REVIEWS

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Subglacial lakes and their changing role in a warming climate

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Abstract | Subglacial lakes are repositories of ancient climate conditions, provide habitats for life and modulate ice flow, basal hydrology, biogeochemical fluxes and geomorphic activity. In this Review, we construct the first global inventory of subglacial lakes (773 in total), which includes 675 from Antarctica (59 newly identified), 64 from Greenland, 2 beneath the Devon Ice Cap, 6 beneath Iceland's ice caps and 26 from valley glaciers. This inventory is used to evaluate subglacial lake environments, dynamics and their wider impact on ice flow and sediment transport. The behaviour of these lakes is conditioned by their subglacial setting and the hydrological, dynamic and mass balance regime of the overlying ice mass. Regions where climate warming causes ice surface steepening are predicted to have fewer and smaller lakes, but increased activity with higher discharge drainages of shorter duration. Coupling to surface melt and rainfall inputs will modulate fill–drain cycles and seasonally enhance oxic processes. Higher discharges cause large, transient ice flow accelerations but might result in overall net slowdown owing to the development of efficient subglacial drainage. Subglacial lake research requires new drilling technologies and the integration of geophysics, satellite monitoring and numerical modelling to provide insight into the wider role of subglacial lakes in the changing Earth system.

Subglacial lakes under ice sheets and glaciers (FIG. 1) affect multiple components of the Earth system. Lakes provide viable habitats for microbial communities[1,2] that might have followed unique evolutionary trajectories and serve as analogues for putative extra-terrestrial ecosystems[3]. Water transfer through subglacial lakes modulates basal hydrology[4–8] and biogeochemical fluxes[2,9] and can cause ice flow variations on sub-decadal timescales[10–13]. Lake drainage transports large volumes of water and sediment downstream[14,15]. Lake sediments contain archives of ice sheet history and climate change[16], similar to ice core records. In Antarctica, water crossing the grounding line into sub-ice shelf cavities[5] can alter ice–ocean interactions[17–20] and can modify ocean circulation[21]. Sudden outburst floods onto the glacier foreland form outwash plains (sandurs) and present a major hazard to infrastructure[22].

Subglacial lakes occur when subglacial meltwater collects in local minima of basal hydrological potential, owing to depressions in bed topography and the glacier surface, ice flow over 'sticky spots'[23], or trapping of basal water behind cold-based ice[24]. In Antarctica, the first evidence of subglacial lakes[25,26] came from unusually strong, sharp, continuous and smooth basal reflections detected in airborne radio-echo sounding (RES) surveys in the late 1960s. However, Antarctic lake inventories were not expanded substantially until further RES investigations were undertaken in the 1990s and 2000s[27,28], while seismic surveying revealed thick water columns[29–31]. Between 2005 and 2008, a class of 'active' lakes was discovered through satellite measurements of ice surface elevation from Envisat and ERS-2 radar and ICESat laser altimetry[4,32,33]. Active subglacial lakes can drain along subglacial flow paths for hundreds of kilometres, and form connected networks[34,35].

Jökulhlaups in Iceland provide the longest record of subglacial lake activity, having been first reported in the Middle Ages and investigated by ground expeditions and aerial reconnaissance since the early twentieth century[36]. Icelandic subglacial lakes form by melting of ice via geothermal heat enhanced by volcanism and influxes of surface meltwater. During lake drainage, their overlying ice surface depressions lower rapidly and slowly recover afterwards as the lake refills[22,37–39]. Elsewhere, small outburst floods have been caused by drainage of large or multiple water-filled subglacial cavities from valley glaciers[40,41].

Grounding line
The boundary where a grounded glacier becomes a floating ice shelf.

Basal hydrological potential
Total head determined by bed topography, weight of the overlying ice and basal drainage characteristics.

Cold-based ice
Ice below freezing point at the ice–bed interface, which is thus frozen to the underlying substrate.

Radio-echo sounding
(RES). A radar technique used to measure the internal structure, ice thickness, bed topography and water content of ice masses.

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Key points

- We report a global inventory of subglacial lakes (773 in total): 675 from Antarctica (59 newly identified here), 64 from Greenland, 6 from Iceland, 2 beneath the Devon Ice Cap and 26 from valley glaciers.
- 80% of subglacial lakes are stable, implying either closed systems or approximately balanced inflow and outflow; the remaining lakes are active and display one of five distinct activity patterns.
- Active subglacial lakes exhibit a quasi-linear relationship between mean discharge and lake volume; lakes in Greenland and Iceland exhibit higher discharge rates for a given lake volume than do lakes in Antarctica.
- Larger active subglacial lakes recharge at a faster rate than smaller lakes, suggesting an underlying control on lake refilling rate associated with lake size.
- Lakes are less likely to occur where climate warming causes ice surface steepening, but drainage will be of higher magnitude, producing transient ice flow perturbations that are more likely to cause a net ice flow reduction.
- Enhanced surface melt and rainfall inputs to the bed will modulate fill–drain cycles, increase the potential for catastrophic drainages and provide a supply of oxygen, sediment, microorganisms and nutrients.

Jökulhlaup
Glacial outburst flood from a subglacial or proglacial lake.

Over the past decade, subglacial lakes have been discovered under other ice masses, such as in Greenland[42–44] and the Canadian Arctic[45]. In Greenland, the first putative subglacial lake was inferred from a flat ice surface elevation anomaly[46]. Since then, analysis of airborne RES data[42–44] and identification of ice surface elevation changes from satellite altimetry and high-resolution, time-stamped digital surface models (DSMs)[15,44,47,48] confirmed the widespread existence of subglacial lakes under the Greenland Ice Sheet. The two subglacial lakes identified beneath the Devon Ice Cap exist at temperatures well below the pressure melting point and probably consist of hypersaline water[45].

In this Review, we construct the first global inventory of subglacial lakes, which enabled us to classify lake characteristics and dynamics. We indicate that subglacial lake character and function, as well as their impact on ice flow, subglacial drainage, sediment transport and biogeochemical fluxes, are dependent on the hydrological, dynamic and mass-balance regime of the ice mass above. Using space–time substitution, we propose a conceptual model for how subglacial lakes, and their influence on the broader environment, will change in a warming world.

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A historical perspective

This section provides a background to detecting and characterizing subglacial lakes, and summarizes previous lake inventories and subglacial hydrological controls on lake formation.

Detecting and characterizing subglacial lakes. The identification and characterization of subglacial lakes and their dynamics have largely come from remote geophysical observations[12,26,44,49–51] (FIG. 2a), owing to the challenge of directly accessing and cleanly sampling water and sediments beneath thick ice[52]. Whillans Subglacial Lake[1,53,54] and Mercer Subglacial Lake[55] in West Antarctica (with ice thicknesses of approximately 600 m and 1,100 m, respectively) and western Skaftá Lake[56] and Lake Grímsvötn[57] in Iceland (with ice thicknesses of approximately 400 m and 300 m, respectively) have been cleanly accessed by drilling, while Lake Vostok in East Antarctica (with ice thickness of approximately 4,000 m) has been drilled but the samples obtained were contaminated[58]. In the French Alps, the geometry and water level of a small subglacial lake under Glacier de Tête Rousse (with ice thickness of 76 m) was successfully accessed and monitored using boreholes and sonar[59].

Innovations in RES have improved the detection and characterization of subglacial water. Increased bandwidth and signal sensitivity of radar systems have improved the detection, resolution and fidelity of radar reflections[60]. Swath radar technology, which enables (pseudo) 3D imaging of bed topography and englacial layers[61,62], resolves basal roughness, hydrological routing and basal melt and freeze-on better than standard radar. Using the scattering characteristics of returned bed echoes, such as the specularity content[63], trailing bed echoes[64], the bed echo coherence index[65,66] and bed echo reflectivity variability[67], has advanced the quantitative identification of subglacial water and understanding of subglacial drainage systems[63,68–70]. Finally, improvements have been made in the automated detection of subglacial lakes[44,71,72], including utilization of machine-learning algorithms[72]. Despite these advances in radar technology, interpretation of specularity remains problematic, because some dynamic lakes might not have particularly smooth ice–water interfaces.

While radar sounding can measure lake extent, seismic reflection surveys are necessary to reveal water column thickness and the structure of lake sediments[30,31,50,73,74]. Active seismic surveys using innovative survey design and analysis (for example, acoustic impedance or amplitude-versus-angle analysis) can confirm the presence of a subglacial lake and characterize lake floor properties (that is, hard bedrock versus sediment, and till porosity)[31,50]. Other geophysical methods, such as gravimetry (for deeper structure) and electromagnetic approaches, can reveal the geological and hydrological settings surrounding subglacial lakes[75–77].

Satellite observations of ice surface displacement derived from Interferometric Synthetic Aperture Radars (InSAR) on ERS-2 (REF.[4]), Radarsat[78] and the Advanced Land Observing Satellite (ALOS)[79], together with elevation measurements from satellite radar and laser altimeters on ERS-2 (REF.[4]), Envisat[51], ICESat[33] and CryoSat-2 (REFS[6,79–81]), have proved crucial in detecting indirect subglacial lake activity and for estimating their change in volume. In particular, improvements in the accuracy, coverage and record length of the new generation of polar orbiting altimeters, starting with CryoSat-2 in 2010, is enabling a transition from opportunistic studies to operational, near-real-time monitoring of subglacial lake activity[6]. Most recently, Sentinel-3 (2016 onwards) and ICESat-2 (2018 onwards) have been used to monitor subglacial lake activity[82,83] (FIG. 2b). Sentinel-3 provides frequent (27-day) temporal sampling and, as an operational mission, guarantees long-term continuity of measurements. ICESat-2, with its 40-m along-track spacing and sub-decimetre precision[84,85], provides unprecedented spatial and temporal sampling of subglacial lake activity[83] (FIG. 2b).

Although the monitoring of active large (10–100 km^2 scale) Antarctic lakes by satellite altimeters is well established, monitoring the numerous smaller (<1 km) lakes discovered in Greenland[44] presents an observational challenge. Recent exploratory work utilized timestamped DSMs (such as ArcticDEM, REMA and TanDEM-X), which were generated from superhigh-resolution (1–10 m) stereoscopic optical imagery[86,87] or single-pass radar interferometry. These data allow the detection of detailed patterns of surface deformation associated with lake volume changes, with high vertical precision[15,48]. Small lakes (<2 km) beneath valley glaciers have also been identified based on the ice surface elevation changes measured using InSAR[88].

