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Persistent Tracers of Historic Ice Flow in Glacial Stratigraphy near Kamb Ice Stream, West Antarctica

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Abstract. Variations in properties controlling ice flow (e.g., topography, accumulation rate, basal friction) are recorded by structures in glacial stratigraphy. When anomalies that disturb the stratigraphy are fixed in space, the structures they produce advect away from the source, and can be used to trace flow pathways and reconstruct ice-flow patterns of the past. Here we provide an example of one of these persistent tracers: a prominent unconformity in the glacial layering that originates at Mt. Resnik, part of a subglacial volcanic complex near Kamb Ice Stream in central West Antarctica. The unconformity records a change in the regional thinning behavior seemingly coincident (~3440 ± 117a) with stabilization of grounding-line retreat along the Ross Ice Shelf. We argue that this feature records both the flow and thinning history far upstream of the Ross Sea grounding line, indicating a limited influence of observed ice-stream stagnation cycles on large-scale ice-sheet routing over the last ~5700 years.

1 Introduction

New constraints on paleo-ice-dynamics are increasingly important in glaciology. They form the basis for validating model hindcasts, which act as a test of model performance, add to our understanding of past ice-sheet and climate interactions, and improve the reliability of future ice-sheet projections (Pollard et al., 2015). But current proxies for past ice-sheet behavior are not well distributed in time and space, limiting our ability to validate model behavior for critical regions of Antarctica and Greenland. Improving the temporal and spatial coverage for proxies in the ice-sheet interior is especially important in regions where significant flow reorganization is currently occurring, such as the Siple Coast, where centennial-scale internal variability (Catania et al., 2012) could easily be misinterpreted as externally forced, multi-millennial trends.

In this study, we present a paleo-flow indicator which we classify as a "persistent tracer" – a feature that forms by a known mechanism at a fixed location in space, independent of the local ice-flow regime, and can be used to infer historic flow direction and/or speed. Like other persistent tracers seen elsewhere in Antarctica (Ross et al., 2011; Woodward and King, 2009), the data presented here provide multi-millennial context for the flow speed and ice dynamic changes that have been observed during the satellite era. We highlight this as one example of a larger class of structures that should be targeted in radar studies of ice sheets.

1.1 Current Methods for Constraining Paleo-Ice Dynamics

Past ice-sheet behavior is primarily inferred from three types of data: sea-level proxies (e.g. Galeotti et al., 2016; Raymo and Mitrovica, 2012), indicators of paleomorphology in currently deglaciated regions (e.g., The RAISED Consortium et al., 2014), and local or in-situ ice-sheet data. Each of these proxies has limitations. Sea-level data are powerful constraints on large-scale ice-mass changes but are limited in their ability to spatially resolve ice-dynamic changes. Deglaciated landscapes can spatially and temporally resolve ice-sheet states (Anderson et al., 2017; Brook et al., 1995; Levy et al., 2017; Stone et al., 2003) but are limited to reconstructions of behavior outboard of current margins. Studies using local or in-situ ice-sheet data are our only method for constraining changes in ice sheet morphology and behavior in the continental interior, but these rely on ice core and borehole data that are logistically challenging to collect and spatially limited (Delmotte et al., 1999; Siddall et al., 2012; Waddington et al., 2005). We seek to expand the archive of ice-dynamic changes in the continental interior, using widely available radar data in West Antarctica.

Thermal, frictional, accumulation, and subglacial topographic anomalies all drive englacial structure formation (Holschuh et al., 2017). The resulting disturbances in the glacial stratigraphy have been used to infer ice-flow reorganization in the Ross Sea sector in the past (Conway et al., 2002; Jacobel et al., 1996; Siegert et al., 2004), but interpreting them can be challenging. With uncertainty in both their formation mechanism and subsequent evolution, many of the englacial structures observed in Antarctica and Greenland do not provide sufficient information to infer paleo-velocities. However, temporally persistent thermal, frictional, and topographic anomalies (i.e. geologic controls) can provide unambiguous locations of structure formation, and can be used to diagnose historic flow behavior.

