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Evidence from ice shelves for channelized meltwater flow beneath the Antarctic Ice Sheet

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Meltwater generated beneath the Antarctic Ice Sheet exerts a strong influence on the speed of ice flow, in particular for major ice streams[1,2]. The subglacial meltwater also influences ocean circulation beneath ice shelves, initiating meltwater plumes that entrain warmer ocean water and cause high rates of melting[3]. However, despite its importance, the nature of the hydrological system beneath the grounded ice sheet remains poorly characterized. Here we present evidence, from satellite and airborne remote sensing, for large channels beneath the floating Filchner–Ronne Ice Shelf in West Antarctica, which we propose provide a means for investigating the hydrological system beneath the grounded ice sheet. We observe features on the surface of the ice shelf from satellite imagery and, using radar measurements, show that they correspond with channels beneath the ice shelf. We also show that the sub-ice-shelf channels are aligned with locations where the outflow of subglacial meltwater has been predicted. This agreement indicates that the sub-ice-shelf channels are formed by meltwater plumes, initiated by subglacial water exiting the upstream grounded ice sheet in a focused (channelized) manner. The existence of a channelized hydrological system has implications for the behaviour and dynamics of ice sheets and ice shelves near the grounding lines of ice streams in Antarctica.

From extensive research in mountain glacier environments, the subglacial hydrological system has been characterized as having two potential states: distributed or channelized[4]. In a system where there is limited meltwater availability, an inefficient, low-volume, high-pressure distributed system exists. When sufficiently large amounts of meltwater are available, the system evolves into an efficient, higher volume, lower pressure channelized system. Channels may be incised into the ice or into the basal substrate. The basal velocity of an ice sheet is a function of the subglacial water depth and pressure, which is, in turn, a function of the nature of the hydrological system. Recent research in Greenland has demonstrated that similar relationships between subglacial water depth and pressure also hold true in ice-sheet settings, where even beneath multi-kilometre-depth ice, both the nature and evolution of subglacial water systems impose significant effects on ice velocity[5,6].

Channelized subglacial water flow beneath former ice sheets has previously been postulated from geomorphological evidence in Antarctica[7] and North America[8]. Subglacial lake drainage in the centre of East Antarctica has also been assumed to be channelized[9]. A key unknown, however, is whether a persistent channelized subglacial hydrological system exists widely beneath the Antarctic Ice Sheet, where water input is solely from basal melt, in the absence of surface melt. As a result, and owing to limits imposed by present ice-sheet-model resolution, existing attempts to incorporate a model of subglacial water flow into ice-sheet models have largely focused on distributed-type water flow[10].

Here we present evidence for persistent subglacial channels beneath the grounded ice sheet, derived from satellite imagery of the continent's floating ice shelves. The MODIS (Moderate Resolution Imaging Spectroradiometer) Mosaic of Antarctica imagery provides a map of surface morphology, enhancing features using a multi-image approach[11]. On some ice shelves around Antarctica, features that are distinct from standard flow stripes[12] are apparent, of the order of 1 km in width, aligned to the flow direction but occasionally migrating across the general flow direction of the ice shelf. These are particularly discernible on part of the Filchner–Ronne Ice Shelf (FRIS; Fig. 1a) but similar features also appear on the Ross Ice Shelf (RIS) and on smaller fringing ice shelves and ice tongues around Antarctica (Fig. 1b–d; see Supplementary Section S1 for imagery of all ice shelves). Here, we focus on the most striking features on the FRIS, but discuss these in the context of the wider coupled Antarctic subglacial-hydrological/ocean system.

Airborne radar measurements over the Institute Ice Stream (IIS) and Möller Ice Stream (MIS) system[13], feeding into the FRIS, cross one of the features downstream of the MIS (Fig. 2). The radar measurements reveal a sub-ice-shelf channel about 250 m in height and around 300 m wide incised upwards into the ice-shelf base. The ice-shelf surface feature is, therefore, the surface expression of a sub-ice-shelf channel, due to the lower flotation level of the thinner ice in the channel. Despite producing a surface expression, corresponding ice surface elevation measurements demonstrate that the ice is not in hydrostatic equilibrium, with bridging stresses preventing the full relaxation of the ice surface[14] (Fig. 2b).

The ice-shelf features identified correspond with the predicted exit location of subglacial meltwater beneath the grounded ice sheet[10] (Fig. 1). We propose, therefore, that the ice shelf features are a sub-ice-shelf extension of subglacial meltwater channels present beneath the grounded ice sheet. The physical mechanism for the creation of a sub-ice-shelf channel has already been described[3,15,16] as follows: subglacial meltwater reaches the grounding line of the ice sheet and, being fresh relative to the sub-shelf ocean water, rises underneath the base of the ice shelf, entraining the warmer

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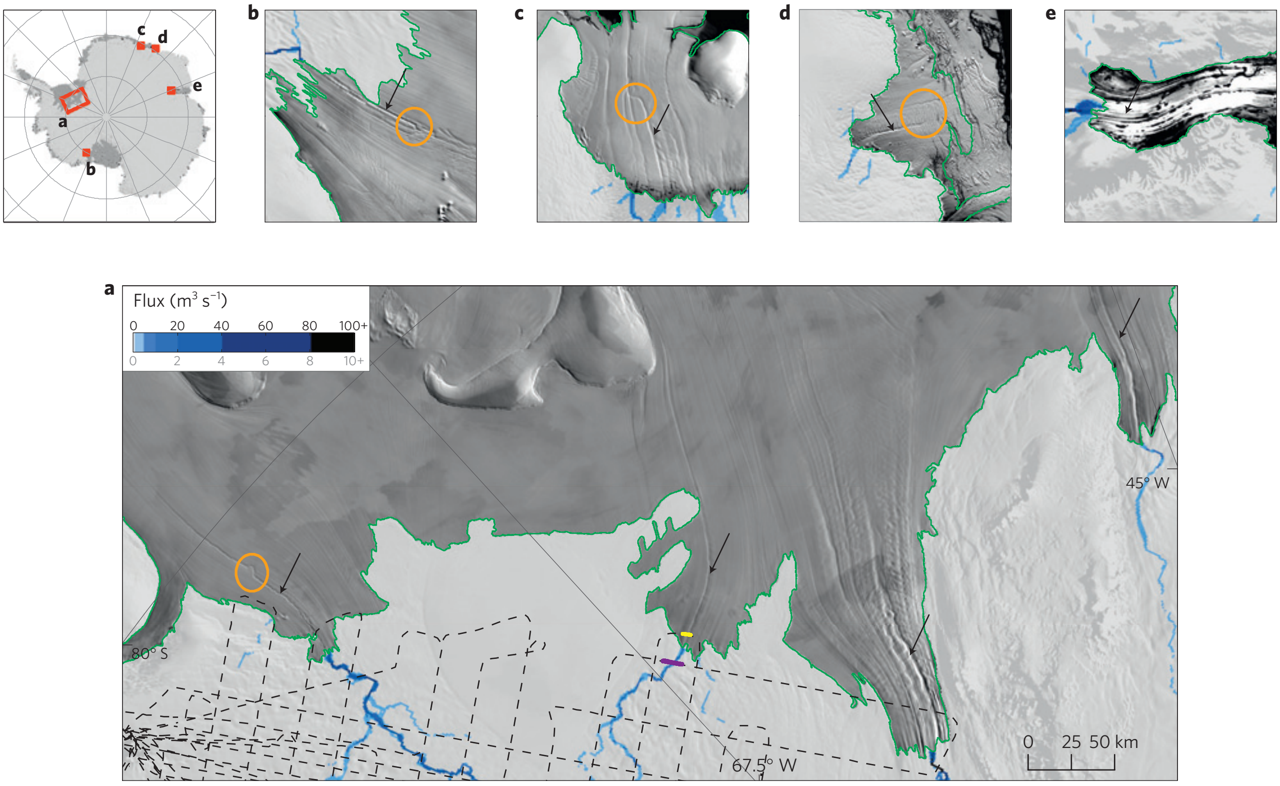

Figure 1 | Selected ice shelf features, with calculated meltwater flux beneath the grounded ice sheet overlain. a, FRIS, arrowed features are downstream of (left to right) Institute, Möller, Foundation and Support Force ice streams. **b**, MacAyeal Ice Stream (RIS). **c**,**d**, Smaller East Antarctic ice shelves. **e**, Lambert Glacier (Amery Ice Shelf). Meltwater flux colour labels in black—parts **a**,**b**,**e**, labels in grey—parts **c**,**d**. Orange circles indicate evidence of migration of the exit point of subglacial channels. The green line is the MODIS grounding line[11]. Dashed lines are airborne radar flight lines, with the yellow section indicating the part shown in Fig. 2, and purple in Supplementary Fig. S4.

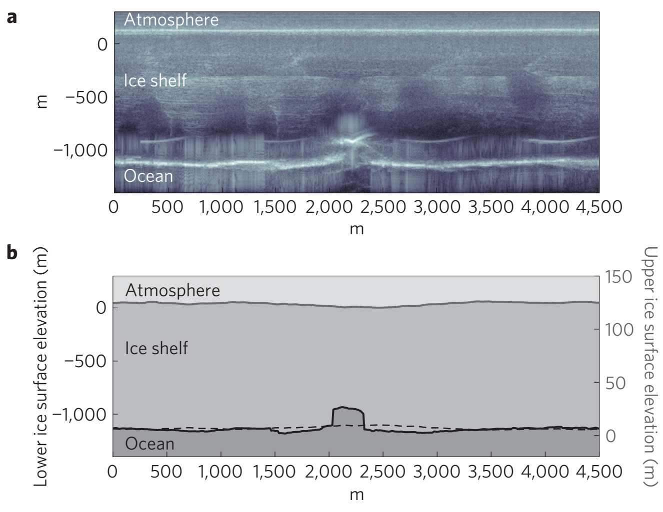

Figure 2 | Geophysical data for the Möller sub-ice-shelf channel. a, Radar echogram. **b**, Measured elevations: lower ice surface elevation picked from the radar data (solid black line), upper ice surface elevation from radar altimeter (solid grey line, note different vertical scale). The dashed line is the lower ice surface as inferred from the ice surface and a hydrostatic assumption (firn correction of 17 m). Ice flow is into the page.

ocean water as it flows (Fig. 3). This process induces large but localized sub-ice-shelf melt rates beneath the ice shelf. Once a small sub-ice-shelf channel is formed, the localized melt rates quickly enlarge it, and the meltwater plume flow is increasingly focused into this channel. Some distance downstream, the water flowing along the channel becomes supercooled, as a result of the falling pressure, and freezes, filling in the channel. This can be seen on the satellite imagery with the disappearance of the feature after several hundred kilometres (Fig. 1).