Subglacial lake distribution and hydrology. Subglacial lakes have been predicted[8,89–91] and identified[44,45,88,92] in diverse settings. Previous inventories have focused on lakes beneath individual ice masses. The most recent inventory of Antarctica in 2012 identified 379 subglacial lakes[92], while 60 subglacial lakes were identified beneath the Greenland Ice Sheet in a 2019 inventory based on an ice-sheet-wide survey and the published literature[44]. Despite a long history of research into Iceland's subglacial lakes[22,37–39,56,93–95], a formal complete inventory is lacking.

Subglacial lake locations and volumes are determined by subglacial hydrology, which results from subglacial water production and the surface and bedrock topography. The distribution and production rate of subglacial water is controlled by the insulation and pressure of the overlying ice sheet[96], geothermal heat (an extreme example is sub-ice volcanism in Iceland)[22], frictional heat generated by fast-flowing ice streams or outlet glaciers[96], and surface water injections[97] (FIG. 1). The flow and storage of subglacial water is governed by basal hydrological potential[98]: the ice surface gradient is about tenfold

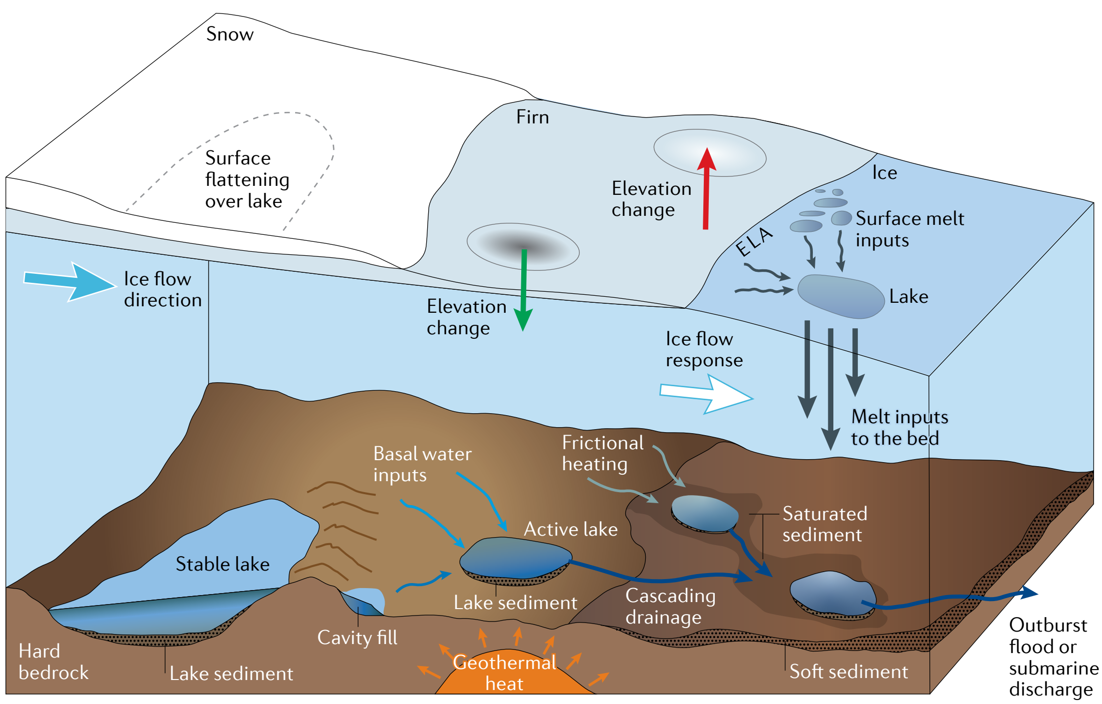


Fig. 1 | **Subglacial lake settings and hydrological links with ice sheets or glaciers.** Subglacial lakes can range from stable systems trapped in topographic (and hydrological potential) depressions towards the interior of ice masses to water bodies in small cavities and active lakes closer to the ice margin that periodically drain downstream. Active lakes often form in regions with enhanced frictional, geothermal or surface melt inputs. Mechanical coupling between subglacial lakes and the overlying ice can cause flattening of the ice surface (especially over large lakes), localized changes in ice surface elevation in response to lake drainage (elevation decrease) and filling (elevation increase), and transient variations in ice flow in response to lake drainages. ELA, equilibrium line altitude.

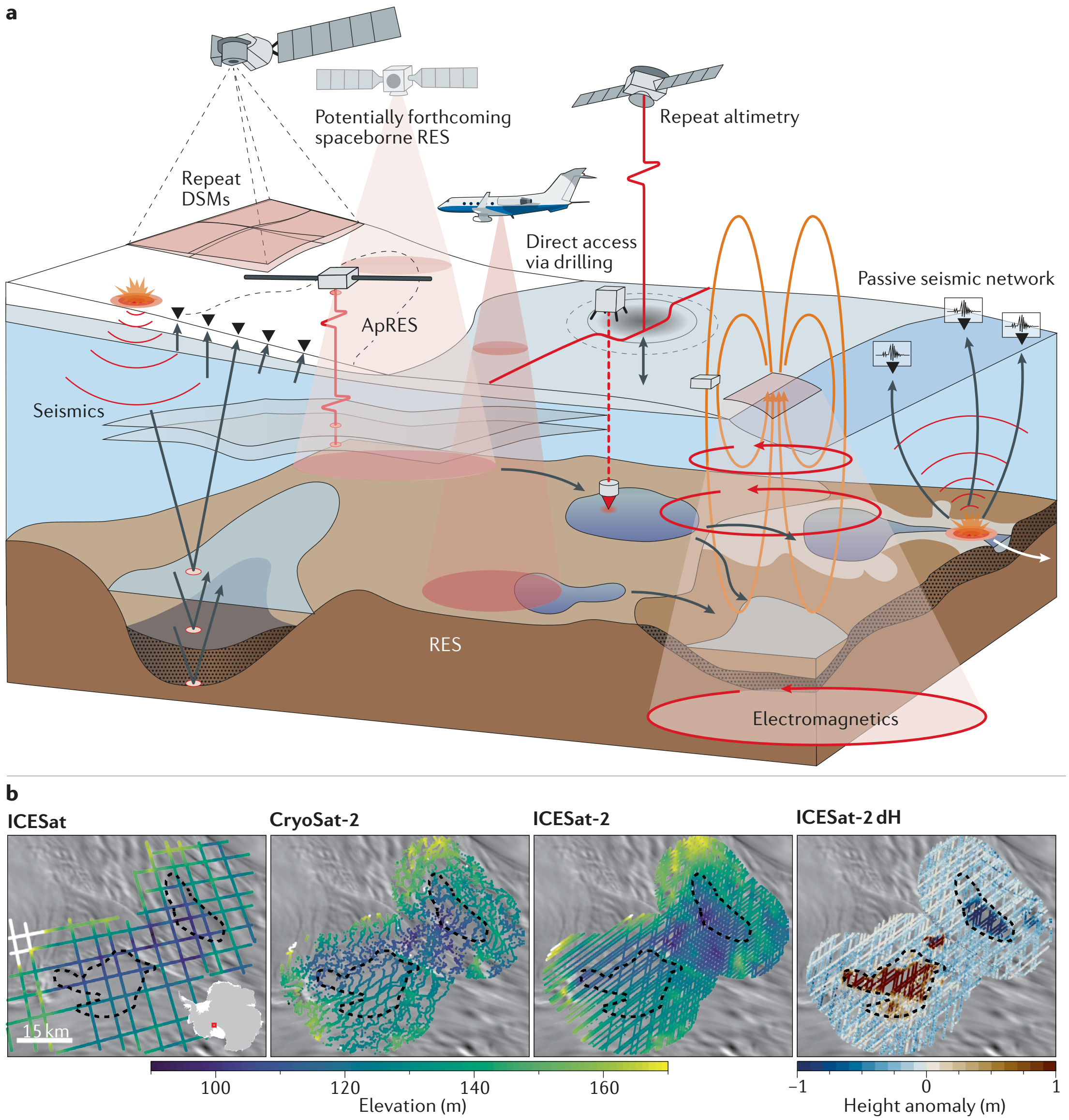


Fig. 2 | **Methods for identifying subglacial lakes and investigating their dynamics. a** | Schematic of the range of different geophysical techniques and satellites for identifying subglacial lakes, probing their environment and monitoring their dynamics. **b** | Comparison between altimetry coverage of active subglacial lakes in Antarctica. Ice surface elevation measurements for three months of Ice, Cloud, and Land Elevation Satellite (ICESat) global Antarctic and Greenland ice sheet altimetry (GLA12) for September 2003 to November 2003, the CryoSat-2 synthetic aperture radar interferometric (SARIn) mode for October 2019 to December 2019, the ICESat-2 land ice height (ATL06) data coverage for October 2019 to November 2019, and the ICESat-2 ATL06-derived ice-surface height anomaly in May 2019 over Conway Subglacial Lake and Mercer Subglacial Lake in West Antarctica. The inset map in the left panel shows the location (red square) of the area depicted in the other three panels in Antarctica. ApRES, autonomous phase-sensitive radio-echo sounding; DSM, digital surface model; RES, radio-echo sounding. Part **b** is adapted from REF.[83], CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/).

more important than the bedrock gradient in controlling hydrological potential and is therefore likely to be a first-order control on lake genesis and stability[99]; lake formation in bed depressions is favoured where ice surfaces and basal slopes are flatter[98]. However, this static hydrological potential gradient does not account for spatiotemporal variations in subglacial water pressure. Lake drainage occurs when the hydropotential seal is broken[100] or when water leakage from the basin produces efficient syphons[101].

