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LETTERS

Large subglacial lakes in East Antarctica at the onset of fast-flowing ice streams

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Water plays a crucial role in ice-sheet stability and the onset of ice streams. Subglacial lake water moves between lakes[1] and rapidly drains, causing catastrophic floods[2]. The exact mechanisms by which subglacial lakes influence ice-sheet dynamics are unknown, however, and large subglacial lakes[3,4] have not been closely associated with rapidly flowing ice streams. Here we use satellite imagery and ice-surface elevations to identify a region of subglacial lakes, similar in total area to Lake Vostok, at the onset region of the Recovery Glacier ice stream in East Antarctica and predicted by ice-sheet models[5]. We define four lakes through extensive, flat, featureless regions of ice surface bounded by upstream troughs and downstream ridges. Using ice velocities determined using interferometric synthetic aperture radar (InSAR), we find the onset of rapid flow (moving at 20 to 30 m yr^{-1}) of the tributaries to the Recovery Glacier ice stream in a 280-km-wide segment at the downslope margins of these four subglacial lakes. We conclude that the subglacial lakes initiate and maintain rapid ice flow through either active modification of the basal thermal regime of the ice sheet by lake accretion or through scouring bedrock channels in periodic drainage events. We suggest that the role of subglacial lakes needs to be considered in ice-sheet mass balance assessments.

Ice streams are huge fast-flowing features within continental ice sheets that transport inland ice to the grounding line where it is discharged to the ocean, influencing global sea level. In West Antarctica and in Greenland, water and sediments provide basal lubrication to the onset of fast flow of ice streams[6–8]. The movement of subglacial water between subglacial lakes and along ice streams[1,9] has been documented through surface elevation changes. In the past 15 million years, large subglacial lakes have repeatedly drained from beneath the East Antarctic ice sheet[2]. Because large subglacial lakes (>1,000 km^2) are capable of both substantial modification of the

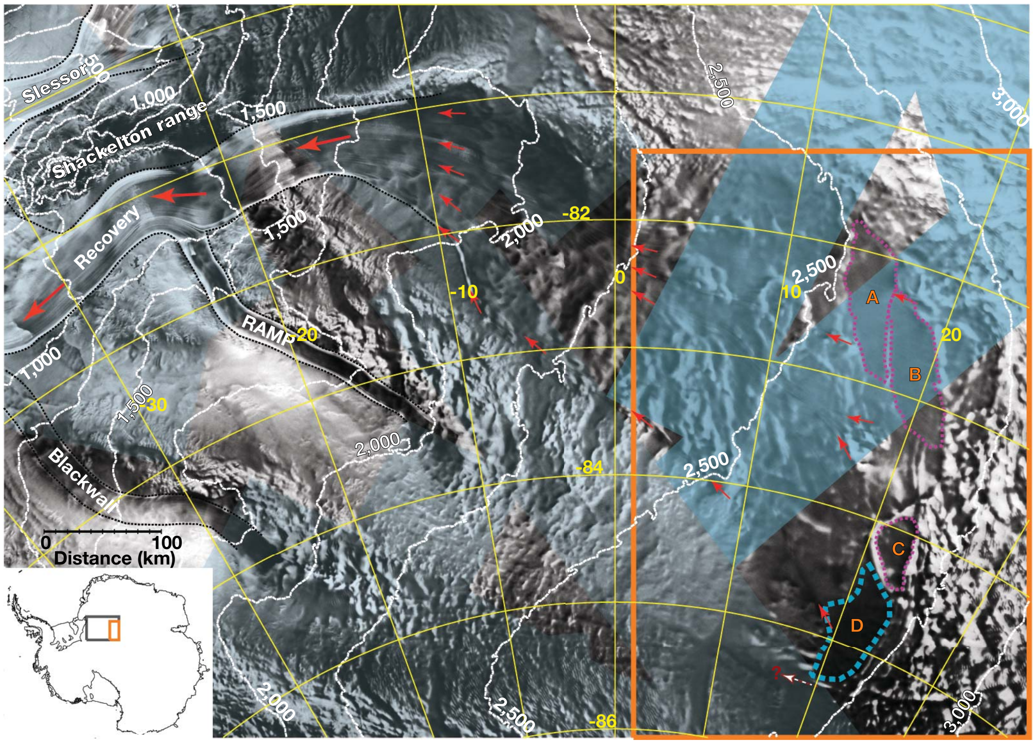

Figure 1 | RADARSAT image of the Recovery ice stream catchment with 250 m ice-surface contours (white) on the basis of the ICESat-derived digital elevation model. Red arrows indicate the location of clearly defined flow features. Blue shading denotes InSAR coverage: light blue, published velocities[11]; darker blue, new InSAR velocities. Areas A, B, C and D (dashed blue and purple outlines) are the flat features identified as the Recovery subglacial lakes. The orange box indicates the region detailed in Fig. 2. The inset shows the location of the Recovery ice stream catchment in Antarctica.