Sub-ice-shelf channels on this scale have been noted previously[17–19]. Similar channels on Petermann Glacier in Greenland were attributed to a purely oceanographic source[17], initiated by irregularities in the ice along the grounding line[16]. The mechanism proposed here to explain the FRIS features does not preclude other features having a purely oceanographic source. However, results from plume models[3,16] demonstrate that the outflow of sub-glacial meltwater at an ice shelf grounding line increases overall melt rates. The additional buoyancy associated with the sub-glacial outflow leads to a more vigorous plume and enhanced transfer of ocean heat to the ice shelf base. Subglacial outflows are thus a more effective means of initiating sub-ice-shelf plumes (and hence of creating sub-ice-shelf channels) compared with an ocean-driven plume alone. The agreement between subglacial water flow routes and sub-ice-shelf channels in Fig. 1 indicates that in this circumstance, the plume is likely to be driven by a focused subglacial water input. Elsewhere, sub-ice-shelf channels on the Amery Ice Shelf have been attributed to suture zones (shear margins) between discrete ice stream flow units[18] that feed the Lambert Glacier and join near the grounding line. However, in many cases on the FRIS, there are no distinct suture zones, and the subglacial channels are away from the shear margins, largely following the basal topography (most notably, MIS; see Supplementary Fig. S4). We can, therefore, dismiss suture zones as the cause of the ice shelf features in the FRIS region (see Supplementary Section S2 for further discussion).

Radar measurements upstream of the MIS grounding line are inconclusive about the presence of a subglacial channel under the

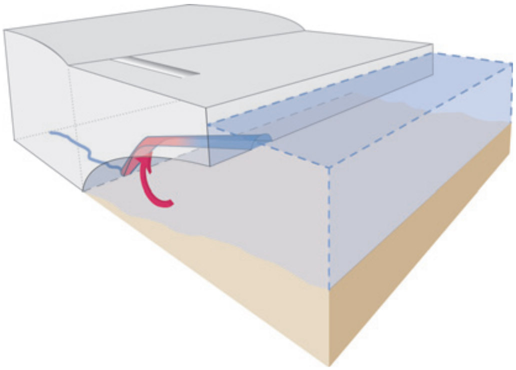

Figure 3 | Proposed mechanism of channel formation. The red arrow indicates the entrainment of relatively warm ocean water to facilitate high localized sub-ice-shelf melt rates. Not to scale.

grounded ice (Supplementary Section S3, also ref. 17), suggesting that any channel is small in comparison with the channel it feeds beneath the ice shelf. Indeed, if the channel was incised into the ice, the subglacial channel need only be a few metres wide to drain the flux ($\sim$10 $m^3 s^{-1}$) under the pressure gradient (Supplementary Section S4) and so would not be easily imaged by radar data with an along-track spatial resolution of $\sim$10 m. The sub-ice-shelf channels are visible on the satellite image close to the grounding line (within $\sim$1 km), so this means a quick transition from a small subglacial channel (metres in width) to a large sub-ice-shelf channel (hundreds of metres in width), requiring high sub-ice-shelf melt rates. The spatially averaged melt rate required to melt the channels is of the order of 5 m yr^{-1} (Supplementary Section S5) between the MIS grounding line and the radar line location (7.8 km from grounding line). Melt rates of this order have been inferred previously for this region[15,20,21].

Despite the failure of the hydrostatic assumption at the scale of the sub-ice-shelf channels, repeat surface-altimetry measurements can provide insight into whether the channels change over time, and, hence, whether the subglacial hydrological system is changing over time. Repeat measurements between 2003 and 2009 are available from the laser altimeter on board the ICESat satellite[22]. The depth of the ice-shelf-surface channels at a specific location does not change significantly over the observation period (Supplementary Figs S6–10); however, there is evidence of advection of the features with ice shelf flow (for example, Supplementary Figs S7b5, S9b5 and S10b11). The advection of changing plume pathways indicates a shift in the outflow point of the subglacial channel at the grounding line (rather than an ocean-based, plume-driven change) and, hence, a reorganization of the hydrological system. The ice shelf, therefore, records a history of the subglacial water flow outlet locations. The more linearly continuous the ice-shelf channel, the more stable the subglacial hydrological system. There is also a distinction between a slow change in the position of the outflow (for example, Fig. 1a, IIS), indicating gradual migration of the channel at the grounding line, and a switch (for example, Fig. 1b,d), indicating a change occurring upstream that alters the location of the outflow point at the grounding line. The switch in Fig. 1d occurs $\sim$40 km from the grounding line; with a velocity[23] of the order of 300 m yr^{-1}, a switch would have occurred around 130 years ago. Figure 1c indicates the gradual splitting of a single channel into three channels at the grounding line.

As mentioned above, the ice shelf features highlighted here are more prominent in our study area of the FRIS (Fig. 1a) than elsewhere on the FRIS and on the RIS (Supplementary Section S1). A question remains as to why plumes form at some grounding lines and not at others. The main influencing factors are likely to be the nature of both the ice/ocean interface and the subglacial hydrological system.

There are two factors to consider about the ice/ocean interface: the thermal driving and ice-shelf-base slope. The freezing temperature of water decreases with increasing pressure, so the potential for the ocean to melt ice (thermal driving) increases with depth. Steeper slopes impart stronger buoyancy forcing on the ice/ocean boundary layer, leading to stronger currents along the ice base, more efficient heat transfer to the ice and hence more rapid melting[3]. Ice thickness and ice-shelf-base slope across the grounding line of the IIS and MIS (those with the most prominent features), are less than other ice streams around the FRIS ($\sim$1,200 m ice thickness for IIS/MIS compared with >1,500 m elsewhere, ice-shelf-base elevation change of 150 m over 50 km compared with >250 m over 50 km elsewhere; ref. 24), so it seems that the nature of the ice/ocean interface is not the explanation for the occurrence of the features. The existence of the ice shelf features is also not a function of subglacial meltwater flux, with predicted subglacial meltwater fluxes comparable across ice streams flowing into both the FRIS and RIS (Supplementary Figs S1–S3). Indeed, MIS has a relatively low meltwater flux, but has a prominent ice shelf feature. This indicates that it is the stability (see Supplementary Section S7 for discussion of this term) of the hydrological system that may be the critical factor for forming these features. The RIS sector ice streams are known to have an unstable hydrological system[25]. In contrast, the widespread occurrence and longer length (up to 200 km) of the sub-ice-shelf features on parts of the FRIS suggests a more stable subglacial hydrological system in this sector of the ice sheet, particularly around the IIS/MIS system. The role of subglacial lakes in either moderating or causing subglacial water flow variations could also be a contributor to the formation and persistence of the ice shelf features.

The observations presented here demonstrate the existence of a persistent channelized subglacial drainage system near the grounding line of major ice streams in Antarctica. A channelized subglacial drainage system has many impacts on how we consider and investigate the behaviour of the ice sheet. A localized input of meltwater to the cavity will have an impact on predicted sub-ice-shelf melt rates, particularly at the grounding line, which will in turn affect predictions of ice stream behaviour. The process described here also has implications for ice shelf structure; it has been shown previously that lineations of accreted marine ice can serve to stabilize ice shelves[26,27]. The nature of the hydrological input to the ocean also has implications for bulk nutrient delivery[28]. Most critically, the conventional use of distributed subglacial hydrological structures in existing numerical ice sheet models of the evolution of the Antarctic Ice Sheet fails to reflect fully the true nature of the system; greater detail is required to adequately represent the role of the hydrological system in the evolution of the ice sheet.

Methods

The subglacial water flow paths beneath the grounded ice sheet were predicted on the basis of modelled subglacial melt rates[29] and routing of the subglacial meltwater down the hydraulic potential[10,30]. The approach follows that of ref. 10, following the steady-state approach, which uses a flux routing algorithm to calculate upstream water flux for each grid cell. The subglacial water routing algorithm makes no assumption about the nature of the subglacial hydrologic system, except that the calculation of the hydraulic potential assumes that the water pressure is at the ice overburden pressure, neglecting variation in water pressure that will result from a channelized system. The hydraulic potential was calculated using the 1 km ice thickness and bed topography from the BEDMAP2 compilation[24]. The subglacial water routing algorithm is, therefore, run at a 1 km resolution, giving a broad scale indication of the flow routes and subglacial water flux, although the channel features are likely to be on a smaller scale than this.

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Author contributions

A.M.L.B. wrote the paper, J.A.G. processed the ICESat data, and N.R. and H.F.J.C. processed the radar data. A.J.P. and A.J. provided expertise on the nature of meltwater plumes and their interaction with the ice shelf. M.J.S., F.F., N.R., R.G.B., H.F.J.C., T.A.J., A.M.L.B. and D.M.R. were involved in the aerogeophysical survey. All authors commented on a draft of the paper.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to A.M.L.B.

Competing financial interests

The authors declare no competing financial interests.

