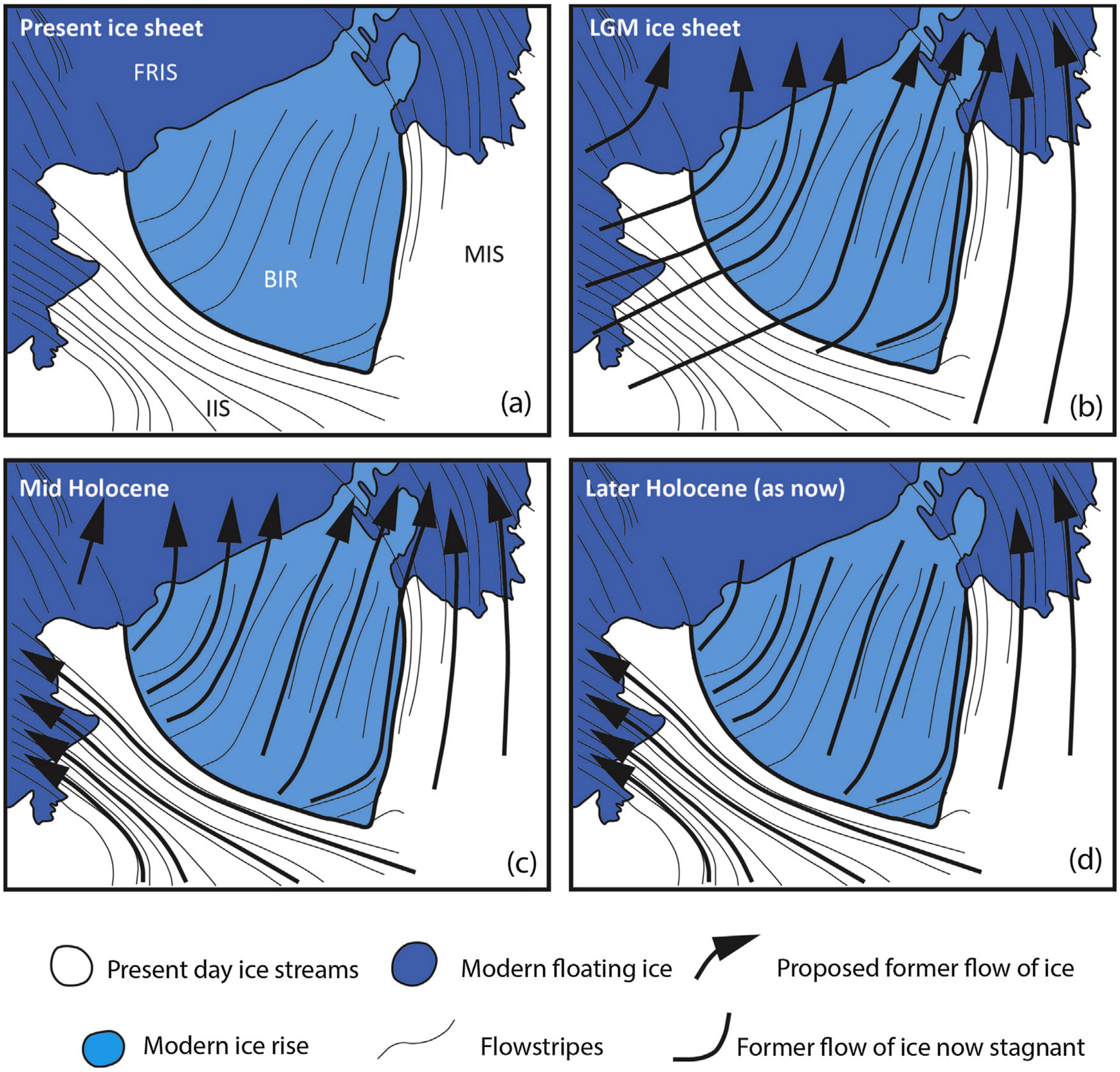

Fig. 5. Schematic description of ice sheet change in the BIR region. (a) The current glaciological situation, with ice flowstripes noted. (b) LGM-type ice sheet, where northward ice flow from the WAIS interior dominates the region cross-cutting the present day trunk of the Institute Ice Stream. (c) Mid Holocene, post-LGM situation, where the Institute Ice Stream becomes active to the south of the BIR. (d) Later Holocene ice configuration, in which ice over the BIR becomes stagnant, thus leading to the present day ice-sheet configuration. This model works for both scenarios of ice sheet history. In the case of a retreat of grounded ice, the Institute Ice Stream activates as a consequence of ice sheet surface lowering and reorganization of the subglacial hydrological regime. In the case of regrounding of the BIR as a consequence of post glacial uplift, the IIS flows along its present direction because of stagnant ice across its northern border.