Subglacial lake inventory

Here, an updated global inventory of subglacial lakes is constructed, based on lakes identified and published in the peer-reviewed literature prior to June 2021 and supplemented with 59 Antarctic lakes newly identified from analysing archived RES data collected in 2002–2019 (Supplementary Data). The newly identified lakes range from 170 m to 9,720 m in length (median 1,320 m), with 46 clustered in the subglacial Gamburtsev Mountains of East Antarctica beneath ice approximately 3,000 m thick.

A subglacial lake is defined as any discrete water body at the base of an ice mass[102], without presuming a minimum area or depth. With this definition, lakes exist across a wide range of length scales:[103] from small (around 1 m) water bodies in basal cavities[104] to large (>100 km) lakes that strongly influence ice dynamics by producing flat ice surfaces[105], and from shallow (about 1 cm or less) water patches connected by saturated sediments[71,106] to deep (approximately hundreds of metres) lakes with their own internal circulation[30,107–110]. Although no minimum size is presumed, the smallest subglacial lakes in the inventory are of the order of 0.0001 km^3.

Using these criteria, 773 lakes were identified in total, including 675 in Antarctica, 64 in Greenland, two beneath the Devon Ice Cap, six beneath the ice caps of Iceland and 26 under valley glaciers (FIG. 3; Supplementary Data). The resulting count for Antarctica is about 80% higher than the 2012 inventory[92], largely owing to new analyses of RES data sets[28,90,111], although this number is still an order of magnitude lower than predicted from hydrological calculations and geostatistical modelling[91]. Although around 90% of inventoried lakes are beneath the Antarctic Ice Sheet, this high percentage in part reflects their larger size on average, making them easier to identify[92], and the greater number of Antarctic surveys.

Subglacial lake setting and behaviour. The inventory indicates a range of lake settings and behaviours: isolated, stable subglacial lakes with a large volume range (from <1 km^3 up to about 5,400 km^3), beneath the Devon Ice Cap and the interiors of Antarctica and Greenland; large (median volume 0.12 km^3) but slowly (over months) cascading lake drainage beneath Antarctic ice streams; subglacial lakes an order-of-magnitude smaller (median volume 0.013 km^3) with higher discharges (for a given lake volume) of shorter duration (days to weeks) beneath the Icelandic ice caps and ablation zone of the Greenland Ice Sheet; and small lakes (of the order of 0.0001 km^3) that drain rapidly (<1 h to days) beneath valley glaciers (FIGS 3,4).

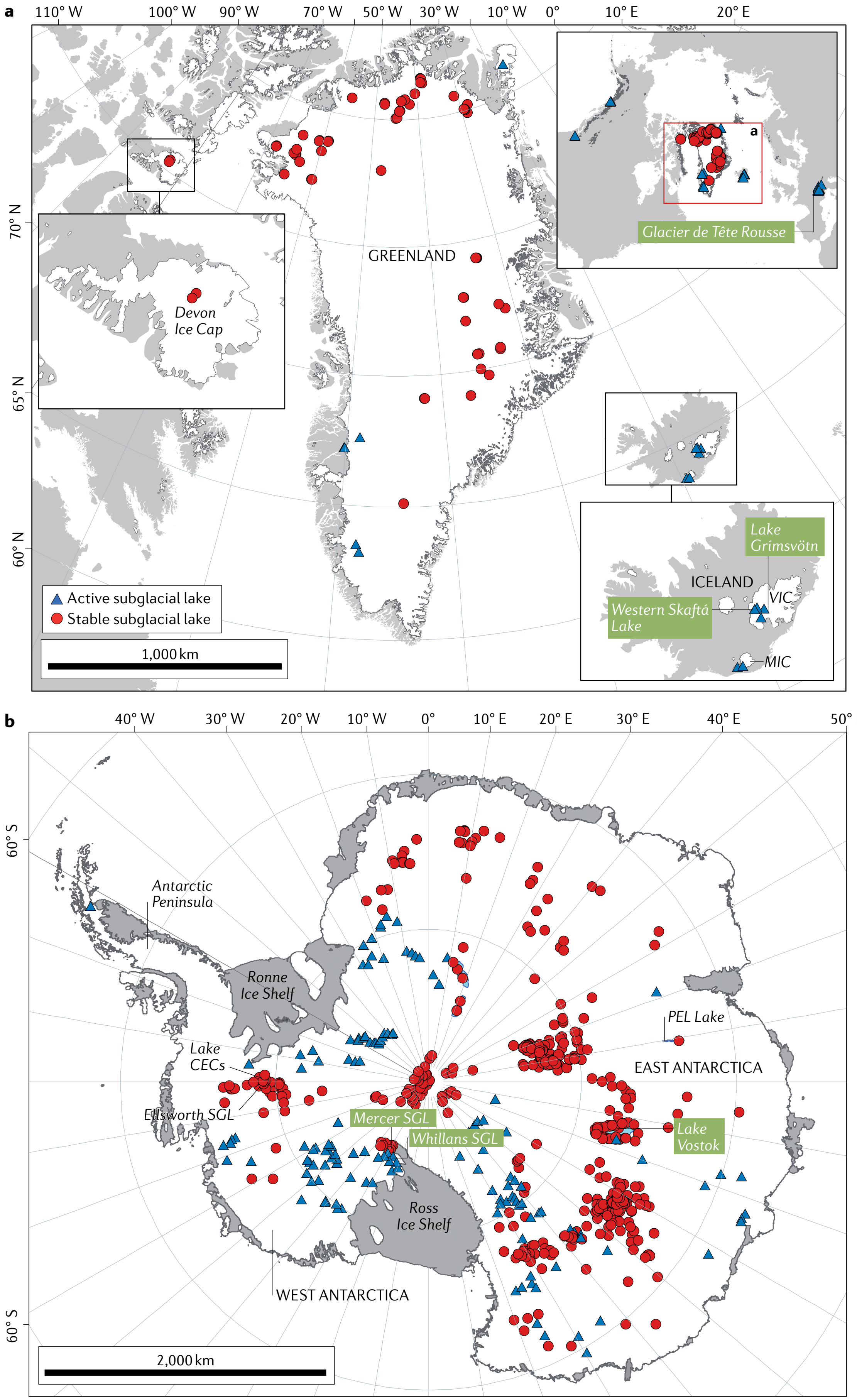
Stable lakes. Over 80% of subglacial lakes in the inventory are not active ('stable' lakes in FIG. 3), which implies that they are closed systems or that inflow and outflow is approximately balanced. These predominantly RES-detected lakes occur where hydrological catchments are small[91] and basal melt rates are low or zero[45]. In Antarctica, RES-detected subglacial lakes occur beneath the warm-based interior of the ice sheet and are typically 1–5 km long, although there are many larger tectonically controlled lakes[112–114], including some >100 km long (such as Lake PEL[115] and Lake Vostok[105,112]). Large clusters of stable lakes occur beneath thick ice (about 3,000 m thick or more) in the subglacial Gamburtsev Mountains, Dome C, the South Pole region and Ridge B beneath East Antarctica, and in the Ellsworth Subglacial Highlands beneath West Antarctica (FIG. 3b). The two RES-detected lakes beneath the Devon Ice Cap are 7.0 km and 8.2 km in length, respectively, and occur in a similar setting to most stable lakes in Antarctica — beneath the central ice divide in bedrock troughs[45]. In Greenland, RES-detected lakes tend to occur away from the relatively flat and cold bed beneath the ice sheet's interior and are typically <2 km in length, with the largest known lake being 5.9 km in length[44]. A cluster of relatively large lakes occurs in the East Greenland subglacial mountain chain, and another cluster of smaller lakes occurs in northern Greenland where the bed relief is subdued (FIG. 3a).

Active lakes. Active lakes in the inventory (FIGS 1,3) have been predominantly identified, and their volumes quantified, from ice surface elevation changes[33] and their outburst floods[116]. Because ice mechanics, ice flow dynamics and basal traction also influence the surface expression of lake drainage[117], lake volume can be overestimated by altimetry[118] and some ice surface changes might not necessarily be due to subglacial lake activity[6,99,119]. Despite these caveats, the inventory indicates that active lakes generally occur closer to ice margins than do stable lakes. Active lakes also have large upstream hydrological catchments and/or form in areas where meltwater is abundant, either owing to frictional melting beneath ice streams and outlet glaciers (for example, in Antarctica)[120], elevated geothermal heating (for example, in Iceland)[22] and/or surface meltwater inputs (for example, in Greenland)[47].

In Antarctica, ice surface elevation histories for 140 active lakes show a median volume change of about 0.12 km^3 per lake during drainage, which is an order of magnitude greater than for active lakes in Greenland, and three orders of magnitude larger than flood volume estimates of valley glaciers. This variation might partly reflect a bias in detection approaches, as smaller lakes have yet to be identified in Antarctica. Most Icelandic subglacial lakes are similar in size to the active lakes in Greenland; an exception is Lake Grímsvötn, which discharges up to 5 km^3 of water during drainage because of a thick ice dam and high geothermal heat flux over a wide subglacial area[22,39].

The inventory includes 26 valley glaciers where outbursts from small subglacial water bodies have been recorded, including 20 in the European Alps[24,40,116,121]. Transient storage in water-filled cavities is probably common to most glaciers[122–126] but their small volume makes it difficult to detect their location and differentiate outbursts from background runoff. Identified outbursts of 10^{-4}–10^{-5} km^3 of water might therefore represent high-magnitude, low-frequency events[127,128]. Although the sample size is small, glaciers with known outbursts tend to be relatively steep[40], consistent with the idea that faster sliding causes greater cavitation[123].