1.2 Ice Stream Variability on the Siple Coast

Ice streams feeding the Ross Ice Shelf exhibit significant internal variability, with tidal forcing and frictional mechanics dictating velocity on hourly timescales (Anandakrishnan et al., 2003; Winberry et al., 2014) and thermodynamic changes resulting in significant local mass-balance variability on century timescales (Catania et al., 2012). During the observational era, this variability has occurred primarily within the ice plains of Whillans and Kamb Ice Streams (Martín-Español et al., 2016), where low-relief subglacial topography and weak driving stresses allow subtle changes in the subglacial hydrologic system to significantly impact ice fluxes through individual ice streams (Siegfried et al., 2016). This variability is superimposed over longer-term changes in ice dynamics due to grounding-line retreat since the LGM, with the majority of that retreat most likely occurring along the western portion of the Ross Embayment (Conway et al., 1999; Spector et al., 2017). The impact of individual ice-stream behavior on overall Siple Coast mass discharge is still uncertain, inviting comparison to braided stream systems, which can maintain a constant discharge despite rapidly changing flow pathways (Fahnestock et al., 2000; Hulbe and

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Fahnestock, 2007; Parizek et al., 2002). With data presented in this study, we evaluate whether century-scale changes at the coast manifest in the ice reservoirs of the ice sheet interior over the last several thousand years.

We use a stratigraphic unconformity within the West Antarctic Ice Sheet (WAIS), imaged using ice-penetrating radar, to identify changes in flow in the ice sheet interior during grounding line retreat from Last Glacial Maximum (LGM). Stratigraphic unconformities are common in East Antarctica, where low accumulation rates allow wind scour and sublimation to disrupt the lateral continuity of annual layering locally (Das et al., 2013; Welch et al., 2009), but they are rare in West Antarctica. We attribute its formation to the presence of Mt. Resnik, a high-relief, subglacial volcanic system upstream (Behrendt et al., 2006), and discuss implications for unconformity formation elsewhere in Antarctica. Additionally, the geometry of the unconformity provides information about flow behavior during the temporal gap between records of recent Siple Coast behavior in Ross Ice Shelf flowstripes (Hulbe and Fahnestock, 2007) and older changes recorded in ice rises and in the Transantarctic mountains (Conway et al., 1999), allowing us to evaluate the effect of the ice-stream stagnation-reactivation cycles on interior dynamics in West Antarctica.

2 Data

2.1 Radar Surveys

Ground-based radar campaigns conducted from the Byrd camp were performed in 2002 as part of the US-ITASE traverse using the St. Olaf College 3 MHz radar system (Welch and Jacobel, 2003) and in 2004 as part of the WAIS divide site surveys using the University of Washington deep-sounding 1 MHz radar system (Figure 1B.i-ii). Radar data processing follows the workflow presented by Christianson et al. (2012). The ITASE data reveal a prominent unconformity within englacial layers in the top 1000m of the ice column (Figure 2.B). The subsequent University of Washington survey shows the unconformity extends to Mt. Resnik, but is absent upstream of the topographic high (Figure 2.A). System noise prevents interpretation of layers shallower than ~250m depth.

2.2 Byrd Core and Reflector Chronology

Radar data from the ITASE traverse connect to the deep ice core retrieved at Byrd station in 1968. Damaged and missing core precluded the counting of annual layers, but a shallow depth-age scale was established using the electrical conductivity method (Hammer et al., 1994). This overlaps with a chronology starting at 870m depth, which maps ages from the well dated Greenland ice cores to Byrd via methane correlation (Blunier and Brook, 2001). Following the methods of Cavitte et al. (2016), we date radar reflectors where they intersect the Byrd ice core, taking into account both published uncertainty values and the magnitude of disagreement between conductivity and methane inferred ages where they overlap. The age and uncertainties of radar layers (presented as years before 2000 A.D. [a]) are given in Figure 2.C. Note the presence of an unconformity, a gently dipping feature with two breaks in slope. We refer to its geometry using the dated layers that truncate nearest to the slope breaks, one near the 1648 ± 92a reflector, and one between the 3011 ± 115a and 3440 ± 117a reflectors.