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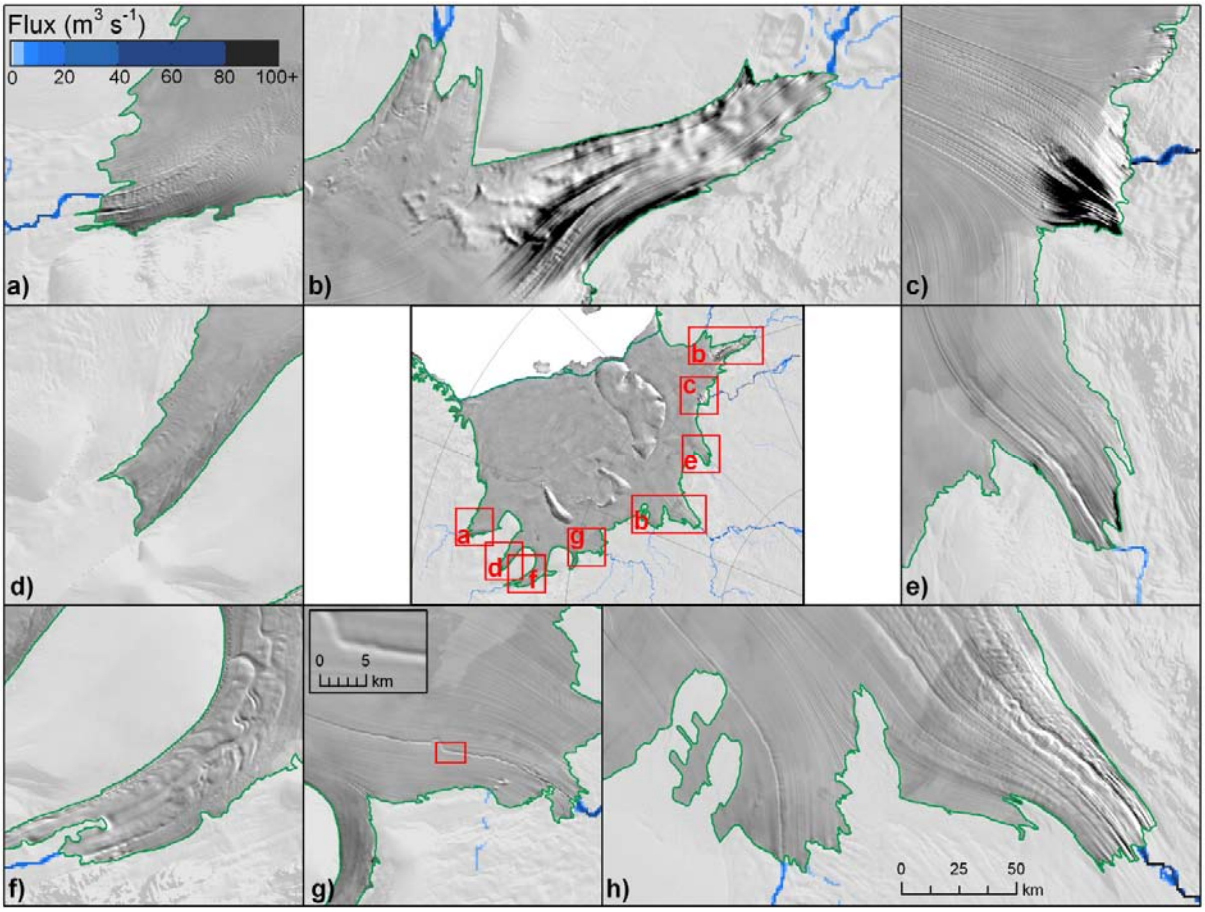
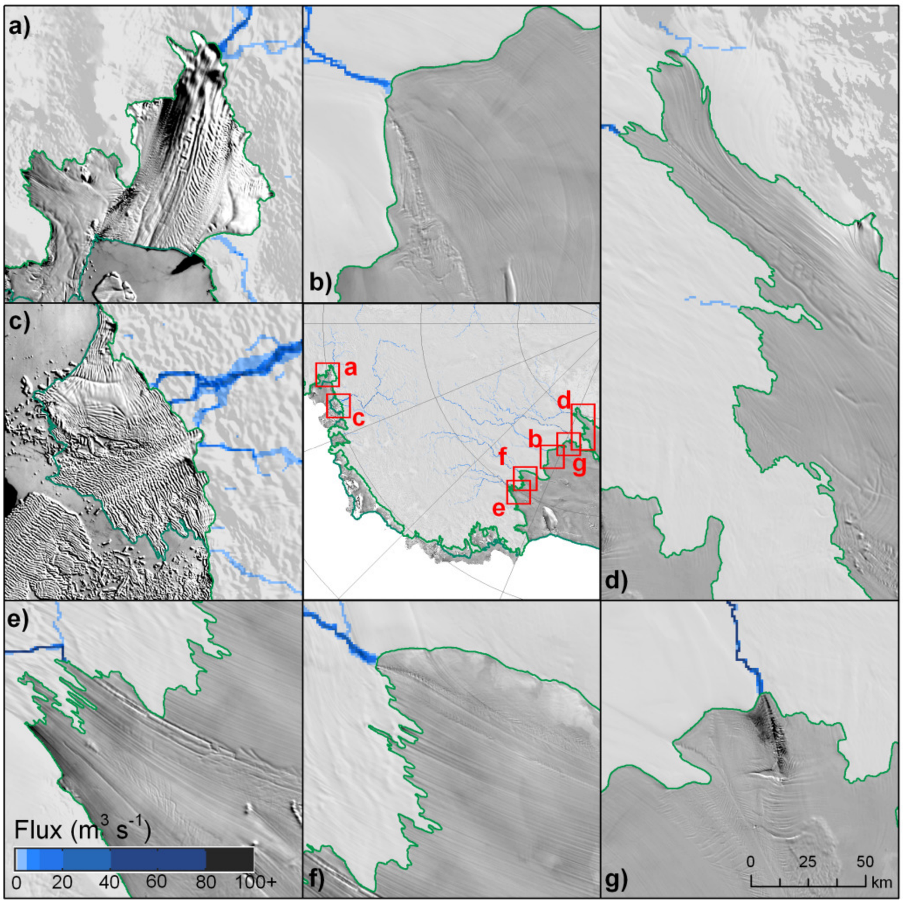
Evidence from ice shelves for channelized meltwater flow beneath the Antarctic Ice Sheet

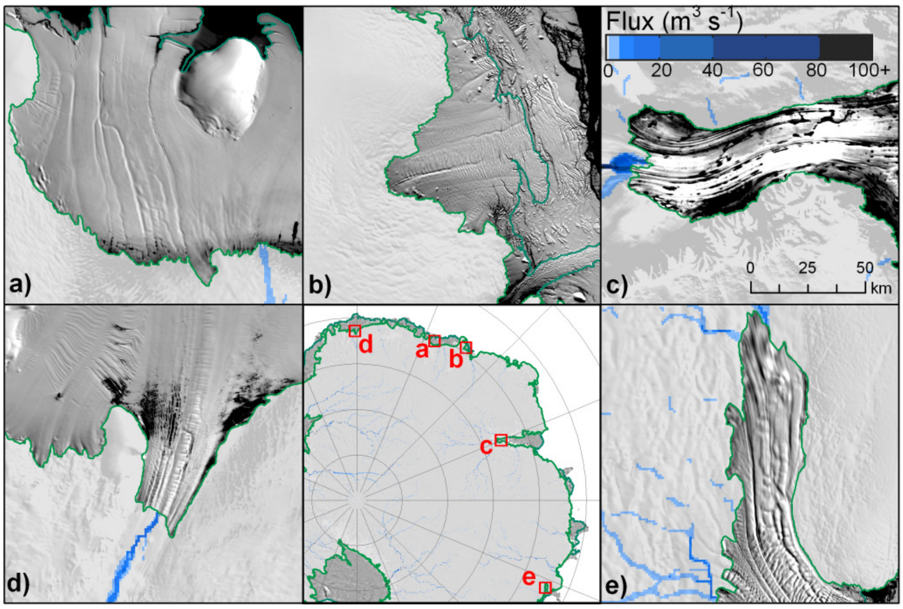
1. Satellite imagery for all ice shelves



Supplementary Figure S1. MODIS Mosaic of Antarctica[1] with predicted meltwater flux overlain on the image, showing features downstream of ice streams feeding into the Filchner-Ronne ice shelf. See Fig. 1 for more details.



Supplementary Figure S2. MODIS Mosaic of Antarctica[1] with predicted meltwater flux overlain on the image, showing features downstream of ice streams feeding into the Ross ice shelf and Amundsen Sea. See Fig. 1 for more details.



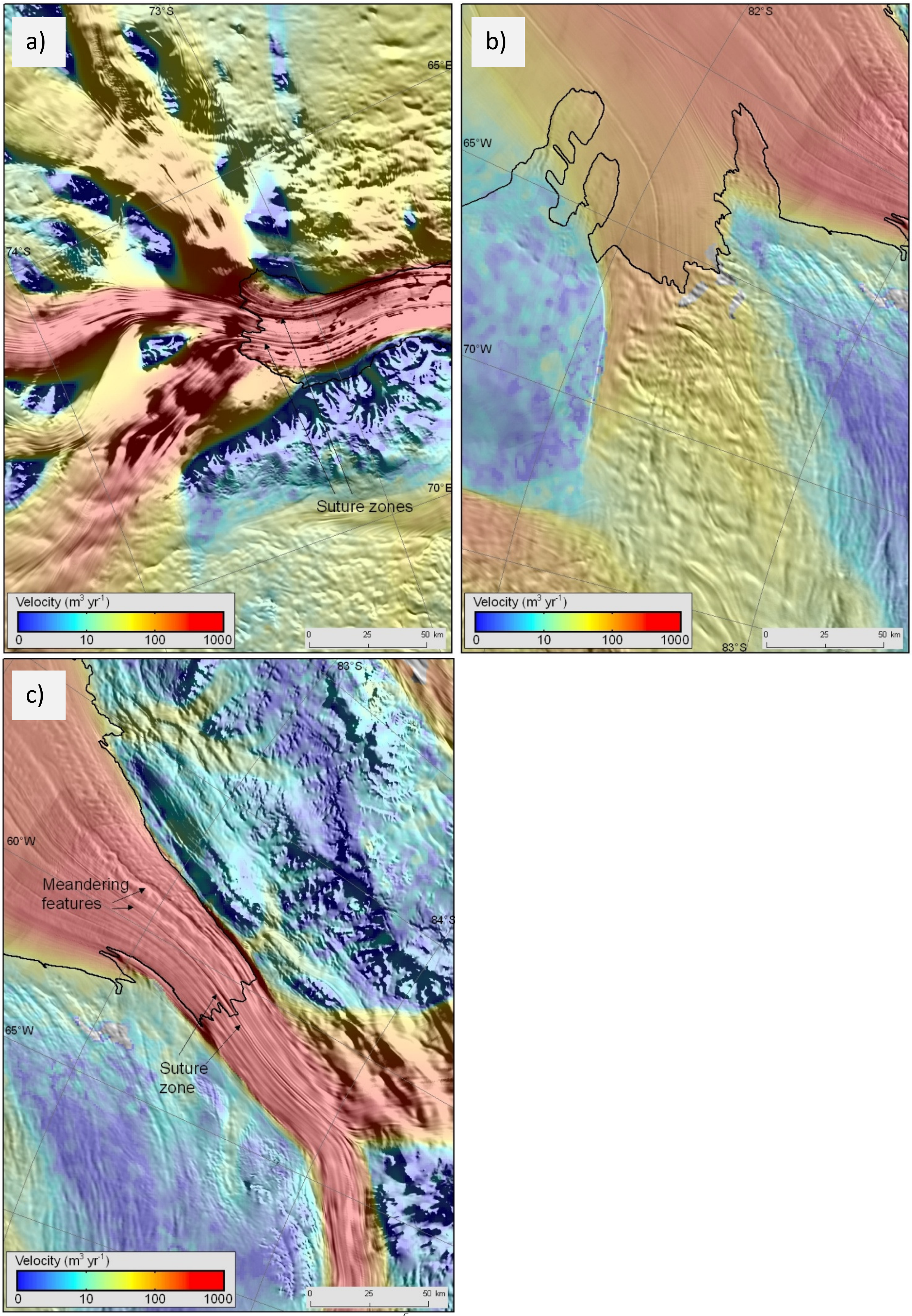
Supplementary Figure S3. MODIS Mosaic of Antarctica[1] with predicted meltwater flux overlain on the image, showing features downstream of East Antarctic ice streams. See Fig. 1 for more details.

2. Discussion of causal mechanisms of ice-shelf features

"Longitudinal surface structures" or "flow stripes" are ubiquitous across ice shelves in Antarctica (Figs S1-3), and have been explained previously by a number of mechanisms: 1) convergence of flow units leading to shear margins or suture zones, and 2) as a result of undulations in the bed topography causing a disturbance to the ice flow [2]. There is, therefore, potential ambiguity in the interpretation of longitudinal surface structures as plume driven features, however, the features highlighted in Fig. 1 have distinctive characteristics which help in their identification. Firstly, they are generally wider than "standard" flowstripes downstream of each ice stream and secondly, they cannot be clearly traced upstream from the ice shelf across the grounding line to the grounded ice sheet. Another distinctive characteristic is their migration across the flow direction of the ice shelf, though this is not always the case. Agreement with the predicted location of subglacial meltwater outflow is, of course, also indicative.