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thermal regime of the ice sheet and catastrophic drainage, these lakes have the potential to control the onset of ice streams. Located within 200 km of ice divides, the known large East Antarctic subglacial lakes—Vostok, 90° E, and Sovetskaya—are static, and isolated from the onset of rapid ice flow and the influence of global climate change[3,4]. A large subglacial lake has been predicted[5] in the onset region of the Recovery ice stream (this was formerly called the Recovery Glacier ice stream), and bright radar basal reflectors in the onset region of East Antarctic rapid flow are interpreted as subglacial lakes[10]. No previous study has clearly linked the onset of rapid ice flow to large subglacial lakes that have sufficient thermal inertia either to modify the ice-sheet thermal regime or to cause outburst flooding.

The Recovery ice stream drains a distinctive funnel-shaped 1×10^6 km^2 catchment that compromises 8% of the East Antarctic ice sheet and contributes 58% of the flux into the Filchner Ice Shelf[6,11] (Fig. 1). With velocities of 100 m yr^{-1} over 500 km inland[6], the Recovery ice stream penetrates further into the East Antarctic ice sheet than any other ice stream[12,13]. In contrast to most ice streams, which get narrower upslope, this ice stream expands from a 30-km-wide feature to a 90-km-wide region east of 15° W. The flow stripes within the Recovery ice stream originate in a 500-km-long region of very flat featureless ice ($<$0.45 m km^{-1}) at a surface elevation of 2,540–2,680 m, coincident with a catchment-wide inflection in the ice-surface slope (Fig. 1). The ice-surface slope upstream and to the east of the flat features is $>$2.0 m km^{-1}, while downstream and to the west, the ice-surface slope is $<$0.6 m km^{-1}.

High-resolution altimetry data combined with spatial imagery were used to define the horizontal extent of subglacial water bodies[3,4,14]. The Vostok, 90° E, Concordia and Sovetskaya subglacial lakes are all characterized by a very flat ice surface ($<$0.3 m km^{-1}) over the lakes, bounded by troughs 2–15 m deep in the ice surface on the upstream side and ice-surface ridges of 2–5 m on the downstream side. These ice-surface troughs and ridges result from the changing basal stress conditions associated with the transition to a floating ice sheet on the upstream side and the subsequent grounding of the ice sheet on the downstream side[15].

The Recovery ice stream catchment in Queen Maud Land, East Antarctica, remains one of the least explored regions of our planet: it is beyond the coverage of many satellites and was last visited during the 1964–66 surface traverse[16]. We used InSAR ice velocities derived from RADARSAT coverage in 1997 and 2000, the Moderate Resolution Imaging Spectroradiometer (MODIS), RADARSAT Antarctic Mapping Program (RAMP) imagery, unpublished ice-penetrating radar data from the 1964–66 Queen Maud Land surface traverse and ice-surface elevations from the Ice, Cloud and land Elevation Satellite (ICESat) to define four structures (A, B, C and D) with the characteristic ice-surface morphology of large subglacial lakes (Fig. 2).