Dating reflectors across the unconformity is challenging, as no radar lines can tie reflectors on the far side of the unconformity through the undisturbed layering upstream of Mt. Resnik. Common reflections were correlated based on their absolute amplitude and their amplitude and waveform characteristics relative to the adjacent reflectors in the stratigraphy. While we have high confidence in the layer correlation, we mark the reflectors not directly linked to the ice core with dotted lines (Figure 2.C).

2.3 Surface Data and Climatology

Englacial unconformities are typically associated with wind-scour and sublimation. Previous studies have related observed wind scour in East Antarctica to two basic surface parameters: the ratio of the surface mass balance to the average wind speed (A/W: [$kgm^{-2}a^{-1}$]/[ms^{-1}]), and the mean surface slope in the wind direction (MSWD) (Das et al., 2015). This empirical framework predicts wind scour in regions where A/W < 9.12 and MSWD > 0.002, with thresholds established using observations from Dome A in East Antarctica. However, the Dome A training data spans a relatively narrow range of surface slopes and accumulation rates, not sampling the values expected over Mt. Resnik. The presence of blue ice at Mt. Resnik would indicate an expanded range of conditions that allow scour, implying possible blue ice areas in other parts of West Antarctica where the regional accumulation rate is high.

We compute the A/W ratio and the MSWD over Mt. Resnik using output from a regional climate model at ~ 30km resolution (RACMO (Noël et al., 2015)) and 8m resolution digital elevation models (DEMs - produced from orthoimagery collected by the DigitalGlobe constellation of satellites, using the SETSM algorithm (Noh and Howat, 2015)). ICESat data were used to remove errors in regional slope in the DEMs. While there is a temporal gap between the DigitalGlobe (01/2015-12/2016) and ICESat data acquisitions (02/2003-10/2009), we do not expect significant changes in regional slope over this time period, given small observed dh/dt signals here (Helm et al., 2014). The coverage of these regional DEMs is provided in Figure 3.A. We also note here the resolution mismatch between the atmospheric forcing and the DEM – we capture local slopes, but only regional surface mass balance and wind speed.

The A/W ratio for this region is significantly higher than the values reported for scour regions around Dome A. 365-day averages from 2000 to 2009 show A/W ratios oscillating around 20.2, more than a factor of 2 higher than the threshold. However, high surface slopes are also found over Mt. Resnik, with MSWD values in both published DEMs from Cryosat [MSWD = 0.018] (Helm et al., 2014) and the regional DEMs produced for this study [MSWD = 0.0192 ± 0.002] exceeding four times those at Dome A. With evidence of surface scour in the stratigraphy, but surface parameters outside the predicted range, we look for direct evidence of modern blue ice in collected satellite imagery.

2.4 Satellite Imagery

Two different methods have been used to identify surface scour from satellite data. Bright reflectivity in MODIS imagery (like that seen at Mt. Resnik in Figure 3.A) indicates local grain-size reduction (Scambos et al., 2007), consistent with surface scour and unconformity generation elsewhere (Welch and Jacobel, 2005). Additionally, calibrated studies of surface spectral properties show that blue-ice with bubbles and snow have comparable reflectance in the visible spectrum, but blue ice is a substantially weaker reflector in the near-infrared (Boresjö Bronge and Bronge, 1999). Using bands 2 (452-512 nm) and 5 (851-579 nm) of Landsat 8 data collected over Mt. Resnik (Path 224, Row 119, acquired Jan 21, 2018), we examine the relative surface reflectivities at the location of high MODIS reflectivity (Figure 3.B-C). With a threshold reflectivity ratio of 2, we identify likely blue ice areas, plotted in Figure 3.C. These correspond with peak elevations in the subglacial topography, and fall along a roughly linear ridge orthogonal to flow. Based on the modern flow field, the downstream unconformity position is roughly consistent with formation at the edge of the blue ice patch observed over Mt. Resnik (Fig. 3.A).

3 Results

Structural data near Mt. Resnik provides a unique source of information about the ice sheet's interior response to both large-scale grounding-line retreat and cyclic ice-stream stagnation along the Siple Coast. Unconformities are rare in West Antarctica, facilitated here by the extreme subglacial relief of Mt. Resnik and its influence on local surface gradients. Additionally, Mt. Resnik sits at the boundary between ice-stream catchments – structures forming here are well poised to capture significant changes in relative flow between the ice streams to the south (Kamb, Whillans, and Mercer) and those discharging into the Ross Ice Shelf to the north (Bindschadler and MacAyeal).