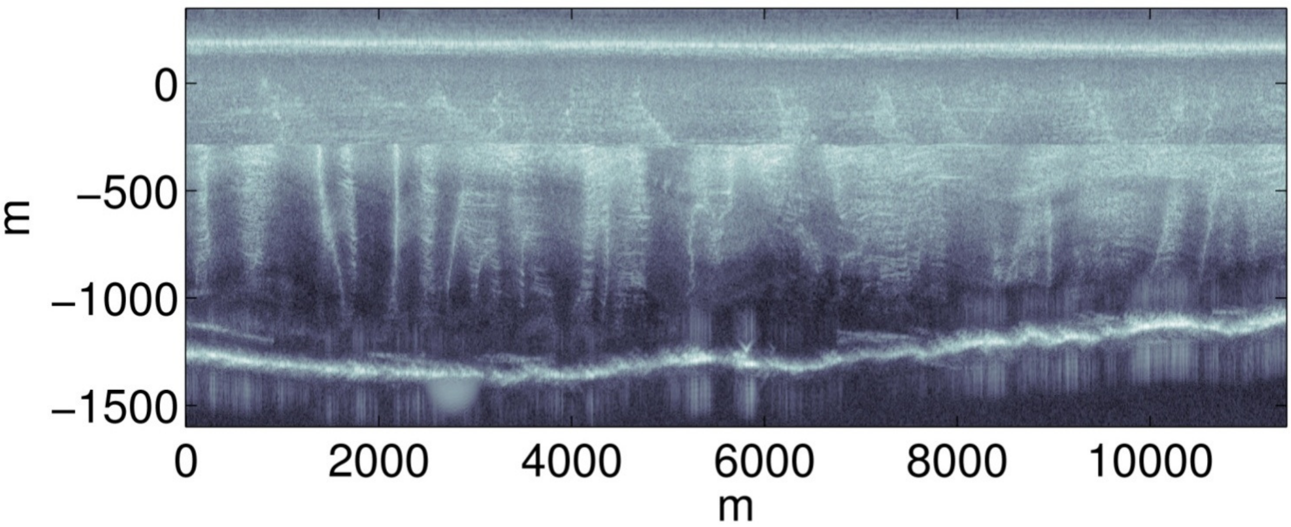
The Amery Ice Shelf is one such example of the role of suture zones (Fig. S4a), with ice-shelf channels corresponding to suture zones from the confluence of three tributaries upstream of the grounding line. Foundation Ice Stream gives a further illustration of the role of a suture zone in producing a longitudinal surface structure (Fig. S4b). The feature labelled "Suture Zone" is a result of a suture zone as it can be traced upstream of the grounding line. The "meandering features", however, fulfil the criteria above in that they cannot be traced upstream and they migrate across the flow direction of the ice shelf. Similarly, the Möller Ice Stream feature cannot be explained by a suture zone, the Möller Ice Stream has no major tributaries (Fig S4c). The feature begins very close to the grounding line and cannot be traced upstream.

Some predicted subglacial water flow paths follow the shear margins of major ice streams[3] (e.g Institute Ice Stream (IIS), Lambert Glacier, Fig. 1e & ref 4), which could lead to the enhancement of flowstripes occurring at shear margins, so it is possible that both factors could lead to enhanced ice shelf features in situations such as the Lambert Glacier/Amery Ice Shelf system.



Supplementary Figure S4. Ice flow velocity[5] overlain on the MODIS image. Black line is MODIS grounding line[1].

3. Upstream Radar cross section



Supplementary Figure S5. Upstream radar plot, corresponds to purple line on Fig 1. Ice flow into the page.

4. Subglacial channel dimensions calculation

The channel width required to drain the subglacial meltwater generated beneath the grounded Möller Ice Stream is calculated as an example, using Rothlisberger's theory of tunnel drainage[6], following eq. 4 from the supplementary information provided in ref 7:

$$Q = 2(\pi/2)^{1/3} S^{4/3} m^{-1} (\phi'/\rho_w g)^{1/2} \tag{1}$$

where Q is the discharge flux, S is the semi-circular cross-section and m is the Manning coefficient and ϕ' is the gradient of hydraulic potential with respect to channel length. Q is taken as 9.3 $m^3\ s^{-1}$ (from the predicted flux rate based on predicted basal melt-rates from ref 8, routed down the hydropotential surface) and we take $m = 0.08\ m^{-1/3}$, $\phi' = 36.7$ Pa m^{-1}, $\rho_w = 1000$ kg m^{-3} and g = 9.81 m s^{-2} to determine $S = 3.5\ m^2$, and hence a diameter of 1.5 m for the subglacial channel.

This calculation simply illustrates the size of channel needed to drain to meltwater flux if it were a channel incised in the ice. The Möller ice stream subglacial flux is low in comparison to other ice streams at 9.3 $m^3 s^{-1}$ and is low in comparison to Greenland meltwater fluxes (e.g. ref 9) and lake outflow discharge[7] and is unlikely to be sufficient to maintain a channel in the ice over a longer period of time due to creep closure acting to close the channel. Ascertaining the nature of the channel (in ice or sediment) requires further investigation.

5. Sub-ice-shelf melt-rates calculation

In order to calculate the basal melt-rate (b) required to produce the sub-ice-shelf-channel at the grounding line downstream of the Möller Ice Stream, we consider the continuity equation:

$$\frac{\partial H}{\partial t} = -\frac{\partial Hu}{\partial x} + a - b$$

(2)

where H is ice thickness, u is ice shelf velocity and a is the surface accumulation (assuming no surface melt). If we then assume that the system is in equilibrium, the following equation holds along the horizontal flow direction:

$$\frac{\partial Hu}{\partial x} = a - b$$

(3)

Integrating eq. 3 with respect to x and solving over the distance from the grounding line (x = 0) to the radar measurement location (l) on the ice shelf gives us:

$$(Hu)_l - (Hu)_0 = (a - b)x$$

(4)

Unfortunately, a measurement of the ice thickness at the grounding line is not available, so we instead infer the ice thickness from the ice sheet surface[10] and a hydrostatic assumption (following ref 11), using a firn correction value of 17 m.

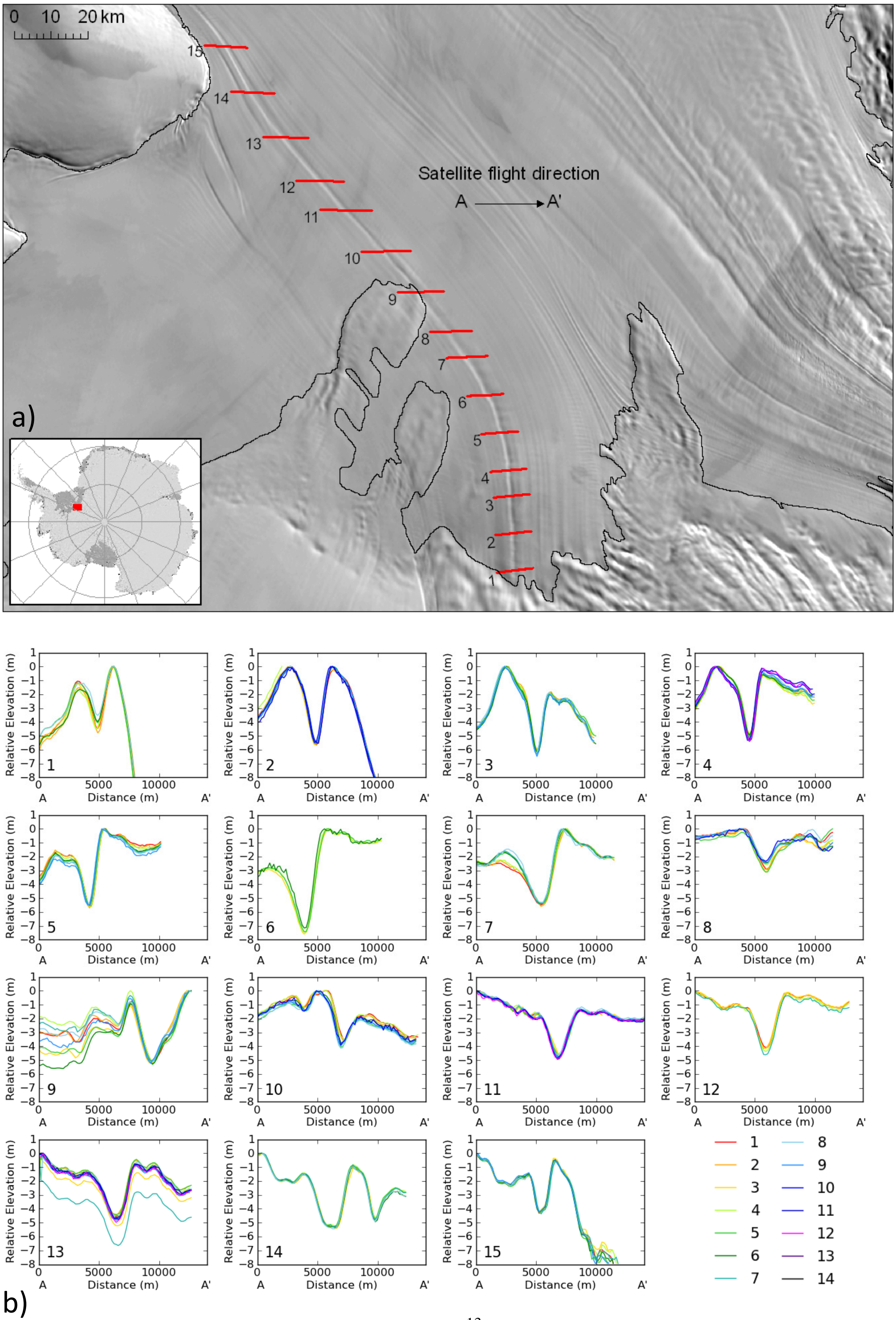
Using H_0 = 1332 m (from hydrostatic assumption), H_l = 1054 m (from radar measurement), u_o = 136.4 m yr^{-1}, u_l = 138.0 m yr^{-1} (ref 5), x = 7800 m and a = 0.165 m yr^{-1} (ref 12), leads to an average melt-rate over the 7.8 km distance of 4.8 m yr^{-1}.