Patterns of subglacial lake activity. For lakes with at least one complete fill–drain cycle on record ($n = 36$), five distinct patterns of ice surface elevation change are identified (FIG. 4a), based on the ratio of filling (ice surface uplift) and draining (ice surface subsidence) durations: slow filling and rapid drainage (ratio >1; pattern 1); similar rates of filling and drainage (ratio about 1; pattern 2); rapid filling and a longer period of drainage (ratio <1; pattern 3); and extended (multi-year) periods of quiescence, at a high stand (pattern 4) or low stand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110° W
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GREENLAND
Devon
Ice Cap
Glacier de Tête Rousse
Lake
Grímsvötn
ICELAND
VIC
Western Skaftá
Lake
MIC
Active subglacial lake
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Antarctic
Peninsula
Ronne
Ice Shelf
Lake
CECs
Ellsworth SGL
Mercer SGL
Whillans SGL
PEL Lake
EAST ANTARCTICA
Lake
Vostok
Ross
Ice Shelf
WEST ANTARCTICA
2,000 km

◀ Fig. 3 | **Global inventory of subglacial lakes. a** | Inventory of Northern Hemisphere subglacial lakes (SGLs). The top right inset shows the location of part **a** (red box) in the Northern Hemisphere. **b** | Inventory of SGLs beneath the Antarctic Ice Sheet. The extents of larger lakes (such as PEL Lake and Lake Vostok) are defined by blue polygons. Red circles represent stable lakes identified from radio-echo sounding (RES), and blue triangles represent active lakes that have been observed to drain at least once during the observation period. Lakes labelled in green have been accessed and cleanly sampled with the exception of Glacier de Tête Rousse, which was monitored using boreholes (water level) and sonar (cavity geometry), and Lake Vostok. Data are included in Supplementary Data. MIC, Mýrdalsjökull Ice Cap; VIC, Vatnajökull Ice Cap.

(pattern 5). Patterns 1, 3 and 4 are the most distinctive, while the difference between patterns 2 and 5 is less clear. For many subglacial lakes outside Iceland, short observational records make it difficult to determine whether the fill–drain cycles and patterns repeat, and whether they are regular and predictable[6]. Drainage of active subglacial lakes is variable[6,15,22,128,129] and does not necessarily result in complete emptying[22].

In Iceland, all lakes exhibit pattern 1, with Lake Grímsvötn draining every 1–10 years[22], roughly depending on ice dam thickness[94] (FIG. 4a). Rapid drainage of Icelandic lakes can take the form of either exponentially rising discharge, consistent with drainage via subglacial channels[39,100,130,131], or of linearly rising discharge triggered by rapid subglacial lake refilling, flotation of the ice dam, and initial drainage as a sheet flood[22,93,132]. This second drainage style is thought to explain rapid discharge (<1 h duration) of water from subglacial cavities[40,128].

The fill–drain patterns of active lakes in Greenland ($n = 7$) and beneath valley glaciers ($n = 26$) are not well constrained owing to limited data. In Greenland, three active lakes have extended high stands (pattern 4), which suggests an external threshold controlling initiation of lake drainage[15]. However, active lakes in Greenland and beneath valley glaciers are strongly influenced by input of surface meltwater or rainfall to the bed, which can trigger drainage[41] through seasonally modulated fill–drain cycles in smaller lakes[88,129] or through late summer drainage of larger lakes[15,47]. Diurnal-to-seasonal drainage of water-filled cavities is hypothesized to occur in response to meltwater driving unstable expansion of the intervening orifices[123,133,134], allowing them to connect[135,136] and empty rapidly down subglacial channels[41,128].

In Antarctica, all five drainage patterns are observed[6], which probably reflects the range of subglacial lake sizes and their topographic, hydrological, geological and glaciological settings. Here, cascades of hydrologically connected lakes have produced complex drainage responses[7,137]. For example, the quiescent phase of lakes characterized by pattern 5 might be due to water capture or interception by an upstream lake, which later drains into the lower lake, triggering its fill–drain response. Patterns 2 and 3 in Antarctica have been replicated by the subglacial Glacier Drainage System (GlaDS) model[7,101], which includes both distributed and efficient drainage and changes in catchment-scale water pressure[138]. The GlaDS model suggests that most active Antarctic lakes have some outflow even during filling periods, and that small changes in pressure and drainage efficiency drive lake filling and drainage[7,101].

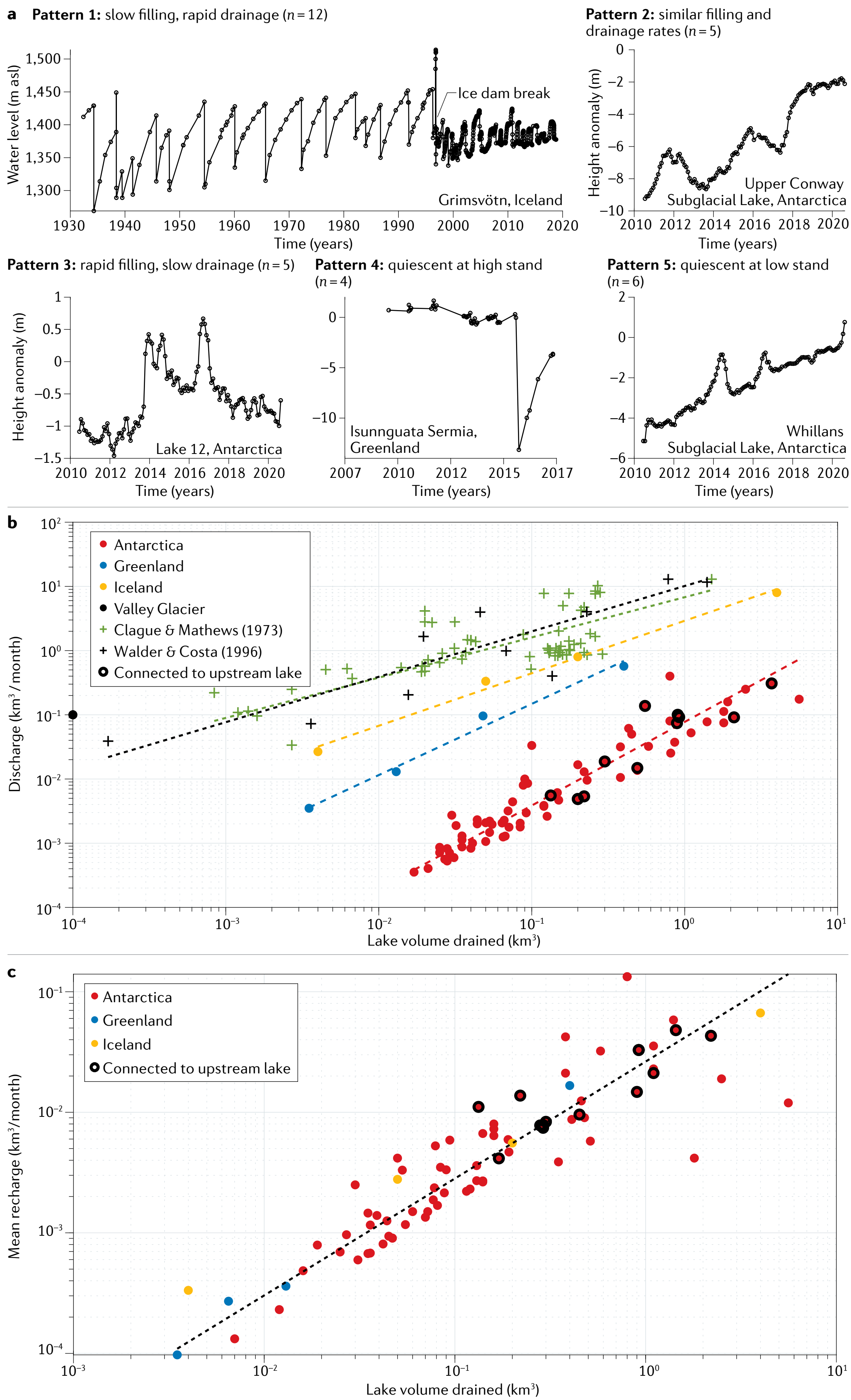
Lake discharge and recharge relationships. Despite uncertainty in lake volumes derived from ice surface elevation changes[118], active subglacial lakes of Iceland, Greenland and Antarctica exhibit consistent quasi-linear relationships between mean discharge Q_m and lake volume V across drainage events (FIG. 4b), with $Q_m \propto V^b$, where b is of order unity, despite variations in lake setting, geometry and dynamics. This finding parallels the empirical Clague–Mathews relationship[139] between flood peak discharge and volume for marginal ice-dammed lakes and is consistent with Nye's theory of lake drainage via subglacial channels[131], which predicts that $b = 1$ for any set of geometrically similar lakes[140]. This relationship suggests that drainage of active lakes in Greenland and Antarctica occurs predominantly through subglacial channels[7,141]. For a given V, Q_m is one to two orders of magnitude higher (and the flood duration is proportionally shorter) for lakes in Greenland and Iceland than for those in Antarctica (FIG. 4b); Antarctic lakes typically take tens of months to drain, whereas lakes in Greenland and Iceland drain in days to weeks. This difference is consistent with jökulhlaup theory in that the hydrological gradient strongly influences the drainage timescale[21,140]. Steeper ice surfaces, and hence higher hydrological gradients, in Iceland and near the Greenland Ice Sheet margin produce greater subglacial lake discharges of shorter duration than the shallower ice surface slopes of Antarctica. Conceivably, lakes beneath steep valley glaciers might drain even faster than those in Iceland and Greenland for a given lake volume, but observations are lacking to test this hypothesis.

The recharge rate of subglacial lakes also displays a consistent power-law relationship with lake volume, where different lake populations have similar recharge rates (FIG. 4c). Larger lakes recharge faster than smaller lakes, indicating an underlying control on lake refilling associated directly or indirectly with lake size. Although this relationship is not fully understood, and recharge rates for smaller lakes are more uncertain as they are more difficult to observe, larger lakes are more likely to form in larger catchments, which are associated with greater meltwater input. A similar scaling relationship is found between the area of subaerial lakes and their catchments[142].

Subglacial lakes and ice dynamics

Observations of the influence of subglacial lake activity on ice flow are limited[10,11,13,15,81,143–145]. Most of our understanding stems from numerical models[100,146,147] and observations of subglacial water drainage from ice marginal lakes[148,149] and surface meltwater inputs to the bed[150].