Unconformities manifest at the boundary between depositional regimes at the ice sheet surface. They can be defined by substantial missing time, due to erosion/ablation or non-deposition in blue ice areas, or can represent the transition from pristine to mechanically reworked snow surfaces, as in the case of the megadunes of East Antarctica (Frezzotti et al., 2002). For an unconformity to appear in radar imagery, surface processes must modify the depth-conductivity profile – snow from one regime must sit on top of snow from another regime.

Downstream of a blue ice area, radar data collected along flow should capture an unconformity that dips away from the zone of surface ablation. This would mark the transition between snow that predates and postdates the missing time in the column. But there may be no indication of an unconformity in radar data collected orthogonal to flow, as the missing time would appear like any other isochrone in the layering. This highlights an important feature of the unconformity seen in radar data downstream from Mt. Resnik: its geometry is quite complex in the cross-flow direction. If it were forming in a simple flow field, from a single blue ice area, we would not expect a sloping feature like the one observed. But under certain static flow fields, or in the presence of some dynamic flow changes, the observed geometry can be explained. Here we analyze the structure in detail,

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focused on two primary components: (1) its trace, as it advects away from Mt. Resnik, and (2) its cross-sectional geometry, which has the potential to constrain more subtle changes in ice dynamics around Mt. Resnik through time.

3.1 Propagation pathway from Mt. Resnik

The formation of the unconformity is unambiguously connected to Mt. Resnik. This is evident from the radar data; the unconformity is absent in data collected upstream of Mt. Resnik, and is visible in all downstream lines (see Fig 2.B, and Supplementary Figure 1). Enhanced driving stress is required to drive ice flow around and over the mountain (in the < 400m of ice that flows over its summit (Morse et al., 2002)), resulting in steep surface gradients observed in the altimetry data, and driving surface scour observed in the imagery. Because Mt. Resnik's position is fixed through time, structures forming in response to ice flow past the volcano act as a persistent tracer, and can be used to back-calculate historic ice-flow direction.

Despite significant variability in the configuration of the modern Siple Coast ice streams, there is very little evidence in the trace of the Mt Resnik unconformity that ice-flow direction here has changed significantly in the last ~5700 years. Its current propagation direction is roughly coincident with the flow paths predicted from the modern velocity field, shown in Figure 3.C. This is surprising given the recent shutdown of Kamb Ice stream, whose tributary dominates ice flow immediately south of Mt. Resnik. Transitions between stagnant and active flow of the Kamb Ice Stream must not have significantly modified the direction of driving stresses in the ice-sheet interior, as ice flowing off Mt. Resnik has not been diverted in-to or out-of the neighboring tributaries.

3.2 Mechanisms to explain the cross-sectional geometry

This unconformity is a time-transgressive structure; it is present across a range of depths (and therefore, a range of ages) within a single cross section. There are essentially three end-member mechanisms that can explain how different parts of the unconformity, which we show formed from roughly the same location (Mt. Resnik), take different amounts of time to arrive at the location where they were imaged by the radar with the observed geometry. We detail these mechanisms in Figure 4, and discuss our favored mechanism and how it can further inform our understanding of ice dynamics near Mt. Resnik.

The first hypothetical mechanism that could generate the observed unconformity (Fig. 4) relies on an erosive anomaly at the surface that mirrors the kinked shape of the unconformity in the subsurface. Assuming that ice flows away from the point of origin and is buried at a constant rate, the deeper components of the unconformity must have formed further away than the shallowest limb. Based on the data presented in Figure 2, we know that the formation period of the unconformity spans at least 3000 years. Given surface velocities of ~5 m/a (consistent with InSAR derived velocities for the region), this mechanism would require a formation zone that extends 15km in the along flow direction to span 3000 years of stratigraphy. Given that the blue ice fields seen in Landsat imagery appear along a roughly linear trace, orthogonal to flow, this formation mechanism is unlikely.