6. ICESat elevation transects

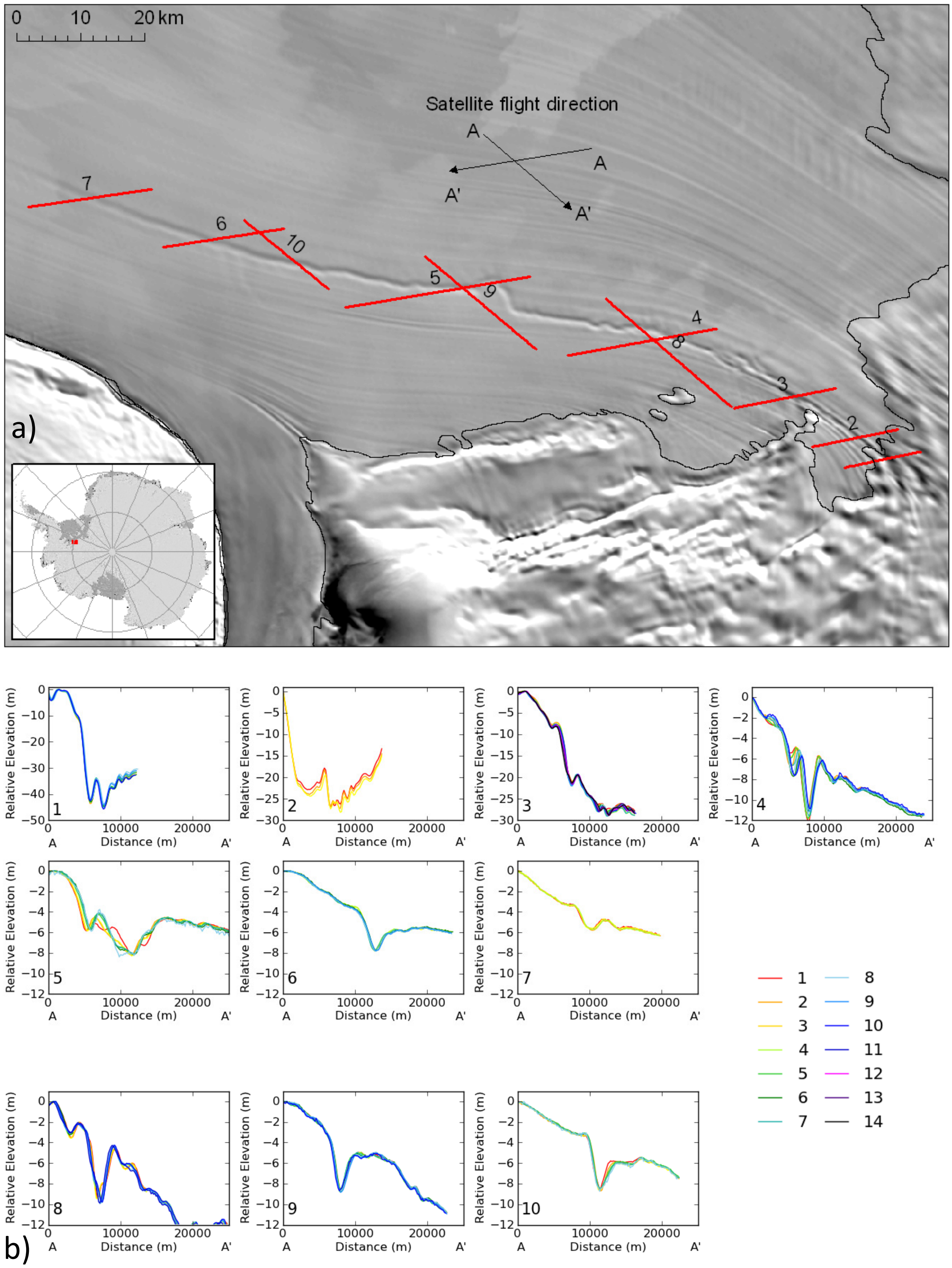
This section provides graphs displaying ICESat data over the most identifiable ice shelf features in Fig. 1, namely the features downstream of Möller, Institute Support Force, MacAyeal and Whillans ice streams.

Surface elevations are from the high accuracy Geoscience Laser Altimeter System (GLAS) onboard the ICESat satellite. ICESat recorded data in 33 to 56 days periods, two or three times per year between 20th February 2003 and 8th April 2009. The level 2 Antarctic and Greenland Ice Sheet Altimetry Data product (GLA12) version 531 was used throughout[13]. The data were extracted using the software provided by the National Snow and Ice Data Center (NSIDC) and transformed from the Topex/Poseidon ellipsoid to the WGS84 ellipsoid for consistency with other datasets. Corrections were applied to account for the saturation of the laser over the ice sheet. Geophysical quality assurance filters were used to remove returns which may have been viewing non-ice surface features[10].

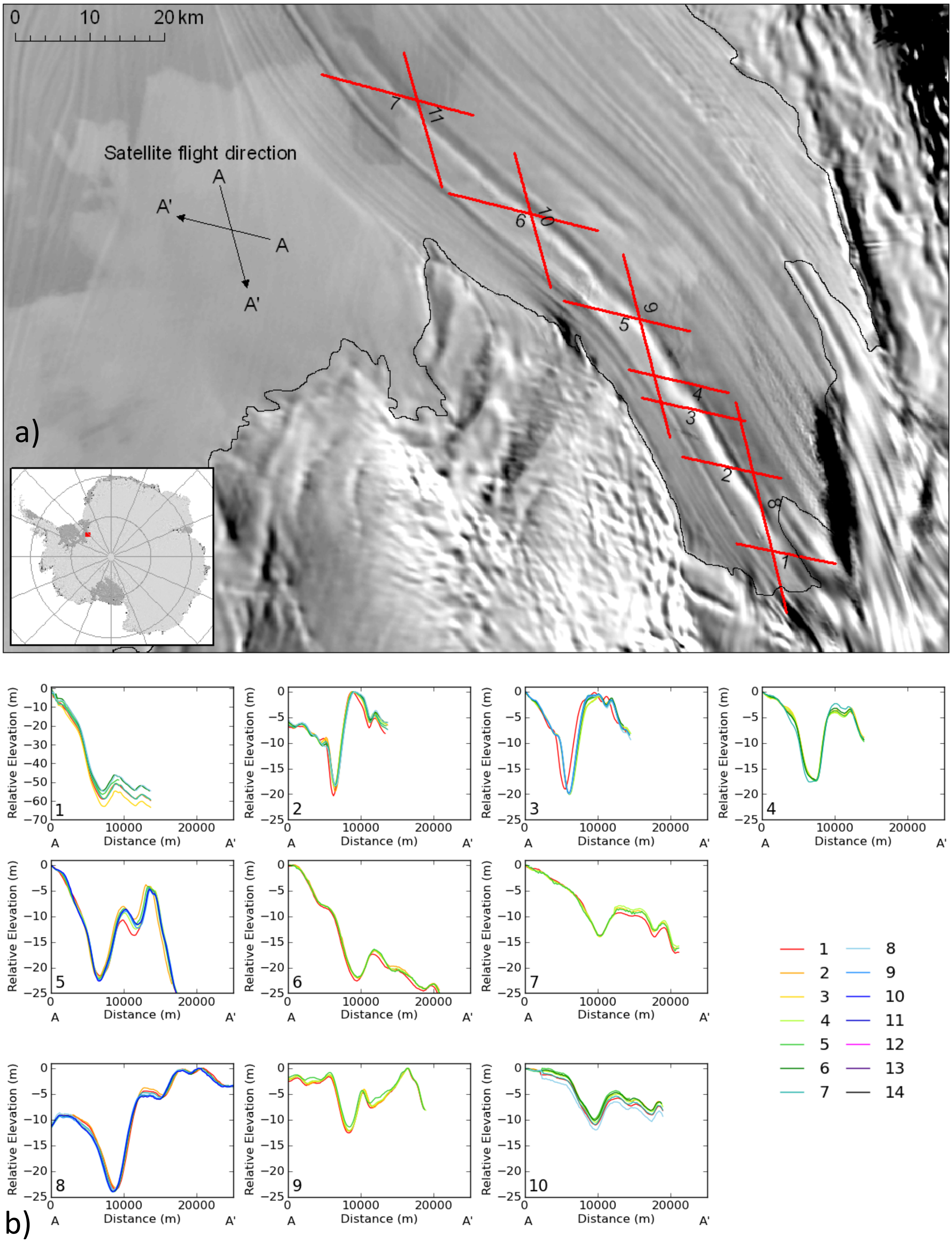
The data were clipped using a 5 km buffer either side of each ice shelf feature. As the satellite tracks do not cross the features perpendicularly, the length of the transects vary for each feature. Despite testing various tide corrections, there remains a small offset in the elevation measurements over the course of time due to tides, so the elevations are plotted relative to the highest point in the transect. Where a transect crosses over the grounding line, and the highest elevation along the transect is over grounded ice, some variability is introduced (e.g. Fig. S6b, plot 9).



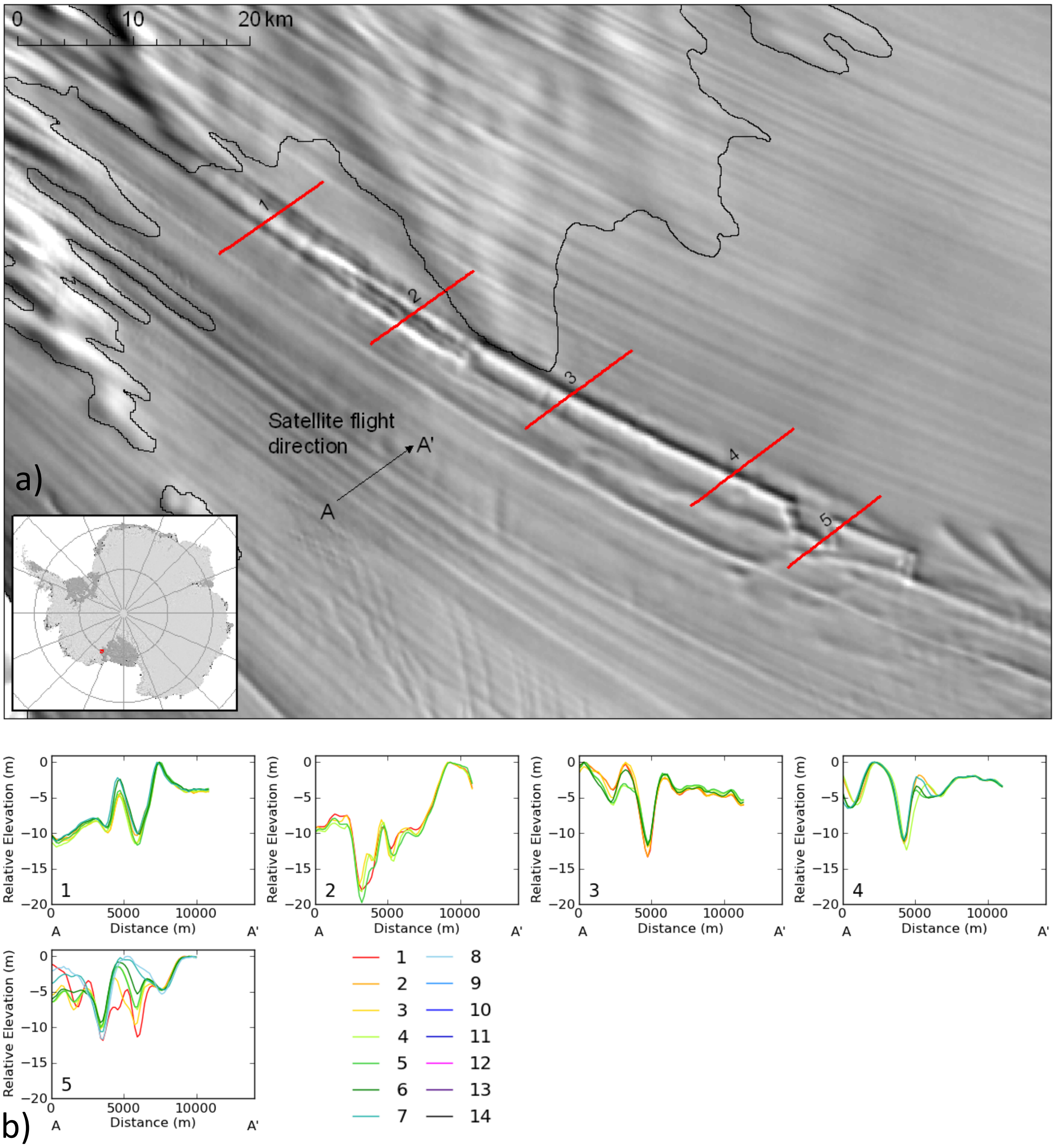
Supplementary Figure S6. ICESat measurements[13] over feature downstream of Möller Ice Stream, a) location of transects shown in plot b), b) elevation relative to the highest elevation in the plot to remove the impact of tides, the colour of the line relates to the order of measurement, i.e. 1 being measured before 2, timestamps for each line are provided in the Appendix.