Subglacial lake drainage can affect ice flow by altering basal water pressure and thus basal traction[143] (FIG. 5). The size of the effect depends on whether, and to what extent, lake discharge exceeds the hydrological capacity of the existing subglacial drainage system. If lake discharge is relatively small and enters an efficient (high hydrological capacity) subglacial drainage system, the ice velocity response will be limited[143] (FIG. 5). These conditions are expected in regions with substantial seasonal surface melt and steep subglacial hydrological potential, such as in Greenland and beneath valley glaciers[44,129].


a
Pattern 1: slow filling, rapid drainage (n = 12)
Water level (m asl)
Ice dam break
Grimsvötn, Iceland
Time (years)
Pattern 2: similar filling and drainage rates (n = 5)
Height anomaly (m)
Upper Conway Subglacial Lake, Antarctica
Time (years)
Pattern 3: rapid filling, slow drainage (n = 5)
Height anomaly (m)
Lake 12, Antarctica
Time (years)
Pattern 4: quiescent at high stand (n = 4)
Isunnguata Sermia, Greenland
Time (years)
Pattern 5: quiescent at low stand (n = 6)
Whillans Subglacial Lake, Antarctica
Time (years)
b
Antarctica
Greenland
Iceland
Valley Glacier
Clague & Mathews (1973)
Walder & Costa (1996)
Connected to upstream lake
Discharge (km³ / month)
Lake volume drained (km³)
c
Antarctica
Greenland
Iceland
Connected to upstream lake
Mean recharge (km³/month)
Lake volume drained (km³)

◀ Fig. 4 | **Subglacial lake activity patterns and the relationship with lake volume.** **a** | Five fill–drain patterns were identified from data for subglacial lakes with at least one complete fill–drain cycle during the observation period (Supplementary Data). Lake draining and filling (discharge and recharge) are estimated from ice surface elevation changes (see main text for caveats with using this method). **b** | Relation between average (circles) or peak (crosses) discharge rates and total drainage volume, for drainage events from subglacial lakes and ice-marginal lakes draining through subglacial channels[139,259], respectively. **c** | Relation between average recharge rate of different subglacial lakes and their lake volume. Dashed lines indicate orthogonal distance regression fits for different lake populations, and black outlines highlight lakes that are fed by the drainage of an upstream subglacial lake. asl, above sea level.

Lake discharge that exceeds the hydrological capacity of the existing subglacial drainage system will cause a transient increase in basal water pressure and enhanced basal sliding[147] (FIG. 5). Initial acceleration will be larger with a greater water pressure perturbation, such as during higher lake discharge, or in a less efficient drainage system. Once discharge falls below the drainage system's hydrological capacity, water pressure decreases and high-pressure water drains from connected areas of the bed, increasing basal traction and reducing sliding over a large area[143]. This behaviour is expected for lake drainages beneath relatively thin ice with steeper hydrological potential gradients, where subglacial channels are more likely to form and take longer to close owing to lower creep closure rates. For example, eight days after the 1996 drainage of Lake Grímsvötn began, downstream ice velocity had increased by 200% over an 8-km-wide area around the subglacial flood path[143], followed by a 50% deceleration in ice flow, which did not fully recover for 4 years[144]. A similar pattern on a shorter timescale has been observed[15] in west Greenland, where, in the month following drainage of a subglacial lake 6 km from the terminus of Isunnguata Sermia, mean ice velocity reduced by about 25%.

Subglacial lake drainages beneath Thwaites Glacier in West Antarctica produced muted (<3%) ice flow accelerations over several days[145]. During a 2012 drainage event, a 2% increase in velocity was followed by a deceleration of about 3% over 6 months. In East Antarctica, drainage of two lakes beneath Byrd Glacier with a mean discharge of 70 $m^3 s^{-1}$ increased ice flow by up to 10% over the 75-km-long glacier trunk between December 2005 and February 2007 (REF.[10]). Five years of continuous Global Positioning System (GPS) data on the Whillans and Mercer ice streams in West Antarctica revealed net ice flow enhancement associated with a cascading lake drainage event[13]. This enhancement comprised three episodic ice flow accelerations of up to 4% over the two-year duration of flow enhancement but no subsequent slowdown to below the pre-drainage event ice velocity. Multi-year ice flow enhancements that are more muted than in observations in Iceland[143] are consistent with lower subglacial lake discharges of longer duration in Antarctica (FIG. 4b). As Antarctic ice streams are typically characterized by abundant subglacial water and saturated sediments[151–153], lake drainages might have a limited additional impact on basal friction. Subdued deceleration on the falling limb of the lake drainage hydrograph is possible for several reasons. First, although theoretically possible[7,141], formation of low-pressure channels is less likely owing to shallow hydrological potential gradients, which limit the generation of turbulent heat, and heat loss to colder overlying ice. Second, any low-pressure channels that form during peak discharge might have limited extent[141] and are likely to be rapidly shut down once discharge wanes, limiting their ability to capture high-pressure water from adjacent connected areas.

The net long-term impact of subglacial lakes on ice velocity depends on the balance of reduced motion (compared to ice motion in the absence of lakes) during lake filling[13], enhanced motion during lake drainage, and reduced motion following the development of efficient downstream drainage, which might in some cases go below long-term average values. These effects depend on evolving and interrelated parameters such as lake filling rate, lake discharge, ice thickness and temperature, subglacial hydrological gradient, and the hydrological capacity of existing subglacial drainage. A universal association between subglacial lake activity and ice motion therefore seems unlikely; indeed, while a net long-term reduction in ice motion resulting from lake filling and drainage is suggested in one instance[12], another study revealed a two-year period of lake filling, followed by a two-year period of lake drainage, resulting in a positive velocity anomaly compared to the long-term average[13].

Landscape impact of subglacial lake drainage

Subglacial lake drainages can erode, transport and deposit large volumes of sediment subglacially, englacially and proglacially. Observations from contemporary subglacial lake outburst floods show evidence of mechanical erosion of subglacial sediments[154–156], rapid deposition of eskers and fracture fills within the ice mass[157,158], the construction of large outwash plains[15,159–162] and proglacial debris flows on steeper slopes[41,128]. In Iceland, repeated outburst floods are thought to dominate sediment supply to the proglacial foreland and contribute to the formation of substantial sandurs[163,164]. Former subglacial lake drainage events have been inferred from large (10^2–10^3 m wide) palaeo-channels cut into the bed[165–169], which can funnel ice flow and influence ice dynamics[170]. For example, estimated peak discharge for the Labyrinth, an outburst flood landscape in the McMurdo Dry Valleys in Antarctica, was $1.6–2.2 \times 10^6 m^3 s^{-1}$ (REF.[169]), which is around two orders of magnitude greater than the largest subglacial lake floods observed today.

Sediment erosion and transport during lake drainage is thought to be roughly proportional to discharge[160,171], although modulated by substrate, sediment availability, and the flood route and hydrograph shape[156,172]. In particular, rapidly rising (with a linear increase in discharge) subglacial lake outburst floods in Iceland cause substantial landscape modification[160]. For example, the 1996 jökulhlaups from Lake Grímsvötn drained 3.2 km^3 of water within 40 h, had a peak discharge of $4 \times 10^4 m^3 s^{-1}$, and flooded the entire outwash plain[22]. The sediment yield was about $1.8 \times 10^8 m^3$, equating to 0.3 m (65,700 m per 1,000 years) of erosion across the glacier bed affected by floodwaters[163,173,174]. This rate of erosion compares to

Eskers
Slightly sinuous ridges of glaciofluvial sediments (such as gravels) that record the former drainage of meltwater under, in or on top of ice masses.

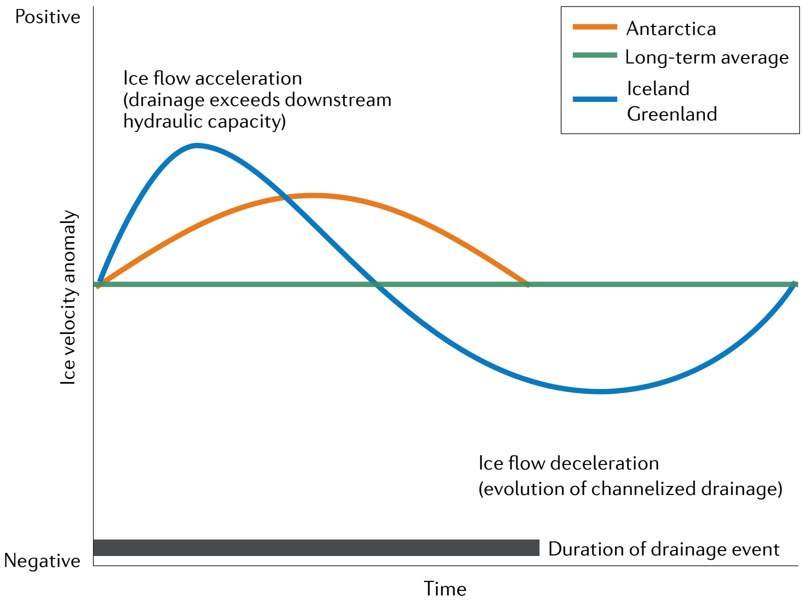


Fig. 5 | **Conceptual model of the influence of subglacial lake activity on ice flow.** For a given subglacial lake drainage event, the ice flow response will depend on whether, and to what extent, lake discharge exceeds the hydrological capacity of the existing subglacial drainage system. Where discharge is low and the lake drains into a pre-existing channel, the ice flow response is likely to be limited (green line). Drainage that exceeds the downstream hydrological capacity (red and blue lines) will result in ice flow acceleration. This acceleration might be followed by a subsequent slowdown (blue line) if water pressure in the main channel reduces and high-pressure water drains from connected areas of the ice bed.

average glacial erosion rates for Vatnajökull Ice Cap of around 0.32 m per 1,000 years[175].

Similar rapid drainages from lakes beneath valley glaciers[41,121] (hours to days) and the Greenland Ice Sheet[15] (<1 month) also result in substantial geomorphic change. Small outburst floods caused by release of subglacial water stored in cavities beneath South Tahoma Glacier on Mount Rainier in Washington typically transform into debris flows as they incorporate proglacial sediment on the valley slopes[116,128,176]. Between 1967 and 1994, at least 23 outburst events have occurred, resulting in substantial incision of sediment and stagnant ice in the upper catchment (>20 mm per year), and aggradation of up to 10^7 m^3 of sediment in the downstream valley[176]. The 2015 outburst of a small (approximately 0.013 km^3) subglacial lake close to the margin of Isunguata Sermia in western Greenland flooded the foreland, aggrading the proglacial channel by up to 8 m close to the outlet.