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The second mechanism (Fig. 4) requires significant lateral velocity gradients to produce the range of arrival times for the unconformity at our radar traces. The unconformity has some characteristics that fit the observed velocity field to first order: it is shallower to the south, closer to the relatively fast flowing remnant tributary of Kamb Ice Stream. The observed velocities inside and outside of fast flow here span a reasonable range, given that the deepest imageable portion of the unconformity arrived approximately 3x later than the shallowest imaged portion. However, this mechanism requires the 3x variability in flow speed to be localized over a narrow (~5km) shear margin, and also requires two striking breaks in slope in the velocity gradients to mirror the kinked shape of the unconformity. These features are not present in the modern velocity field.

As with the first mechanism, our third mechanism (Fig. 4) relies on structure formation that spans a finite distance along-flow to generate the time-transgressive unconformity. However, instead of a static surface feature, the boundary between depositional regimes at the surface would move through time. To recreate the unconformity geometry observed at Mt. Resnik, the Resnik blue ice area would need to gradually grow southward in time, with punctuated changes in the growth rate corresponding to the breaks in slope. This way, snow that is reworked and deposited in the turbulent regime downstream of the now larger Resnik blue ice area will sit atop snow that was deposited under more quiescent conditions, and the boundary would appear sloping as it does in the radar data. The northern boundary, however, would stay fixed, leading to no cross-flow unconformity signature in the data on that side.

In the case of Mt. Resnik, if the ice sheet were to progressively thin, the subglacial topography would exert more local control on the surface gradients, and the blue ice area would expand. Steep slopes and smooth surfaces over blue ice enhance the winds, and drive turbulence that reworks snow in the depositional areas downstream. This process has been seen elsewhere in Antarctica, and was highlighted in Figure 4 of Bintanja (1999), who show that changing ice thickness in the vicinity of rugged subglacial topography will induce changes in the local depositional regime.

3.3 Favored formation mechanism

We use the kink location within the unconformity as our primary means for selecting a favored formation mechanism. The kink can either be explained by the spatial characteristics of the formation mechanism (as in mechanisms 1 and 2), or in the temporal characteristics of formation (as in mechanism 3). Without any evidence for a kinked structure in either the velocity field or the blue ice patches observed, we turned to the dated reflectors to estimate what ages would be associated with the kinks, should they have formed due to temporal variability in formation. The deeper of two kinks in the unconformity falls between reflectors dated at ~3.4ka and 3.0ka. This is contemporaneous with the activation (Conway et al., 1999) and migration of divide flow in the region (Nereson and Raymond, 2001), rapid grounding-line retreat to its present position in the south western Ross Embayment (Spector et al., 2017), and a change in the thinning behavior in western Marie Byrd Land (Stone et al., 2003). The agreement between the time of known change and the depth of the kink in the unconformity leads us to favor mechanism 3, a southward migration of the edge of the erosional zone, driven by changes in local ice thickness over Mt. Resnik.

This allows us to further interpret the structure geometry in terms of temporal changes in the flow behavior over Mt. Resnik. Between 3.2ka and 1.1ka, there is a limited record of dynamic change in the region from other sources. This means that the second transition, corresponding to a slope break at ~1.65ka, would represent a previously undocumented transition in thinning rates upstream of the Siple Coast. This may represent the temporal lag between grounding-line stabilization around 3ka and the resulting equilibration in the ice-sheet interior. Other records of ice-sheet behavior post-dating 1.65ka are consistent with continued southward migration of the scour surface at Resnik, as thinning of the southern Siple Coast ice streams continued through the past ~1000 years (Nereson and Raymond, 2001).

4 Conclusions

Here we provide evidence for the existence of persistent tracers of historic ice flow within the Antarctic ice sheet. Like hot spot tracks on the ocean floor, these form in response to a spatially locked forcing (either by topography, basal friction, accumulation, melt, or some other boundary condition to the ice-flow equations) and propagate away from their source, recording the flow vector for the ice sheet in that process. The location of persistent tracers within the ice sheet can be predicted from both model inversions and from preliminary sparse data, so future field expeditions should seek them out as proxies for changes in flow behavior in our most dynamic or poorly understood regions of Antarctica and Greenland.