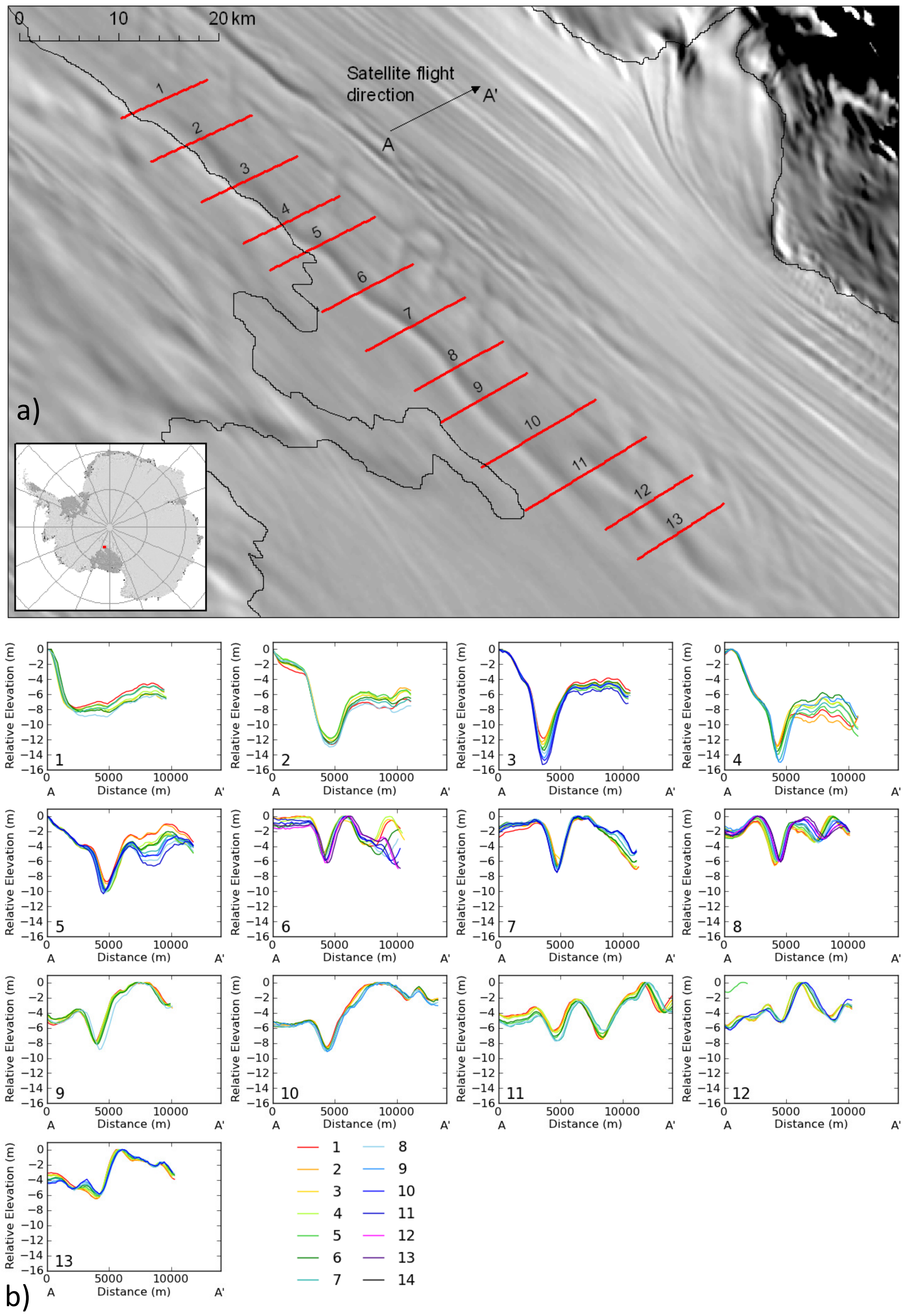
Supplementary Figure S7. ICESat measurements[13] over feature downstream of Institute Ice Stream, a) location of transects shown in plot b), b) elevation relative to the highest elevation in the plot to remove the impact of tides, the colour of the line relates to the order of measurement, i.e. 1 being measured before 2, timestamps for each line are provided in the Appendix.



Supplementary Figure S8. ICESat measurements[13] over feature downstream of Support Force Ice Stream, a) location of transects shown in plot b), b) elevation relative to the highest elevation in the plot to remove the impact of tides, the colour of the line relates to the order of measurement, i.e. 1 being measured before 2, timestamps for each line are provided in the Appendix.



Supplementary Figure S9. ICESat measurements[13] over feature downstream of MacAyeal Ice Stream, a) location of transects shown in plot b), b) elevation relative to the highest elevation in the plot to remove the impact of tides, the colour of the line relates to the order of measurement, i.e. 1 being measured before 2, timestamps for each line are provided in the Appendix.



Supplementary Figure S10. ICESat measurements[13] over feature downstream of Whillans Ice Stream, a) location of transects shown in plot b), b) elevation relative to the highest elevation in the plot to remove the impact of tides, the colour of the line relates to the order of measurement, i.e. 1 being measured before 2, timestamps for each line are provided in the Appendix.

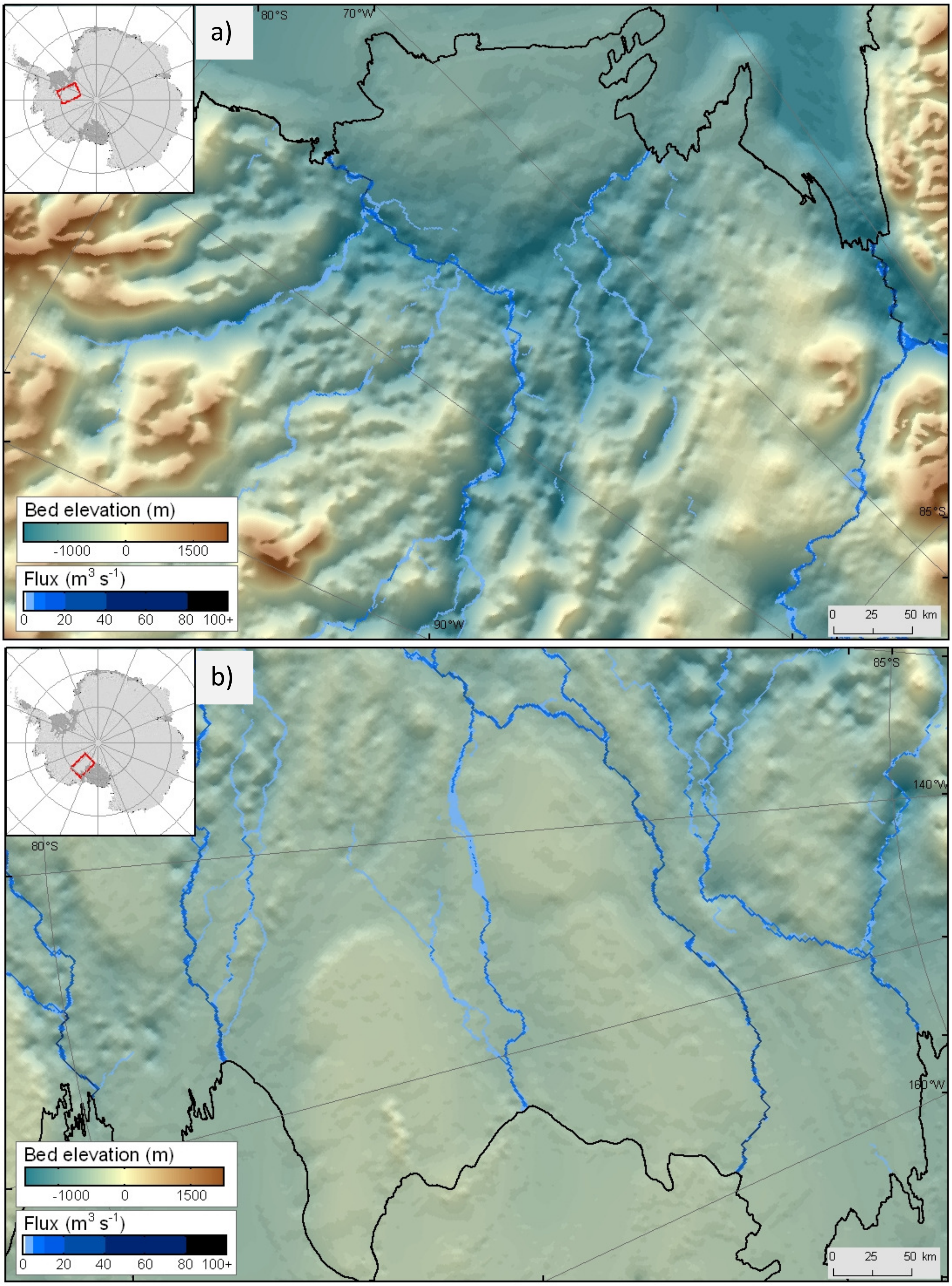
7. Hydrology

Formation of linearly continuous ice-shelf features, requires both a stable meltwater flux and outflow location. However, we must be careful here in how we define stability of the subglacial hydrological system - an inherently unstable environment due to the control of the overlying ice[14,15]. Here, where we use the term “stable”, we mean long periods of stable meltwater flux and outflow location, but in a system still susceptible to change at intervals. For example, below we discuss the Institute Ice Stream catchment as having a relatively stable hydrological system, yet there is some evidence of migration of the outflow location from the ice shelf feature downstream of the ice stream.

Linearly continuous features exist, most notably, downstream of the Institute and Möller Ice Streams, indicating a relatively stable hydrological system with well constrained subglacial water flow routes. A recent geophysical survey of the Institute/Möller drainage system[16] identified a complex topography, with high relief, meaning a strong basal topographic control on water drainage routes and subglacial lakes (see Fig. S11), making the subglacial water system potentially more stable than those in the RIS sector. The RIS sector ice streams are known to have an unstable hydrological system[14,17] and be underlain by sediments[18] with low topographic relief. It also has a network of connected subglacial lakes, constrained largely by the pressure from the overlying ice, rather than the subglacial topography, which fill and drain over short intervals[17]. All these conditions make the sector less conducive to forming persistent and stable subglacial water channels and hence sub-ice-shelf meltwater plumes.

Subglacial lake drainage may lead to intermittent high subglacial water flux, potentially explaining an intermittant feature downstream of Whillans Ice Stream (Fig. S2d). Active subglacial lakes identified beneath the Whillans ice stream alternate between filling and draining[19]. In contrast, the small number of active subglacial lakes identified in the Institute/Möller drainage system were filling over the entire ICESat observation period. The Institute and Möller ice shelf features begin at the grounding line, which indicates active meltwater plume formation and melt when the image was captured in 2003, corresponding to the start of the ICESat observation period of lake filling. Active plume formation concurrent with lake filling suggest that subglacial lakes do not play a major role in the formation of the meltwater plumes in the Institute/Möller catchment.