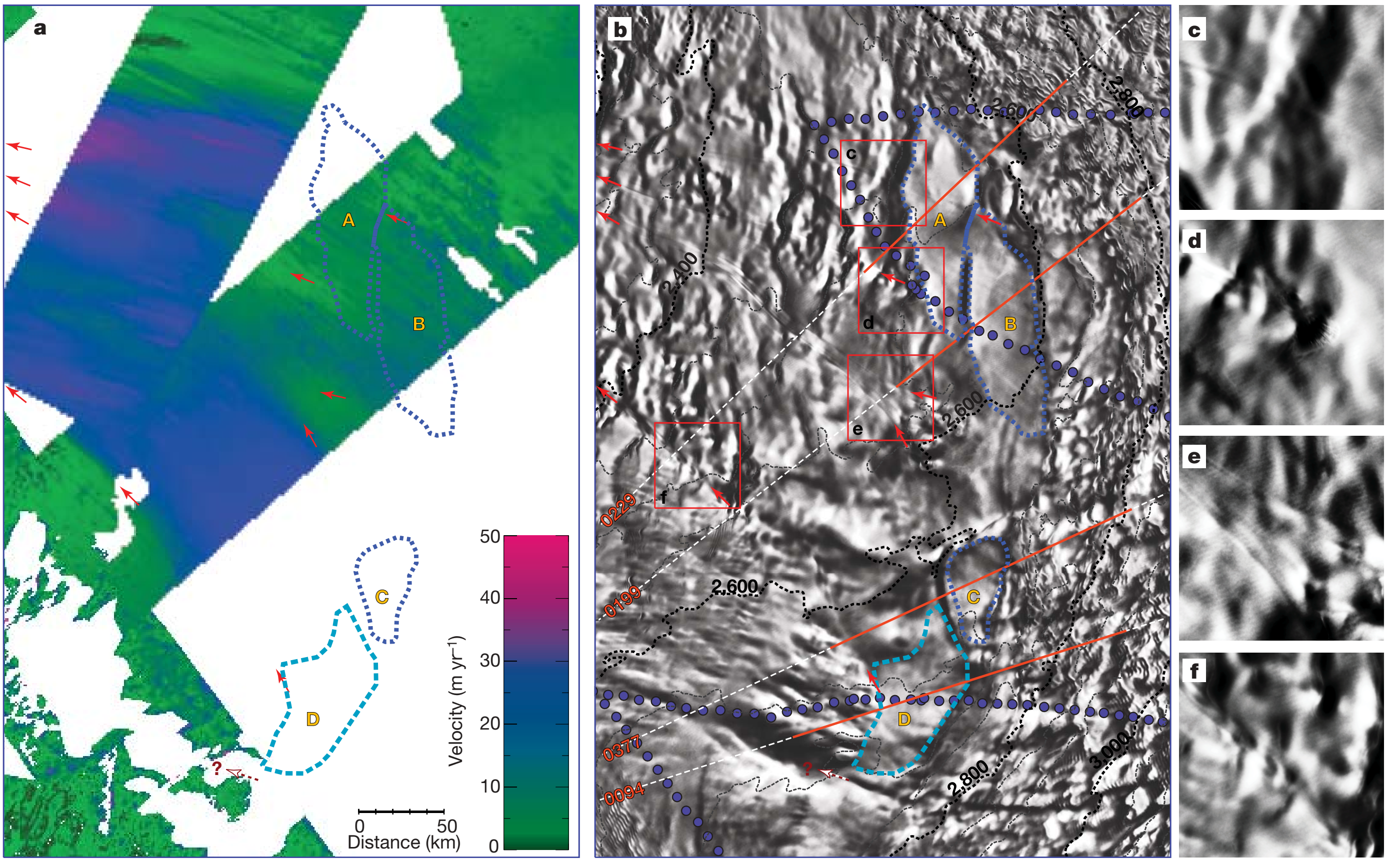

Figure 2 | InSAR ice velocity data and surface imagery of the Recovery ice stream catchment. The location of panels **a** and **b** is presented in Fig. 1. **a**, InSAR relative ice-surface velocity in m yr^{-1}. The southern margin of lake D is close to a distinct topographic trough marked by an arrow and question mark that may indicate a subglacial drainage pathway. **b**, MODIS surface image of the Recovery ice stream catchment with the location of the Recovery subglacial lakes A–D. Included are ICESat-derived surface elevation contours (50 m), the location of clearly defined flow stripes (red arrows) and the route of the 1964–66 South Pole Queen Maud Land traverse (blue dots). The locations of the four ICESat profiles presented in Fig. 3 are shown in dark red and by track number (0229, 0199, 0377 and 0094); the remainder of their profiles (not shown) are white dashed lines. **c**–**f**, Enhanced resolution MODIS imagery illustrating flow features over the Recovery subglacial lakes region. The locations of the 50 km × 50 km insets are shown as red boxes in **b**. **c**, Flow stripe emanating from lake A. **d**, Arcuate crevasse field and associated flow stripes downslope of lake A. **e**, Circular region of rough surface topography between lakes B and C and a 20-km-wide band of flow stripes downstream that can be clearly traced to the middle of the Recovery ice stream. **f**, Linear flow stripe zone coincident with the southern margin of the fast ice flow that can be traced upslope for more than 120 km to the linear surface depressions originating at the downstream margin of lake D.