Mt. Resnik produces an unconformity in the glacial stratigraphy in central West Antarctica that acts as a persistent tracer for ice flow through the Kamb / Bindschadler Ice Stream systems. The trace of the unconformity indicates no gross changes in ice-flow direction in the Siple Coast catchment over the last ~5700 years recorded in the stratigraphy, despite dramatic changes in flow regime for more coastal regions both observed during the satellite era and inferred from flow-striping on the Ross Ice Shelf. Thus, we believe these data imply that the response time for the ice-sheet interior exceeds the stagnation-activation time scales for the Kamb Ice Stream system, damping the signal and recording only long-term average behavior.

Detailed interpretation of the slope breaks in the Resnik unconformity seem to agree with other lines of evidence indicating a sharp change in grounding-line retreat behavior between ~3.4ka and 3.0ka. If our preferred mechanism for unconformity formation is correct, it records a thinning trend in the ice sheet interior, with a second (1648 ± 92a) undocumented event punctuating a change in acceleration in thinning inboard of the Siple Coast. The trace of the unconformity indicates that the ice-sheet interior accommodates large-scale grounding-line retreat without dramatic changes in flow orientation. This implies that the ice catchments are less sensitive to more-rapid changes in ice dynamics associated with ice-stream stagnation-reactivation cycles, limiting these cycles' effect on the total flux to the ocean during the time period recorded by the unconformity.

Data Availability

Radar data are accessible through the University of Washington's ResearchWorks Archive (*doi available after acceptance*).

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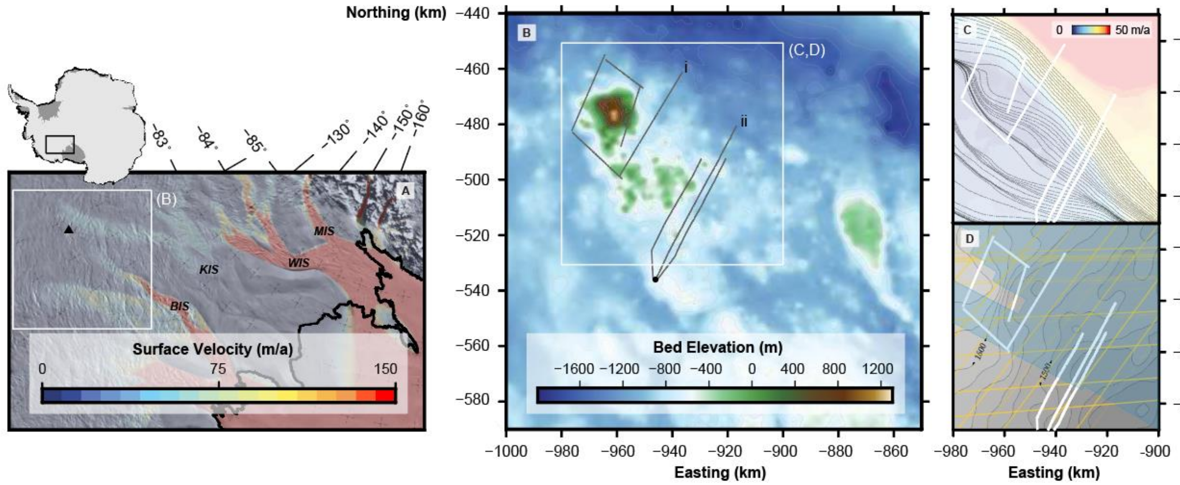

Figure 1: (A) Region map showing the modern flow field of Bindschadler (BIS), Kamb (KIS), Whillans (WIS), and Mercer (MIS) ice streams. Mt. Resnik, a subglacial volcanic complex (plotted as a black triangle), sits adjacent to a tributary of the stagnating Kamb Ice Stream, near the catchment divide between Kamb and Bindschadler Ice Streams. (B) Map of the subglacial topography at Mt. Resnik (Morse et al., 2002). Two ground-based radar surveys are plotted in black: (i) 1 MHz data collected by the University of Washington in 2004, and (ii) 3 MHz data collected by St. Olaf College in 2002. (C) Map of modern flow speeds and flow pathways over Mt. Resnik (dashed lines) (Joughin and Tulaczyk, 2002), indicating a dominant flow direction orthogonal to the primary radar survey orientation. (D) Contoured surface elevation (Helm et al., 2014), plotted with the coverage region for high resolution DEMs produced as part of this study (blue) calibrated using ICESat altimetry (ground-tracks in orange).