LGM relaxation of an expanded ice sheet should lead to steady predictable rates of post-glacial uplift. While several models depict the Weddell Sea sector of WAIS to be experiencing uplift today none of them match current measurements of crustal elevation change, which are low to negligible compared with other regions of the WAIS (Thomas et al., 2011). One explanation for this mismatch is that the glacial history of the region is more complex than thought previously.

An alternative explanation for the formation of the BIR and its englacial structure is that it is a recaptured ice-rise. In this scenario, grounding line retreat from the LGM position to the stable interglacial location up to ~100 km inland of the present grounded margin (Ross et al., 2012) occurred earlier in the Holocene. In this configuration, the FRIS would have been present over what are now the downstream IIS and MIS and the BIR. The shelf would inherit, and preserve, both flowstripes and buckled layers from the grounded ice upstream.

As a consequence of early-Holocene grounded ice retreat, isostatic uplift would occur. Owing to the relatively elevated bed topography (Fig. 1c), the ice shelf over the BIR regrounded. This regrounding altered the ice-shelf stress field, which led to enhanced ice flow around it, stagnation of ice and the formation of an ice rise (Hulbe and Fahnestock, 2004; Favier et al., 2011). Subsequently, we would expect rapid back-filling of the grounded ice sheet into what is now the deep subglacial basin, and the positioning of the present-day grounding-line on a steep retrograde slope. It should be noted that theories of marine ice instability predict unstable advance on reverse slopes under appropriate conditions (Schoof, 2007). Extensive basal melting could have occurred during the period in which the ice was afloat, potentially affecting our approximate dating of the transition between buckled and conformable layers (i.e. making the calculated age of 4000 years greater than it should be). Hence, dates of a few centuries (as residence time modelling indicates, Fig. 4) are feasible, which would make the preservation of flowstripes as surface linear features easily explicable. Evidently, re-grounding of an ice-shelf would, as with the retreat scenario, be associated with the presence of water at the base of the ice-rise. The Crary ice-rise

Table 1
Summary of evidence in support of, and against, scenarios explaining the formation and structure of the BIR.

	Scenario for BIR formation	Evidence in support	Evidence against
1	Ice stream reconfiguration during retreat of ice sheet leading to ice stagnation	Buckled internal layers underlie conformable layers, revealing a change in ice dynamics from fast to slow flow	Misinterpretation of stratigraphy, due to RES transect orientation offers a source of uncertainty in the boundary of this change
		Date of the transition from slow to fast flow ~4000 years from compression modelling	This is a maximum age, and does not take into account possibly large rates of basal melting or the uncertainty noted above
		Flowstripes on BIR reveal former direction of ice flow at an angle to present	Flowstripe preservation for 4000 years is difficult to reconcile with evidence from other regions
		The dip of subglacial 'thrusting' features perpendicular with flowstripes, supports their identification as being associated with ice flow, and possibly provides a rheological explanation for flowstripe preservation	Uncertainty remains about the origin of these 'thrusting' features
2	Recaptured ice rise due to isostatic uplift in the foreground of a post LGM ice sheet more restricted that at present, leading to recent glacial expansion	Buckled internal layers underlying conformable layers, revealing a change in ice dynamics from fast (floating) to slow (grounded) flow – in this case buckled layers being inherited within the ice shelf from upstream grounded ice	
		Uplift measurements surrounding the BIR reveal little present vertical motion, and are inconsistent with models of post LGM uplift, which predict considerable present-day positive vertical motion	
		Flowstripes explained as a consequence of ice shelf regrounding – folding of surface flowstripes downstream of the northern edge of the IIS provides a minimum constraint on the age of ice direction changes ~400 years ago and, thus, an explanation for flowstripe preservation over the BIR	Back-filling of the deep basin upstream of the BIR would need to be rapid and very recent. This isn't necessarily evidence against the idea, but it signals a conceptual hurdle, which has implications for other marine sections of the ice sheet
3	Combination of above scenarios: BIR uplift during ice stream retreat and reorganisation	Can explain buckled layers as in#1 without the need for deglaciation of the large trough and subsequent rapid glaciation as in#2	

(Bindschadler et al., 1990) is an analogy of this, where measured internal ice temperatures indicate a warm-base. This early unloading and reloading is consistent with current low rates of regional isostatic uplift (Thomas et al., 2011). If true, the model would likely mean extremely rapid recent glaciation of the deep subglacial basin upstream of the current IIS and MIS grounding lines.