The geomorphic impact of Antarctic subglacial lake drainages is constrained by large bedrock[166,167,177] palaeo-channels, active[178] and palaeo[179] sediment channels, and eroded or restricted landform growth at the grounding line (for example, grounding zone wedges)[179]. Larger Antarctic subglacial lakes (FIG. 3b) with drainage of longer duration might enable the transport of more sediment if there is an abundant sediment supply[180]. However, gradual leakage of water from Antarctic lakes[7] and their lower mean discharge (FIG. 4b) suggest that they might be less effective geomorphic agents than lakes in other settings.

Redox reactions
Chemical reactions in which one molecule becomes reduced and another becomes oxidized.

Chemosynthesis
The fixation of single-carbon molecules into organic biomass using energy from the oxidation of inorganic electron donors.

Methanogenesis
A metabolic process that yields energy for microbial growth while releasing methane.

Necromass
Organic material consisting of or derived from dead organisms.

Subglacial ecosystems

Subglacial lacustrine systems store, transform and export carbon and nutrients[9,181]. Although these fluxes are poorly understood owing to limited direct observations, dissolved elements and sediments in subglacial discharge and any turbulent mixing resulting from discharge dynamics can enhance primary productivity in downstream environments such as proglacial lakes, fjords and the polar oceans[182]. The hydrological and glaciological context of subglacial lakes influence in situ geochemical conditions, which, in turn, control the metabolic regime and distinct genomic adaptations of resident microorganisms. To date, only four active subglacial lakes have been directly sampled for microbial analyses[1,55–57] (FIG. 3). However, these limited samples retrieved directly from subglacial lake water and sediments confirm the presence of active microbial communities[183].

Subglacial lacustrine ecosystems (FIG. 6) must contend with permanent darkness, high pressures and low temperatures. In the case of hypersaline lakes, cells must also manage salt stress. The absence of sunlight requires that microorganisms harness energy from thermodynamically favourable and predictable chemical reactions known as redox reactions[184], with primary production via chemosynthesis[1,2,57,185,186]. A wide range of materials provide electrons for reduction in the subglacial setting, including geological sources such as bedrock minerals (either in situ or scoured during lake drainage and refill), reduced compounds such as sulfur from geothermal fluids, and biological sources such as the byproducts of microbial sulfate reduction or methanogenesis. Organic matter might be transported from the surface or originate from 'legacy' ecosystems overridden by advancing ice sheets, including marine or terrestrial necromass, or any labile organic matter in underlying sediments[187,188]. Any available oxygen in the subglacial environment would be rapidly consumed through microbial oxidation of reduced substrates, including organic matter or inorganic compounds such as sulfide, ammonia, methane or Fe(II). Given sufficient electron donors and no new input of oxygen, subglacial systems will be driven to anoxic conditions, in which some microorganisms can respire using diverse alternative electron acceptors, with predictably decreasing energetic yield. Evidence for iron reducers, denitrifiers, sulfate reducers and methanogens, which respire Fe(III), nitrate, sulfate and carbon dioxide, respectively, has been observed in subglacial lake settings[1,189–191].

Active lakes along continental margins, such as Whillans Subglacial Lake (FIG. 6a), might accumulate solute-rich porewaters generated by upstream basal melt. The formation of steep chemical, physical and biological gradients at lake water–sediment interfaces can influence microbial abundance and productivity[192]. Accumulated solutes and recycled organic matter can provide nutrients for energy-yielding metabolisms and cellular biosynthesis. Data from Whillans Subglacial Lake (FIG. 6a) indicate that ammonium ions are an important energy source for biosynthesis[2,193], and taxa related to nitrogen-cycling microorganisms, for example, the betaproteobacterium '*Candidatus* Nitrotoga arctica', are abundant[1,194]. This group is known to mediate the oxidation of nitrite to nitrate, an important step

Nitrification
The oxidation of reduced nitrogen compounds to nitrite or nitrate.

Chemolithotrophic
The metabolic oxidation of inorganic compounds to yield energy and fix single-carbon compounds into organic biomass.

in nitrification[195]. Sediment–water interfaces, where ions diffuse upwards into the water column[1,196], create a niche for enhanced microbial activity and higher rates of dark carbon fixation[2]. Transitioning into lake sediments, microbially mediated methane[189] and sulfur oxidation[190] are key processes.

Active subglacial lakes below Vatnajökull Ice Cap in Iceland (FIG. 6b) provide a redox gradient of oxygenated glacial melt and reducing geothermal fluid, which can also support chemolithotrophic communities[186]. Microbial assemblages in western Skaftá Lake, for example, utilize sulfide, sulfur or hydrogen as electron donors and oxygen, sulfate or CO_2 as electron acceptors[56,57]. Similarities in the microbial community between distinct lakes below Vatnajökull suggest a subsurface hydrological connectivity that can seed these transient lakes with cellular biomass and nutrients discharged in jökulhlaups[186], which ultimately impacts downstream biological communities including fishing grounds.

Greenland's active subglacial lakes (FIG. 6c) are largely thought to be filled by the rapid injection of surface melt via moulins[47], which would provide oxygen and photosynthetically derived organic matter, supporting aerobic metabolism. This seasonal delivery could create physical turbulence, which scours legacy organic material as drainage systems expand[197]. Aerobic respiration would eventually exhaust the supply of oxygen, driving the system to anoxia as winter temperatures freeze out fresh surface melt. Although Greenland subglacial lakes have yet to be directly accessed, multiple lines of evidence suggest that microbial methane production, an anaerobic process, occurs at its bed[198–200]. In fact, Greenland lakes might be quite diverse, with evidence suggesting the presence of hypersaline or geothermally heated systems[201], both scenarios that shape microbial communities.

Substantially less is known about the deep, closed-basin lakes under the thick (>1 km) interior of ice sheets, although they are also anticipated to host ecosystems, owing to possible geothermal stirring of nutrients[107] and inputs of oxygen derived from sediments and/or the ice above. Samples of accretion ice above Lake Vostok contained tens to hundreds of DNA-containing cells per millilitre of melt water[202] and, although these numbers are low compared with the approximately 100,000 cells present in the same volume from Whillans Subglacial Lake, uncontaminated samples from Lake Vostok water remain elusive[58]. Regardless, water column samples collected at a discrete depth might not be representative of water body dynamics, as subglacial lakes can be thermally unstable[2], which drives internal mixing[107]. Hypersaline lakes beneath the Devon Ice Cap[45] present an intriguing end-member system, where microbes must survive in high solute concentrations.

Future evolution of subglacial lakes

A range of subglacial lake behaviours have been identified (FIG. 7), which provide a proxy for how their role might evolve in the future under changes in local conditions. This range includes large stable lakes beneath ice mass interiors, slowly cascading lake drainage beneath Antarctic ice streams (FIG. 7a), faster-draining smaller lakes beneath the Icelandic ice caps and the ablation zone of the Greenland Ice Sheet (FIG. 7b,c), and water-filled cavities that drain rapidly beneath valley glaciers (FIG. 7c). The progression coincides with steeper ice surface slopes, thinner ice and enhanced meltwater inputs. Similar temporal changes are expected as climate warming causes ice mass loss, recession and thinning[203,204], increased surface[205] and basal[206] (caused by faster ice flow and surface melt inputs) melting, inland expansion of ablation areas[207,208], and ice acceleration (caused by, for example, thinning and loss of buttressing ice shelves)[209,210].