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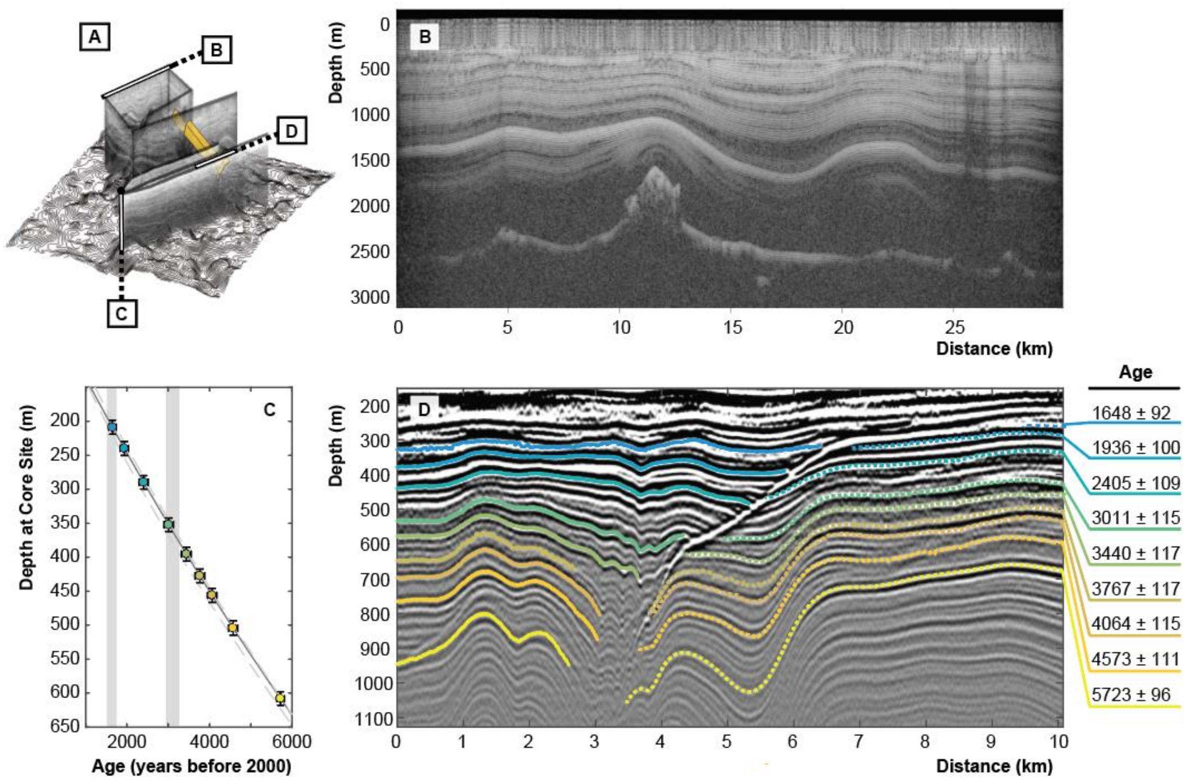

Figure 2: (A) Fence diagram, indicating the positions of the upstream radar survey (B), the Byrd Ice Core (C), and an example downstream line containing the unconformity of interest (D). (B) The radar profile immediately upstream of Mt. Resnik, highlighting conformable layering. (C) Dated reflectors and their associated uncertainties, plotted as a function of depth at the Byrd ice-core site. Grey bars indicate dated slope breaks in the unconformity, potential indications of historic ice dynamic changes (discussed in section 3.2). (D) Dated reflectors traced on the 3 MHz ITASE radargram, with ages (in years before 2000 A.D.) labelled. Dotted lines indicate reflectors dated by amplitude and waveform correlation across the unconformity, solid lines are traced continuously from the ice core site.