At present, the ice at the centre of the BIR is of the order of 400 m above the level of flotation. Under the uplift-induced theory for its formation, the BIR must have either accumulated this ice since re-grounding and/or experienced subsequent uplift. Assuming the former, it would take a few thousand years to build this ice under the present day ice accumulation rate ($\sim$0.2 m yr^{-1}), confirming the origin of the ice rise in the Late Holocene. This age is reduced, possibly to the order of centuries, if bed uplift is accounted for or if the ice accumulation rate was greater when the ice rise elevation was lower. As suggested by the thrust faulting, there is also the possibility of along-flow compression leading to ice thickening, like in the upstream reaches of Kamb Ice Stream (Price et al., 2001). It is difficult to estimate the rate at which this might occur, or its magnitude, however.

5.3. Ice-flow direction change

The interpretation of surface lineations as ice-surface flowstripes can be explained in both models. In the former case (deglaciation), the stripes formed either directly at the site of the BIR or they formed upstream and were not modified due to the bed being smooth and the ice being near to flotation (plug flow). In the latter (re-glaciation), the flowstripes are relic features from upstream that had not yet disappeared from the floating ice shelf at the time of regrounding. In both cases, the flowstripes were preserved on the ice rise despite subsequent accumulation of snow and ice. While it is not yet possible to resolve these two models, and indeed they may operate in tandem (e.g. uplift of the BIR area during ice stream retreat and reorganisation), it is unlikely there is any other discrete explanation. Both models are consistent with satellite altimetry (Pritchard et al., 2012) that shows thickening of grounded ice in this area. They both support a conclusion that the region has been susceptible to significant change (Fig. 5), and that the deep upstream basin is at risk of becoming ungrounded; the first model as a consequence of further retreat, the second model as a consequence of it having occurred previously within the last few millennia.

5.4. Internal layers and RES transect orientation

In Siple Coast ice streams, the buckling of englacial layers is related to ice flow (Jacobel et al., 1993; Siegert et al., 2003). Because of the anisotropic nature of englacial buckling, RES transects aligned orthogonal to ice flow will reveal buckling, whereas flow parallel transects may show little or no evidence of buckling. RES transect alignment is therefore critical to the identification and interpretation of buckled internal layers. Over the BIR none of the available RES transects are aligned exactly orthogonal to the surface lineations, so a sharp englacial transition between buckled and conformable layering cannot be unequivocally verified. As a consequence, the age of the transition ($\sim$4000 yrs) remains uncertain. It is possible that the transition observed in data presented here is a consequence of oblique survey line orientations (e.g. Leysinger Vieli et al., 2007), and that the transition would be less apparent were data acquired in different orientations. If true, it could mean a very recent (400 years ago) change in ice stream dynamics is more likely, making the interpretation of surface lineations as flowstripes easily explicable.

6. Summary and conclusions

RES was used to measure the englacial stratigraphy of the BIR, which separates the IIS and MIS in the Weddell Sea sector of West Antarctica. Previous analysis of RES from this region has revealed the present-day grounding line to be positioned on a major steep reverse bed slope, making the ice sheet potentially susceptible to ice loss (Ross et al., 2012). The available RES data reveal the BIS to comprise two forms of internal structures. In the upper ~600 m, internal layers lie conformably and are traceable over long distances. Such layers accumulate under slow stable flow conditions. Below this, there is a transition to disturbed, buckled layers, formed through former enhanced flow of ice. The disrupted layers are evidence that the BIR has experienced major glaciological change. We offer two scenarios to explain this change (summarized and critiqued in Table 1). First (de-glaciation), ice stream thinning and reconfiguration during post LGM retreat, similar to that thought to have occurred in the Siple Coast of West Antarctica, no more than ~4000 years ago. Second (re-glaciation), post LGM uplift-induced regrounding and consequent ice advance no sooner than ~400 years ago. We do not believe any other explanation is likely, although it is feasible that both may have acted together during a phase of post LGM lithospheric uplift of the BIR region as the IIS/MIS underwent retreat and reconfiguration. Both scenarios suggest the region has experienced significant recent ice sheet alteration, the latter particularly so as it would mean the former recent loss (and re-glaciation) of a major deep basin upstream of the present grounding line. Our observations are consistent with the hypothesis, based on marine geophysical data, that the LGM ice drainage pathways in the interior Weddell Sea embayment were different from those of the present-day (Larter et al., 2012).

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