The reason for the absence of distinct features on the FRIS downstream of other ice streams outside of those highlighted in Fig. 1 needs further investigation, to fully determine whether the explanation is hydrological or oceanographic. Targeted coupled ice-shelf/plume modelling e.g. ref 20 is required to investigate this further.



Supplementary Figure S11. Subglacial topography and predicted flow routes for a) catchment of Institute and Möller Ice Streams and b) catchment of Siple Coast Ice Streams. Note that the subglacial water flux has been routed down the hydraulic potential, but plotted over the basal topography, to demonstrate the influence of the basal topography on the water flow routes. Black line is MODIS grounding line.

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Appendix

Table S1: Timestamps for ICESat flight lines in Fig S6 (Möller Ice Stream feature)

Subplot	Line	Seconds since 2000	Date	Time
1	1	120922976	31/10/2003	13:42:56
1	2	139474352	02/06/2004	06:52:32
1	3	151468032	19/10/2004	02:27:12
1	4	171227376	04/06/2005	19:09:36
1	5	184515344	05/11/2005	14:15:44
1	6	228262048	26/03/2007	22:07:28
1	7	257857952	03/03/2008	11:12:32
2	1	132312456	11/03/2004	09:27:36
2	2	152158128	27/10/2004	02:08:48
2	3	164065504	13/03/2005	21:45:04
2	4	203756801	16/06/2006	07:06:40
2	5	217044768	17/11/2006	02:12:48
2	6	228952144	03/04/2007	21:49:04
2	7	246640672	25/10/2007	15:17:52
2	8	258548033	11/03/2008	10:53:53
2	9	281931424	07/12/2008	02:17:04
3	1	140854544	18/06/2004	06:15:44
3	2	164755587	21/03/2005	21:26:26
3	3	172607568	20/06/2005	18:32:48
3	4	204446896	24/06/2006	06:48:16
3	5	217734864	25/11/2006	01:54:24
3	6	229642240	11/04/2007	21:30:40
3	7	259238128	19/03/2008	10:35:28
3	8	282621536	15/12/2008	01:58:56
4	1	130845288	23/02/2004	09:54:48
4	2	138697264	24/05/2004	07:01:04
4	3	150690960	10/10/2004	02:36:00
4	4	162598320	24/02/2005	22:12:00
4	5	170450304	26/05/2005	19:18:24
4	6	202289632	30/05/2006	07:33:52
4	7	215577600	31/10/2006	02:40:00
4	8	245173504	08/10/2007	15:45:04
4	9	276926560	10/10/2008	04:02:40
4	10	290387072	14/03/2009	23:04:32
5	1	120835992	30/10/2003	13:33:12
5	2	139387360	01/06/2004	06:42:40
5	3	171140400	03/06/2005	19:00:00
5	4	228175058	25/03/2007	21:57:37
5	5	245863600	16/10/2007	15:26:40
5	6	257770960	02/03/2008	11:02:40
5	7	277616672	18/10/2008	03:44:32
5	8	281154368	28/11/2008	02:26:08
6	1	216957776	16/11/2006	02:02:56
6	2	228865152	02/04/2007	21:39:12
6	3	246553696	24/10/2007	15:08:16
6	4	281844448	06/12/2008	02:07:28
7	1	132915568	18/03/2004	08:59:28
7	2	140767552	17/06/2004	06:05:52
7	3	172520592	19/06/2005	18:23:12
7	4	204359920	23/06/2006	06:38:40
7	5	229555248	10/04/2007	21:20:48
7	6	259151152	18/03/2008	10:25:52
7	7	282534560	14/12/2008	01:49:20
8	1	130758310	22/02/2004	09:45:09
8	2	138610288	23/05/2004	06:51:28
8	3	150603968	09/10/2004	02:26:08
8	4	162511344	23/02/2005	22:02:24
8	5	170363328	25/05/2005	19:08:48
8	6	194350672	27/02/2006	10:17:52
8	7	245086528	07/10/2007	15:35:28
8	8	256993888	22/02/2008	11:11:28
8	9	308074912	05/10/2009	16:21:52
9	1	120749008	29/10/2003	13:23:28
9	2	151294064	17/10/2004	02:07:44
9	3	171053424	02/06/2005	18:50:24
9	4	184341382	03/11/2005	13:56:21
9	5	202892752	06/06/2006	07:05:52
9	6	228088080	24/03/2007	21:48:00
9	7	245776614	15/10/2007	15:16:53
9	8	257683984	01/03/2008	10:53:04
9	9	290990186	21/03/2009	22:36:26
10	1	121439104	06/11/2003	13:05:04
10	2	132138496	09/03/2004	09:08:16
10	3	171743520	10/06/2005	18:32:00
10	4	203582848	14/06/2006	06:47:28
10	5	216870800	15/11/2006	01:53:20
10	6	228778176	01/04/2007	21:29:36
10	7	246466704	23/10/2007	14:58:24
10	8	258374080	09/03/2008	10:34:40
10	9	281757472	05/12/2008	01:57:52
11	1	122129200	14/11/2003	12:46:40
11	2	132828592	17/03/2004	08:49:52
11	3	140680576	16/06/2004	05:56:16
11	4	152674256	02/11/2004	01:30:56
11	5	172433616	18/06/2005	18:13:36
11	6	204272944	22/06/2006	06:29:04
11	7	217560896	23/11/2006	01:34:56
11	8	229468272	09/04/2007	21:11:12

11	9	247156800	31/10/2007	14:40:00
11	10	259064176	17/03/2008	10:16:16
11	11	282447568	13/12/2008	01:39:28
12	1	119971936	20/10/2003	13:32:16
12	2	138523312	22/05/2004	06:41:52
12	3	170276352	24/05/2005	18:59:12
12	4	183564304	25/10/2005	14:05:04
12	5	290213120	12/03/2009	22:45:20
13	1	120662032	28/10/2003	13:13:52
13	2	131361424	29/02/2004	09:17:04
13	3	170966448	01/06/2005	18:40:48
13	4	184254400	02/11/2005	13:46:40
13	5	202805776	05/06/2006	06:56:16
13	6	216093728	06/11/2006	02:02:08
13	7	228001104	23/03/2007	21:38:24
13	8	245689632	14/10/2007	15:07:12
13	9	257597008	29/02/2008	10:43:28
13	10	277442696	16/10/2008	03:24:56
13	11	280980416	26/11/2008	02:06:56
13	12	290903200	20/03/2009	22:26:40
14	1	171656544	09/06/2005	18:22:24
14	2	184944496	10/11/2005	13:28:16
14	3	203495872	13/06/2006	06:37:52
14	4	216783824	14/11/2006	01:43:44
14	5	228691200	31/03/2007	21:20:00
14	6	246379728	22/10/2007	14:48:48
14	7	258287104	08/03/2008	10:25:04
15	1	122042224	13/11/2003	12:37:04
15	2	140593600	15/06/2004	05:46:40
15	3	172346640	17/06/2005	18:04:00
15	4	185634592	18/11/2005	13:09:52
15	5	196333984	22/03/2006	09:13:04
15	6	204185968	21/06/2006	06:19:28
15	7	217473920	22/11/2006	01:25:20
15	8	247069824	30/10/2007	14:30:24

Table S2: Timestamps for ICESat flight lines in Fig S7 (Institute Ice Stream feature).

Subplot	Line	Seconds since 2000	Date	Time
1	1	130329192	17/02/2004	10:33:12
1	2	193921552	22/02/2006	11:05:52
1	3	226968864	11/03/2007	22:54:24
1	4	244657408	02/10/2007	16:23:28
1	5	256564768	17/02/2008	11:59:28
1	6	276410464	04/10/2008	04:41:04
1	7	307645792	30/09/2009	17:09:52
2	1	217908848	27/11/2006	02:14:08
2	2	229816229	13/04/2007	21:50:29
2	3	259412128	21/03/2008	10:55:28
3	1	120319896	24/10/2003	14:11:35
3	2	131019288	25/02/2004	10:14:48
3	3	150864947	12/10/2004	02:55:47
3	4	162772320	26/02/2005	22:32:00
3	5	170624304	28/05/2005	19:38:24
3	6	183912272	29/10/2005	14:44:32
3	7	194611648	02/03/2006	10:47:28
3	8	202463632	01/06/2006	07:53:52
3	9	215751600	02/11/2006	03:00:00
3	10	227658960	19/03/2007	22:36:00
3	11	257254864	25/02/2008	11:41:04
3	12	277100576	12/10/2008	04:22:56
3	13	290561088	16/03/2009	23:24:48
4	1	121009992	01/11/2003	13:53:12
4	2	139561360	03/06/2004	07:02:40
4	3	151555050	20/10/2004	02:37:29
4	4	171314400	05/06/2005	19:20:00
4	5	203153728	09/06/2006	07:35:28
4	6	216441696	10/11/2006	02:41:36
4	7	228349060	27/03/2007	22:17:40
4	8	257944960	04/03/2008	11:22:40
4	9	281328352	30/11/2008	02:45:52
5	1	121700088	09/11/2003	13:34:48
5	2	132399476	12/03/2004	09:37:56
5	3	152245150	28/10/2004	02:19:10
5	4	229039168	04/04/2007	21:59:28
5	5	246727696	26/10/2007	15:28:16
5	6	258635058	12/03/2008	11:04:17
5	7	282018464	08/12/2008	02:27:44
6	1	140941568	19/06/2004	06:26:08
6	2	152935248	05/11/2004	02:00:48
6	3	185982560	22/11/2005	13:49:20
6	4	229729264	12/04/2007	21:41:04
6	5	247417792	03/11/2007	15:09:52
6	6	259325157	20/03/2008	10:45:56
7	1	130932320	24/02/2004	10:05:20
7	2	170537344	27/05/2005	19:29:04

7	3	183825296	28/10/2005	14:34:56
7	4	227572000	18/03/2007	22:26:40
8	1	122076744	13/11/2003	22:12:24
8	2	132776136	16/03/2004	18:15:35
8	3	140628128	15/06/2004	15:22:08
8	4	152621808	01/11/2004	10:56:48
8	5	185669120	18/11/2005	22:45:20
8	6	204220481	21/06/2006	15:54:40
8	7	229415824	09/04/2007	06:37:04
8	8	247104352	31/10/2007	00:05:52
8	9	259011712	16/03/2008	19:41:52
8	10	282395104	12/12/2008	11:05:04
9	1	132086038	08/03/2004	18:33:57
9	2	163839072	11/03/2005	06:51:12
9	3	171691056	10/06/2005	03:57:36
9	4	203530384	13/06/2006	16:13:04
9	5	216818351	14/11/2006	11:19:10
9	6	246414256	23/10/2007	00:24:16
9	7	258321616	08/03/2008	20:00:16
9	8	281705024	04/12/2008	11:23:44
10	1	139247920	30/05/2004	15:58:40
10	2	184288928	02/11/2005	23:22:08
10	3	202840288	05/06/2006	16:31:28
10	4	228035616	24/03/2007	07:13:36
10	5	257631520	29/02/2008	20:18:40
10	6	290937728	21/03/2009	08:02:08

Table S3: Timestamps for ICESat flight lines in Fig S8 (Support Force Ice Stream feature).