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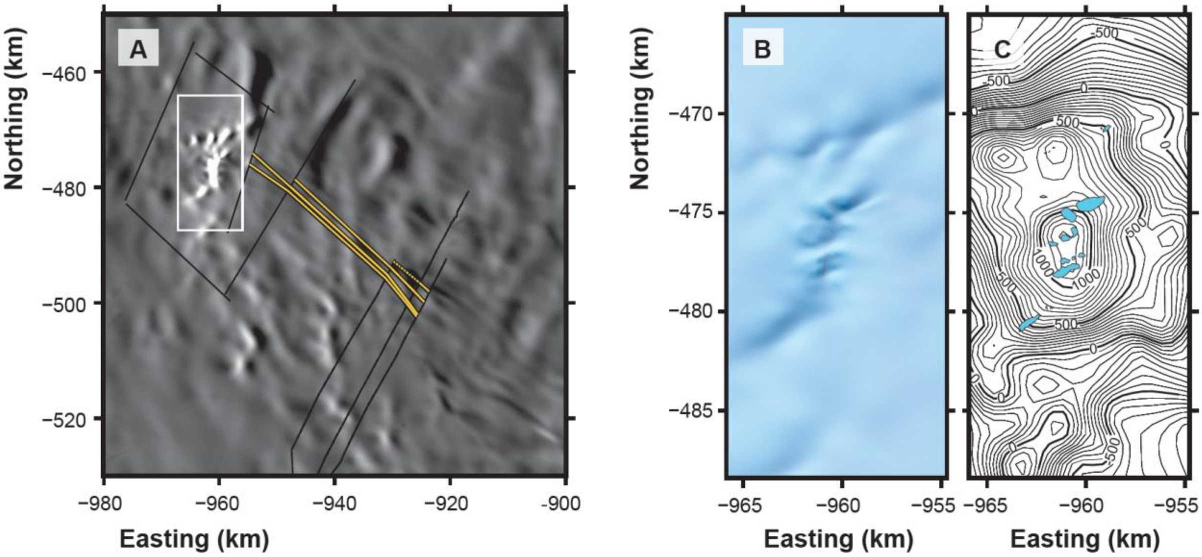

Figure 3: (A) MODIS Imagery for the region (Haran et al., 2014), showing high reflectivity at the source of the unconformity over Mt. Resnik. Traces of slope-breaks in the unconformity are plotted in orange. (B) False-color Landsat 8 imagery collected over Mt. Resnik, using the near-infrared (band 5), green (band 3), and blue (band 2). (C) Contoured basal topography, with blue-ice areas (inferred from blue to near-infrared reflection intensity ratios > 2) highlighted.

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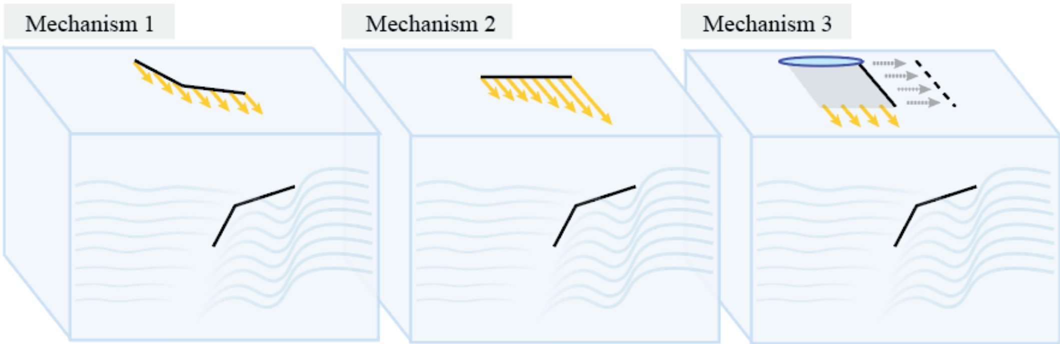

Figure 4: Schematic detailing end-member mechanisms for unconformity formation with the distinctive, kinked geometry observed in the radar data: (1) a stationary surface feature orthogonal to flow that mirrors the shape of the unconformity in the subsurface, advecting away and buried with constant velocities, (2) a stationary surface feature orthogonal to flow that is advected and buried in a spatially variable velocity field, with velocity gradients that mirror depth gradients of the structure, or (3), a feature whose boundaries drift with time, with the slope of the unconformity varying as a function of the rate of drift. We believe that mechanism 3 is most consistent with the unconformity geometry, with kink positions corresponding to the dates of ice-dynamic changes in the region.