ICESat data over these features reveals distinctive upstream troughs and downstream ridges. Over four features (A, B, C and D), the ICESat altimetry data and the MODIS imagery shows the upstream troughs to be 3–15 m deep and the downstream ridges to be 2–10 m high (Fig. 3) (with the exception of D, which lacks a well-defined downstream ridge). The surface roughness and the shoreline morphology of these four features closely resemble the known large subglacial lakes such as Vostok and 90° E (Fig. 3). Lake D appears to be a drained lake because the MODIS surface is less homogeneous, and the downstream shoreline ridge is poorly developed. Each of these new lakes is among the largest identified subglacial lakes (A, 3,915 $\mathrm{km^2}$; B, 4,385 $\mathrm{km^2}$; C, 1,490 $\mathrm{km^2}$; D, 3,540 $\mathrm{km^2}$) and is comparable in area to lakes 90° E (2,420 $\mathrm{km^2}$), and Sovetskaya (1,745 $\mathrm{km^2}$). Together, the Recovery subglacial lakes' area (13,300 $\mathrm{km^2}$) is similar in scale to that of Lake Vostok (15,690 $\mathrm{km^2}$). The ice thickness over these subglacial lakes, from radar and seismic soundings[16], ranges from 3,500 m over A and B to 3,100 m over D (Supplementary Fig. 1). Flexural modelling of the traverse gravity data indicates that the Recovery subglacial lakes are coincident with a tectonic boundary similar to those of lakes Vostok and 90°E but are shallower (Supplementary Fig. 2).

New InSAR velocities[11] for the upper reaches of the Recovery ice stream define a 280-km-wide region of elevated ice velocities (20–30 $\mathrm{m\,yr^{-1}}$)—the onset of rapid ice flow—that develops along the downstream margin of the Recovery subglacial lakes. This expansive onset region is characterized by crevasses and flow stripes (Fig. 2c) and extends from the northern edge of lake A to the distinctive lineations (Fig. 2f) aligned with the western margin of lake D in the south (Fig. 2b). The southern margin of lake D is also close to a distinct topographic trough indicative of a subsurface drainage pathway (Fig 2a). Also indicative of the onset of rapid ice flow is the 15-km-wide crevasse field at the downstream margin of lake A, associated with a bedrock peak that rises 1,800 m above the lake surface, as resolved in the traverse radar data (Supplementary Fig. 1)[16]. The large crevasse field was encountered by the 1964–66 traverse party and resolved in the MODIS imagery (Fig. 2d). Similarly, east of lake B a circular region of rough surface topography produces a 20-km-wide band of flow stripes downstream that can be clearly traced to the middle of the Recovery ice stream (Fig. 2e). The relatively slow InSAR ice-surface velocities (<5 $\mathrm{m\,yr^{-1}}$) over these features and downstream flow stripes indicate that these are topographically controlled pinning points within this broad onset region. From our interpretation of the InSAR velocities, flow stripes, topographic slope changes, and other surface features, we conclude that the Recovery subglacial lakes are the onset region of the East Antarctic ice stream, the Recovery ice stream.