Subplot	Line	Seconds since 2000	Date	Time
1	1	151636192	21/10/2004	01:09:52
1	2	195382896	11/03/2006	09:01:36
1	3	203234880	10/06/2006	06:08:00
1	4	216522848	11/11/2006	01:14:08
1	5	228430208	28/03/2007	20:50:08
1	6	246118752	19/10/2007	14:19:12
1	7	258026112	05/03/2008	09:55:12
2	1	121781232	10/11/2003	12:07:12
2	2	164233664	15/03/2005	20:27:44
2	3	185373616	15/11/2005	12:40:15
2	4	196072992	19/03/2006	08:43:12
2	5	203924976	18/06/2006	05:49:36
2	6	229120304	05/04/2007	20:31:44
2	7	246808832	27/10/2007	14:00:32
2	8	282099616	09/12/2008	01:00:16
3	1	119623976	16/10/2003	12:52:55
3	2	162076400	18/02/2005	21:13:20
3	3	169928384	20/05/2005	18:19:44
3	4	193915728	22/02/2006	09:28:48
3	5	226963040	11/03/2007	21:17:20
3	6	244651584	02/10/2007	14:46:24
3	7	256558944	17/02/2008	10:22:24
3	8	276404640	04/10/2008	03:04:00
4	1	141022704	20/06/2004	04:58:24
4	2	172775744	22/06/2005	17:15:44
4	3	186063712	23/11/2005	12:21:52
4	4	196763088	27/03/2006	08:24:48
4	5	217903024	27/11/2006	00:37:04
4	6	259406304	21/03/2008	09:18:24
5	1	120314068	24/10/2003	12:34:27
5	2	138865440	26/05/2004	05:44:00
5	3	170618480	28/05/2005	18:01:20
5	4	183906448	29/10/2005	13:07:28
5	5	202457808	01/06/2006	06:16:48
5	6	215745776	02/11/2006	01:22:56
5	7	277094752	12/10/2008	02:45:52
5	8	290555264	16/03/2009	21:47:44
6	1	139555536	03/06/2004	05:25:36
6	2	228343232	27/03/2007	20:40:32
6	3	246031776	18/10/2007	14:09:36
6	4	257939136	04/03/2008	09:45:36
6	5	281322528	30/11/2008	01:08:48
7	1	171998672	13/06/2005	17:24:32
7	2	195986016	18/03/2006	08:33:36
7	3	229033332	04/04/2007	20:22:12
7	4	282012640	08/12/2008	00:50:40
8	1	131732328	04/03/2004	16:18:48
8	2	139584314	03/06/2004	13:25:14
8	3	203176672	09/06/2006	13:57:52
8	4	228372016	28/03/2007	04:40:16
8	5	246060544	18/10/2007	22:09:04
8	6	257967904	04/03/2008	17:45:04
8	7	281351296	30/11/2008	09:08:16
9	1	131042232	25/02/2004	16:37:12
9	2	138894208	26/05/2004	13:43:28
9	3	170647248	29/05/2005	02:00:48
9	4	183935216	29/10/2005	21:06:56
9	5	277123520	12/10/2008	10:45:20
10	1	130352141	17/02/2004	16:55:40
10	2	138204112	18/05/2004	14:01:52
10	3	193944502	22/02/2006	17:28:22
10	4	226991814	12/03/2007	05:16:54

10	5	244680352	02/10/2007	22:45:52
10	6	256587715	17/02/2008	18:21:55
10	7	289893920	09/03/2009	06:05:20

Table S4: Timestamps for ICESat flight lines in Fig S9 (MacAyeal Ice Stream feature).

Subplot	Line	Seconds since 2000	Date	Time
1	1	185773488	20/11/2005	03:44:48
1	2	196472880	23/03/2006	23:48:00
1	3	204324864	22/06/2006	20:54:24
1	4	217612816	23/11/2006	16:00:16
1	5	247208720	01/11/2007	05:05:20
1	6	259116096	18/03/2008	00:41:36
2	1	140042400	08/06/2004	20:40:00
2	2	195782784	16/03/2006	00:06:24
2	3	203634768	14/06/2006	21:12:48
2	4	246518628	24/10/2007	05:23:47
3	1	120800936	30/10/2003	03:48:56
3	2	131500328	01/03/2004	23:52:08
3	3	171105344	03/06/2005	09:15:44
3	4	216232640	07/11/2006	16:37:20
3	5	228140001	25/03/2007	12:13:21
3	6	257735904	02/03/2008	01:18:24
4	1	138662208	23/05/2004	21:16:48
4	2	183703216	27/10/2005	04:40:16
4	3	227449920	17/03/2007	12:32:00
4	4	245138448	08/10/2007	06:00:48
4	5	276891520	09/10/2008	18:18:40
5	1	122268111	16/11/2003	03:21:51
5	2	164720544	21/03/2005	11:42:24
5	3	185860480	21/11/2005	03:54:40
5	4	196559872	24/03/2006	23:57:52
5	5	217699808	24/11/2006	16:10:08
5	6	247295712	02/11/2007	05:15:12
5	7	282586464	14/12/2008	16:14:24

Table S5: Timestamps for ICESat flight lines in Fig S10 (Whillans Ice Stream feature)

Subplot	Line	Seconds since 2000	Date	Time
1	1	121833264	11/11/2003	02:34:24
1	2	132532656	13/03/2004	22:37:36
1	3	140384640	12/06/2004	19:44:00
1	4	172137680	15/06/2005	08:01:20
1	5	185425632	16/11/2005	03:07:12
1	6	217264960	19/11/2006	15:22:40
1	7	246860864	28/10/2007	04:27:44
1	8	282151648	09/12/2008	15:27:28
2	1	100348368	07/03/2003	10:32:48
2	2	121143173	03/11/2003	02:52:53
2	3	131842560	05/03/2004	22:56:00
2	4	151688224	21/10/2004	15:37:04
2	5	171447584	07/06/2005	08:19:44
2	6	195434928	11/03/2006	23:28:48
2	7	216574864	11/11/2006	15:41:04
2	8	228482240	29/03/2007	11:17:20
3	1	120453080	26/10/2003	03:11:20
3	2	139004448	27/05/2004	20:20:48
3	3	150998131	13/10/2004	15:55:30
3	4	162905504	28/02/2005	11:31:44
3	5	170757488	30/05/2005	08:38:08
3	6	184045456	31/10/2005	03:44:16
3	7	215884784	03/11/2006	15:59:44
3	8	245480688	12/10/2007	05:04:48
3	9	277233760	13/10/2008	17:22:40
3	10	290694272	18/03/2009	12:24:32
4	1	130462377	18/02/2004	23:32:56
4	2	138314352	19/05/2004	20:39:12
4	3	183355360	23/10/2005	04:02:40
4	4	194054736	24/02/2006	00:05:36
4	5	215194688	26/10/2006	16:18:08
4	6	244790592	04/10/2007	05:23:12
4	7	276543648	05/10/2008	17:40:48
4	8	290004160	10/03/2009	12:42:40
4	9	307778976	02/10/2009	06:09:36
5	1	121920248	12/11/2003	02:44:08
5	2	132619640	14/03/2004	22:47:19
5	3	140471625	13/06/2004	19:53:45
5	4	152465312	30/10/2004	15:28:32
5	5	164372672	17/03/2005	11:04:32
5	6	172224656	16/06/2005	08:10:56
5	7	196212000	20/03/2006	23:20:00
5	8	204063984	19/06/2006	20:26:24
5	9	217351952	20/11/2006	15:32:32
5	10	229259328	07/04/2007	11:08:48
5	11	282238624	10/12/2008	15:37:04
6	1	99054808	20/02/2003	11:13:28
6	2	100435376	08/03/2003	10:42:56

6	3	118382752	02/10/2003	04:05:52
6	4	139781536	05/06/2004	20:12:16
6	5	184822528	09/11/2005	03:35:28
6	6	216661856	12/11/2006	15:50:56
6	7	228569232	30/03/2007	11:27:12
6	8	246257760	21/10/2007	04:56:00
6	9	258165120	07/03/2008	00:32:00
7	1	120540064	27/10/2003	03:21:04
7	2	131239455	27/02/2004	23:24:15
7	3	139091440	28/05/2004	20:30:40
7	4	151085120	14/10/2004	16:05:20
7	5	162992496	01/03/2005	11:41:36
7	6	170844480	31/05/2005	08:48:00
7	7	194831824	04/03/2006	23:57:04
7	8	215971760	04/11/2006	16:09:20
7	9	227879136	22/03/2007	11:45:36
7	10	245567664	13/10/2007	05:14:24
7	11	257475040	28/02/2008	00:50:40
8	1	138401344	20/05/2004	20:49:04
8	2	150395024	06/10/2004	16:23:44
8	3	162302400	21/02/2005	12:00:00
8	4	170154384	23/05/2005	09:06:24
8	5	183442336	24/10/2005	04:12:16
8	6	194141728	25/02/2006	00:15:28
8	7	201993712	26/05/2006	21:21:52
8	8	215281664	27/10/2006	16:27:44
8	9	227189040	14/03/2007	12:04:00
8	10	256784944	20/02/2008	01:09:04
8	11	276630656	06/10/2008	17:50:56
8	12	290091136	11/03/2009	12:52:16
8	13	307865980	03/10/2009	06:19:39
9	1	122007232	13/11/2003	02:53:52
9	2	132706624	15/03/2004	22:57:04
9	3	140558608	14/06/2004	20:03:28
9	4	152552288	31/10/2004	15:38:08
9	5	172311648	17/06/2005	08:20:48
9	6	204150976	20/06/2006	20:36:16
9	7	282325600	11/12/2008	15:46:40
10	1	121317144	05/11/2003	03:12:24
10	2	132016528	07/03/2004	23:15:28
10	3	151862192	23/10/2004	15:56:32
10	4	228656208	31/03/2007	11:36:48
10	5	246344743	22/10/2007	05:05:42
10	6	258252112	08/03/2008	00:41:52
10	7	281635520	03/12/2008	16:05:20
11	1	151172101	15/10/2004	16:15:00
11	2	163079472	02/03/2005	11:51:12
11	3	170931456	01/06/2005	08:57:36
11	4	184219424	02/11/2005	04:03:44
11	5	202770784	04/06/2006	21:13:04
11	6	216058752	05/11/2006	16:19:12
11	7	245654656	14/10/2007	05:24:16
11	8	257562016	29/02/2008	01:00:16
12	1	138488320	21/05/2004	20:58:40
12	2	150482016	07/10/2004	16:33:36
12	3	162389376	22/02/2005	12:09:36
12	4	170241360	24/05/2005	09:16:00
12	5	183529328	25/10/2005	04:22:08
12	6	194228704	26/02/2006	00:25:04
12	7	215368656	28/10/2006	16:37:36
12	8	227276032	15/03/2007	12:13:52
12	9	276717632	07/10/2008	18:00:32
13	1	122094216	14/11/2003	03:03:36
13	2	132793608	16/03/2004	23:06:48
13	3	164546656	19/03/2005	11:24:16
13	4	172398624	18/06/2005	08:30:24
13	5	185686592	19/11/2005	03:36:32
13	6	217525920	22/11/2006	15:52:00
13	7	229433296	09/04/2007	11:28:16
13	8	247121824	31/10/2007	04:57:04
13	9	259029184	17/03/2008	00:33:04
13	10	282412576	12/12/2008	15:56:16