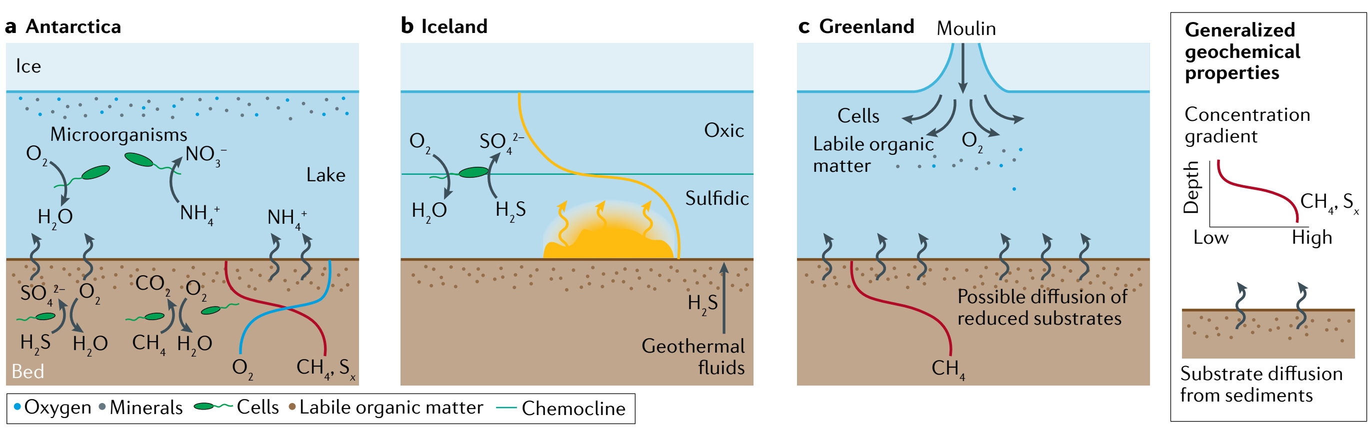
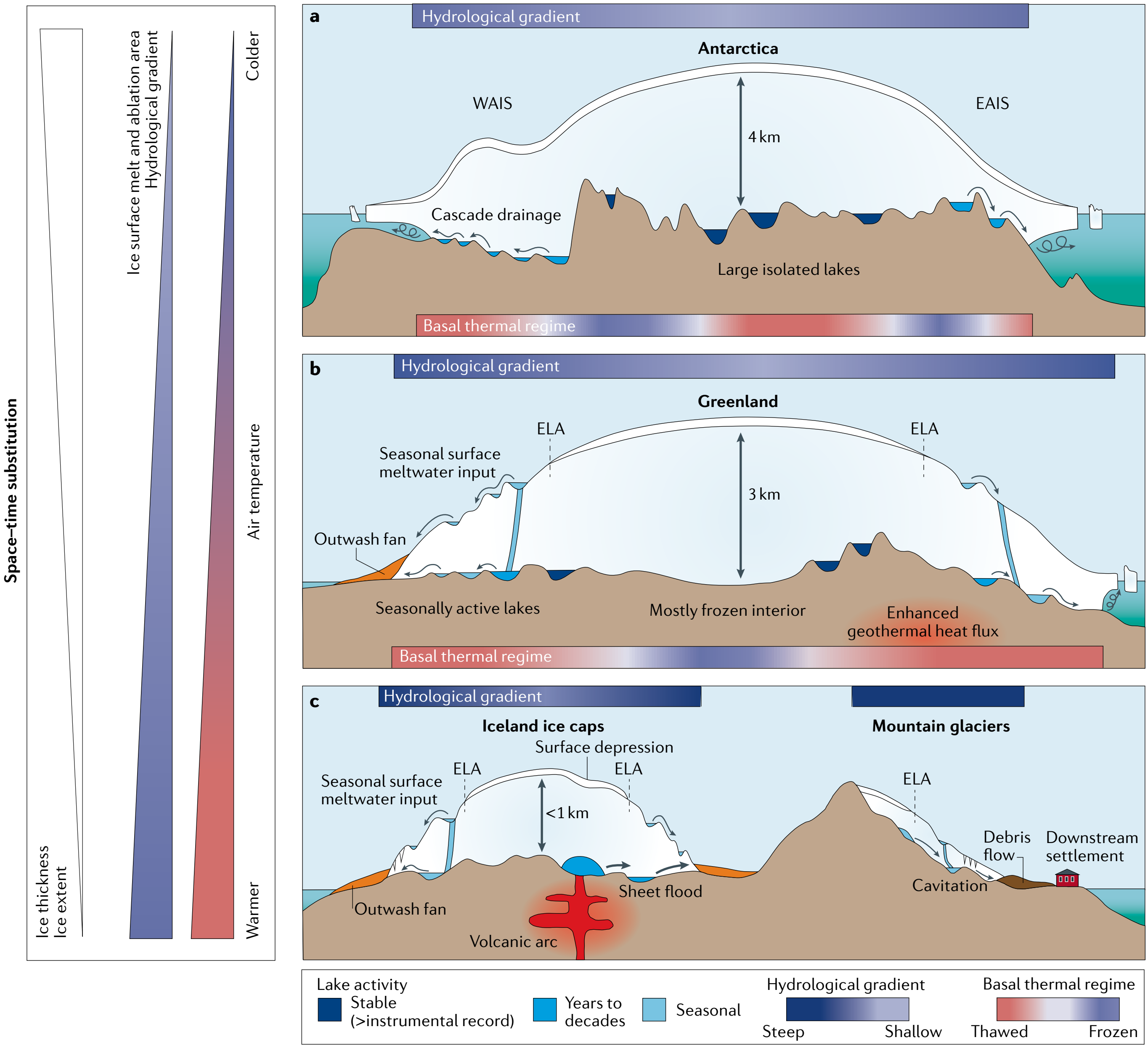


Fig. 6 | **Microbial redox reactions across a range of lake settings.** In the absence of sunlight, microbial systems in subglacial lakes derive primary production from chemosynthesis. Solute-rich porewaters deliver nutrients from the lake catchment, while sediment ions diffuse upward at the sediment–water interface. In sediments, redox transitions are influenced by oxygen availability and penetration with depth, and microbial metabolic groups shift accordingly. Schematic depiction of three examples of lake settings. **a** | In active Antarctic lakes such as Whillans Subglacial Lake, basal ice interacts with the surface water column, but these lakes generally lack surface connectivity, which restricts oxygen resupply and delivery of photosynthetically derived nutrients within glacial melt. **b** | Icelandic lakes formed from active hydrothermal systems under ice contain chemically and thermally stratified water columns, which result from the melting of oxygenated glacial ice and the flux of sulfidic geothermal fluid. At the chemocline, sulfur-oxidizing microorganisms dominate. **c** | In an active Greenland lake, recharge from surface meltwater through moulins can deliver substantial volumes of supraglacial materials, including photosynthetically derived organic matter that influences redox gradients. S_x, sulfur compound.



In general, subglacial lakes are predicted to be less abundant beneath smaller ice masses, as recession produces steeper mean surface slopes (higher hydrological gradients), which reduces the potential for hydrological minima[89,99]. Thus, as ice masses shrink, the relative area of the bed occupied by subglacial lakes should decrease (FIG. 7). This decrease is consistent with the reduction in water volume stored in Icelandic ice-dammed lakes since the early twentieth century as their ice dams lower in response to climate warming[22], and with the drainage of a subglacial lake beneath Crane Glacier in the Antarctic Peninsula due to ice surface steepening following ice shelf collapse[11]. Warming of around 1.8 °C (above pre-industrial temperature levels) in Greenland[211] is predicted to lead to irreversible ice mass loss over multiple millennia, while 2–3 °C warming (above pre-industrial temperature levels) in Antarctica[212,213] is likely to cause substantial grounding-line retreat and the collapse of major marine drainage basins in West Antarctica[214]. Thus, ice surface steepening due to grounding-line retreat and loss of ice shelves is likely to trigger lake drainage and reduce the potential for subglacial ponding. In general, East Antarctic Ice Sheet decline is predicted to be initiated at approximately 6–7 °C warming (above pre-industrial temperature levels) and will probably be dominated by the melt elevation feedback[212,213,215]. Here, subglacial lakes are likely to remain relatively stable over multi-millennia timescales, and might even increase in number around the margin owing to enhanced surface melt and its input to the bed.

Although a general decline in lake abundance and total water volume is predicted as large ice masses shrink, spatial heterogeneity in subglacial lake distribution beneath the Antarctic and Greenland ice sheets (FIG. 3) suggests that this pattern is complicated by local

◀ Fig. 7 | **Impact of climate warming on the future distribution, geometry and activity of subglacial lakes.** The impact of climate change is assessed by space–time substitution using spatial variations in the behaviour of subglacial lakes beneath modern ice masses. Conceptual models of the hydrological systems of modern ice masses are depicted. **a** | Antarctica is dominated by very large, stable lakes close to ice divides, whereas active lakes that drain slowly (in months to years) tend to occur beneath ice streams closer to the ice margin. **b** | Greenland is largely devoid of lakes in the near-frozen interior. Stable lakes are typically found above the equilibrium line altitude (ELA), whereas active lakes recharged by surface water are found at or below the ELA and are associated with higher discharge rates than those in Antarctica (draining in days to weeks). Similar discharge rates are found in Icelandic subglacial lakes, with lake formation and activity influenced by subglacial volcanism and occasionally experiencing large sheet floods owing to rapid lake refilling. **c** | Valley glaciers are associated with small lakes that can drain rapidly (in <1 h to days), with fill–drain rates that are modulated by surface melt and rainfall inputs. Note that the space aspect has large gaps (for example, Antarctica is much larger than Greenland, and Greenland is much larger than the ice caps of Iceland), and little is known about how changes in lake volume, distribution and activity will manifest as ice masses shrink. As climate warms and ice sheets recede and thin, surface slopes steepen in response to ice shelf loss and grounding-line retreat, and surface melt intensifies and expands, we predict that the size of subglacial lakes and their relative coverage of the bed will generally decrease beneath the Greenland and West Antarctic ice sheets (although modulated by factors such as bed roughness and heat flux) but that these lakes will become more active. Beneath smaller ice masses (such as valley glaciers), changes in lake abundance will be strongly controlled by local factors. Warming is likely to enhance the potential for surface coupling (for example, melt and rainfall inputs), resulting in higher overall discharges of shorter duration, and more frequent sheet floods. The reduction in ice overburden pressure might also stimulate volcanic activity, resulting in enhanced basal melting and lake formation. EAIS, East Antarctic Ice Sheet; WAIS, West Antarctic Ice Sheet.

factors, including bed roughness, basal thermal regime and geothermal heat flux[91] (FIG. 7). Rough beds can promote cavitation[124] and have more topographic depressions for subglacial water storage. For example, lakes are clustered within the Ellsworth Subglacial Highlands[111] and subglacial Gamburtsev Mountains[28] in Antarctica. These lakes, particularly those associated with deep tectonic troughs (for example, Lake Vostok)[113], are more likely to withstand ice sheet changes. Basal thermal regime controls the availability of water to form lakes and will change in response to ice sheet evolution[216] and reorganization of water or ice flow[217–219]. Currently, there are abundant large, stable lakes beneath the warm interior of Antarctica, whereas the near-freezing interior of Greenland is largely devoid of lakes[44] (FIG. 3). Increases in the aerial extent and intensity of basal melt beneath the Greenland Ice Sheet[206] could facilitate inland expansion of new subglacial lakes. Any increase in saturated sediments would facilitate enhanced rock–water interactions, liberating solutes for microbial processes. Thinning of ice overlying subglacial magma systems, such as those beneath the West Antarctic Ice Sheet[220], Iceland[221] and Chile[222], could stimulate volcanic activity[223–225], resulting in more numerous and active lakes.

Mountain glaciers are undergoing widespread recession and thinning in response to climate warming[226]. However, the link between climate and subglacial water storage beneath these smaller ice masses is poorly constrained and likely to be strongly influenced by local factors. For example, debris-covered glaciers are undergoing a reduction in surface gradient caused by a down-glacier increase in debris thickness that focuses the highest rates of surface lowering in the mid-ablation zone[227]. This change in gradient might enhance storage of subglacial water in these glaciers. The storage capacity of subglacial cavities[124] will also control the distribution and extent of ponding at the bed and is likely to be a key mechanism beneath mountain glaciers (FIG. 7c). Cavitation is expected to be greatest on rough and steep beds and where basal sliding is high[123,133]. Thus, steep valley glaciers on rough beds could have an abundance of small, seasonally draining subglacial lakes[40], which could become more common as melt inputs increase basal sliding. Finally, the susceptibility of a glacier to surging has been linked to increased basal water storage beneath longer (and shallower) glaciers and between cold–dry and warm–temperate climate extremes[228].