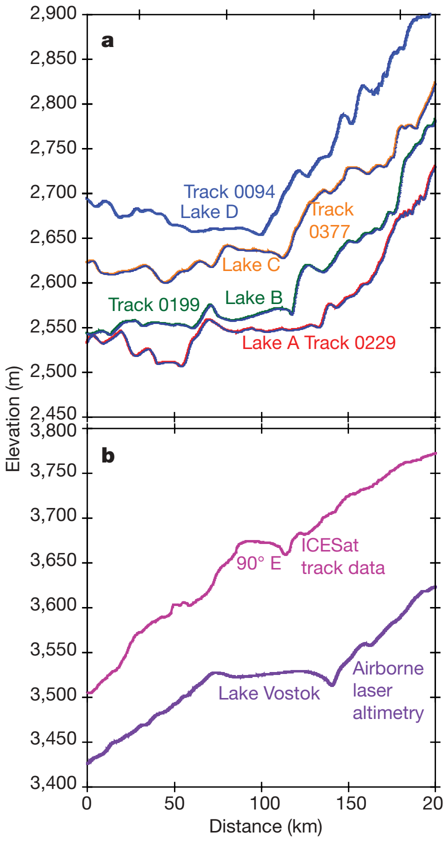

Figure 3 | Detailed elevation profiles across the Recovery subglacial lakes and known lakes. a, Recovery subglacial lakes profiles along the ICESat track segments shown in Fig. 2b in dark red. Ice surface morphology characteristic of subglacial lakes, upstream troughs and downstream ridges bounding relatively flat featureless regions is shown. These profiles illustrate the location of Recovery subglacial lakes at major inflections in ice-surface slope between the relatively steep ice-surface slope (>2 $\mathrm{m\,km^{-1}}$) upstream to the relatively flat ice-surface slope downstream (<0.6 $\mathrm{m\,km^{-1}}$). Ice-surface elevation over the lakes ranges from 2,540–2,660 m. **b,** Laser altimetry profiles across Lake Vostok (airborne laser altimetry[4,22]) and the 90° E lake (ICESat). The ice-surface slope on both sides of these lakes is >1.4 $\mathrm{m\,km^{-1}}$. Ice-surface elevation over these lakes ranges from 3,500 to 3,670 m, and all elevations have been geoid-corrected.

This first linkage of large subglacial lakes to the onset of rapid ice flow in the Recovery subglacial lakes region is both directly visible and pervasive. The gently sloping, very broad (280 km) onset region of rapid ice flow is aligned along the full extent of the margins of the Recovery subglacial lakes. These lakes are of fundamental importance to the onset of rapid flow. Earlier studies[9,10] have suggested that lakes provide a reservoir of water delivering a steady supply of lubricant to the ice stream bed downstream, facilitating the process of rapid sliding and buffering the ice stream base against local freeze-on and associated slowing. If lakes trigger the onset of rapid flow through the continuous delivery of subglacial water, the water drainage would occur through the hydrologic minima, such as relatively narrow valley-like features[17], which would imply that the onset region should be similarly narrow (10–20 km). Here, the width of the onset region (280 km), and the clear spatial linkage between the large subglacial lakes and flow onset, requires other mechanisms to initiate broad accelerated ice flow, such as the modification of the ice-sheet basal thermal regime and periodic, catastrophic drainage.

Large subglacial lakes have the potential to affect the basal thermal conditions of the ice sheet along their full length through the freezing of lake water to the base of the ice sheet, a process observed over large subglacial lakes[18,19]. As an ice sheet encounters a subglacial lake, basal shear stress drops to zero, resulting in rapid acceleration of the ice sheet. This acceleration will thin the ice sheet, causing the basal thermal gradient to steepen and increasing the rate of heat conduction. For subglacial lakes to cause enhanced flow downstream, the lake must significantly modify this steep basal thermal gradient. The freezing of lake water onto the ice sheet will flatten the basal thermal gradient and reduce the upward flow of heat into the ice[20]. The lake water acts as a thermal source, warming the basal ice by the heat released during the accretion process for 3,000–70,000 years as the ice above traverses the basin. When this flattened basal thermal gradient is preserved downstream of a lake, the ice sheet will not freeze to the bed when it regrounds downstream and hence streaming flow will result over a broad region.

Water in the largest subglacial lakes may also play a part in regional and global climate in a more catastrophic manner. Sudden lake water releases or outburst floods are known to originate in the interior of East Antarctica and to reach the coast. The Recovery subglacial lakes collect basal water from a larger area (387,890 $\mathrm{km^2}$) than any other subglacial lake system yet studied, and subsequently may fill faster and be more dynamic than lakes closer to the ice divides. Assuming a basal melt rate of 1 $\mathrm{mm\,yr^{-1}}$ over the catchment, the Recovery subglacial lakes have sufficient water input to have filled since the Last

Glacial Maximum, unlike Vostok and other large interior lakes. Rapidly filling lakes may periodically drain, flush down the ice streams and scour bedrock channels, enhancing rapid ice flow the same way that basal water produces rapid ice motion during a glacier surge[21]. An outburst similar in scale to the lake-to-lake drainage in East Antarctica[1] ($1.8\,\mathrm{km}^3$) would have a periodicity of $\sim$4.5 years, whereas an event of scale of the order of the East Antarctic outburst floods[2] would have a periodicity of thousands of years. Episodic draining of large subglacial lakes provides another mechanism for the initiation of climatically significant rapid ice flow with ice streams developing along the scoured channels.

The Recovery subglacial lakes capture water from a large area, effectively concentrating the energy from basal melting and re-releasing it where it can have a significant impact on ice flow through either basal accretion or catastrophic drainage. Contributing 35 gigatons per year of ice to the global oceans[11], the Recovery subglacial lakes and the associated Recovery ice stream tributaries have the potential greatly to affect the drainage of the East Antarctic ice sheet and its influence on sea level rise in the near future. Subglacial lakes and the associated hydrologic systems are crucial components in the dynamic evolution of ice sheets and need to be incorporated into ice-sheet models that are used for climate predictions.

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

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