Larger, stable lakes tend to be located beneath or near to ice sheet divides where surface slopes are generally low, while hydrologically active lakes occur closer to ice margins where the hydrological gradient is steeper (FIG. 1). Consequently, an evolution from ice sheet centre to margin dictates lake formation and associated hydrological processes. Ice masses with steeper hydrological gradients (FIG. 7a,b) produce higher subglacial lake discharges of shorter duration[21,140] (FIG. 4b), and ice surface melt and rainfall inputs to the bed can trigger[121,128] or modulate drainage[47,129]. For example, outburst floods from beneath South Tahoma Glacier usually occur during hot or rainy weather in summer or early autumn, and the probability of an outburst increases with temperature[128]. As surface melt intensifies and expands inland[207], and where ice-margin retreat and ice shelf loss causes hydrological gradients to steepen, more vigorous lake activity can be expected over a greater proportion of the bed (FIG. 7). In particular, ablation zone expansion could create new drainage pathways, facilitating the drainage of formerly isolated lakes beneath ice mass interiors, such as in Greenland[44]. Although subglacial lakes are currently isolated from surface processes in Antarctica, evidence of water penetrating to the bed of grounded ice in the Antarctic Peninsula[229] hints at a future with increasing coupling between supraglacial and basal hydrology near the grounding line as surface melt intensifies[207]. Atmospheric warming of around 3 °C (above pre-industrial temperature levels) could trigger widespread collapse of the large ice shelves fringing Antarctica[213,215], resulting in steepening of ice surface slopes[11]. The stability of Antarctic ice shelves is therefore likely to play a key part in controlling any shift to more rapid lake drainage.

Large melt inputs into a subglacial lake can trigger flotation of the ice dam, causing a sheet flood with a rapidly rising discharge[22] and mobilization of large volumes of sediment[22,163,173,174]. These catastrophic drainages might become more frequent with large and rapid surface melt and rainfall inputs[230] and thinning of ice dams, providing a potential hazard to downstream populations and infrastructure in glaciated mountain regions (FIG. 7c). The increased erosive capacity might also (partially) remove sediment deposits contained within lakes, reducing their potential as archives of climate conditions. The link between deglaciation and drainage periodicity is less clear. In Iceland, periodicity has been related to ice dam thickness[94]. However, there

Equilibrium line altitude
(ELA). The elevation at which the accumulation and ablation of ice are in balance over a given time period (typically, 1 year).

is no clear difference in drainage periodicity between lakes in Iceland and Antarctica[6], which is supported by the consistent power-law relationship between recharge rate and lake size in different settings (FIG. 4c), suggesting a more complex relationship between deglaciation and drainage periodicity.

We also consider how future evolution of subglacial lake drainage (FIG. 7) will affect the environment and ice dynamics. Increased lake activity is likely to enhance the hydrological and biogeochemical connectivity between lakes and their surroundings[186], locally enhancing transport of sediment, solute and nutrients to downstream ecosystems[9,181] and water across the grounding line of marine-terminating glaciers[5]. The regional impact of lake drainages on ecosystems is likely to shift over time, as drainage direction is highly sensitive to small changes in ice sheet geometry[89,231]. Increased routeing of water through lakes, coupled with steepening ice-surface slopes, will affect melt–refreeze patterns at the ice–water interface, potentially disrupting lake stratification and circulation patterns, with implications for the lake ecosystem and sediment deposition[16]. Enhanced nutrient mixing might promote microbial productivity throughout the water column; however, a large discharge of sediments could reduce light penetration in proglacial waters, thereby inhibiting photosynthetic production. Large, episodic surface meltwater inputs into subglacial lakes[47,128] provide a supply of oxidants, sediment, microorganisms and labile organic matter, which might seasonally enhance oxic processes (FIG. 6c). Conversely, scoured beds, reduced time for rock–water interactions and dilution by supraglacial meltwaters could inhibit some subglacial biogeochemical activity, but the overall impact is uncertain because of inadequate access and sampling of lake environments. Increased discharge of subglacial lake water at marine-terminating glaciers or ice streams can modify freshwater budgets and nutrient supply within sub-ice-shelf cavities and the wider ocean[5,21]. This pattern will probably be modulated by the environment into which the water discharges and the circulation in the sub-ice shelf cavity or fjord.

Subglacial lake drainage across grounding lines can enhance plume-driven frontal ablation[232–234], affecting ice margin and shelf stability[5,20]. Embayments at subglacial lake outflow points[5], and surface depression and crevassing of ice above the grounding line following the 2003 drainage of Subglacial Lake Engelhardt, West Antarctica[20], demonstrate the potential of lake drainage events to enhance frontal ablation. An expanding ablation zone will increase the chances of lake drainage entering an existing, efficient subglacial drainage system[143] and thus having a limited impact on ice dynamics. However, higher discharge floods of shorter duration (FIG. 4b) are more likely to exceed the existing downstream hydrological capacity, resulting in large initial ice flow enhancements[143], followed by a reduction in ice flow as channels develop and discharge falls below the system's hydrological capacity[15,144] (FIG. 5). More extensive and long-lived efficient subglacial drainage will increase the probability that the fill–drain cycle of a subglacial lake causes net reduction in ice flow.

Summary and future perspectives

The storage of water under ice masses is widespread and occurs in a range of settings[103] and climatic regimes. This diversity has resulted in a wide spectrum of subglacial lake environments, behaviours and impacts. The global inventory of 773 lakes suggests that this diversity is related to the characteristics of overlying ice masses and the topography and material of the ice bed. Grounding-line retreat[212] and ice shelf loss of the West Antarctica Ice Sheet[213,215] might result in fewer and smaller lakes that drain more rapidly. As melt intensifies and expands further inland owing to climate warming (for example, in Greenland)[205], more subglacial lakes might become coupled to surface melt and rainfall inputs, increasing the number of active lakes and the potential for catastrophic drainages. Data on subglacial lakes beneath small ice caps and valley glaciers are limited (FIG. 3), and the impact of local controls (for example, bed roughness) and glacial processes (such as debris-covered glaciers) is likely to result in large variations in the response of subglacial lakes to warming. Increased lake activity will drive large initial ice-flow enhancements, followed by a reduction in ice flow as efficient drainage develops and discharge falls below the system's hydrological capacity. The probability that the fill–drain cycle of a subglacial lake causes a net reduction in ice flow will increase as efficient subglacial drainage becomes more extensive and long-lived. As hydrological connections are made between lakes, their subglacial surroundings and the ice surface, fluxes of sediment, solute and nutrients will be temporarily stored and then released downstream, modulating the nourishment of downstream subglacial and proglacial ecosystems and providing conditions for both aerobic and anoxic processes.

Hydrological predictions suggest that there are many thousands of undetected subglacial lakes[89–91], while our global inventory of subglacial lakes is heavily skewed towards Antarctica (675 of 773 lakes) owing to the geophysical data currently available (FIG. 3). Therefore, future efforts should aim to expand the identification and characterization of lakes under valley glaciers, ice caps and the Greenland Ice Sheet. In particular, for mountain glaciers, the sudden drainage of lakes poses a hazard to human populations downstream[124,235]; thus, a better understanding of water storage and drainage beneath glaciers in vulnerable areas and how the risk might change due to climate warming should be a priority. Improvements in spatial and temporal coverage and resolution of satellites[6,79,82,83], and the increased availability of high-resolution multi-temporal DSMs[87,236] coupled with lake detection automation[72] (for example, using machine learning algorithms)[237] will probably enable these gaps to be filled, particularly for smaller lakes, which are inherently more difficult to detect[15,44,48]. Future satellite missions, including the European Space Agency's Copernicus Polar Ice and Snow Topography Altimeter (CRISTAL)[79,81] and the P-band Biomass Earth Explorer[238], will help to identify and monitor long-term changes in subglacial lakes. An orbiting radar sounder could also provide unprecedented spatial and temporal coverage of the Earth's cryosphere, as well as a homogeneous sampling of the ice sheet at a uniform radar frequency and quality[239,240].

Another challenge is to improve understanding of subglacial lake fill–drain cycles. Subglacial lakes exhibit diverse drainage patterns (FIG. 4a), but observations spanning at least one complete cycle are available for only 36 lakes; longer-term records that show how fill–drain cycles respond to changes in climate are restricted to Iceland[22] and some valley glaciers[41]. Operational, near-real-time monitoring of subglacial lake activity from polar orbiting satellites is already providing improvements in the coverage and length of observational records. Integration of remote observations and numerical modelling has potential for characterizing the timing, volumes and processes associated with lake drainage and refilling. For example, application of passive seismology (FIG. 2a), which monitors acoustic vibrations caused by turbulent subglacial water flow[241], would enable continuous monitoring of subglacial lake dynamics and the evolving hydrological properties[242] of water inflow and outflow. Satellite and geophysical observations can, in turn, be used to constrain and force catchment-scale numerical ice sheet models[7,243] to analyse fill–drain characteristics, and their coupling with the wider hydrological system and overlying ice. A longer-term (centennial to millennial) perspective on past lake drainages and their role in topographic evolution beneath retreating ice sheets can be gleaned from geological landform analysis and sediment records[179,244,245], and the inclusion of sediment dynamics in subglacial hydrology models[146,246,247].

Coupling between lake volume and ice motion is currently poorly constrained and its investigation requires data with high temporal resolution, ideally gapless acquisition over one or more fill–drain cycles, and broad spatial coverage to quantify the downstream dynamic effect of lake discharge. Coupled subglacial hydrology and ice dynamic modelling can utilize these ice-velocity and subglacial hydrology data to determine the primary drivers of ice motion. Efforts must focus on constraining the initial ice dynamic response and net long-term impact of subglacial lake drainages for a range of discharge magnitudes and glaciological settings. Recent and planned SAR-imaging satellite missions, such as the European Space Agency's Sentinel-1 constellation and NASA's NASA-ISRO SAR (NISAR), respectively, have high spatial resolution (2.7–22 m) and short repeat cycles (6–12 days), which will improve the likelihood of obtaining high-quality ice motion and surface topography data from image cross-correlation and (differential) interferometric aperture radar[236], even for ice masses that experience substantial surface melting or snowfall. Coupling of subglacial hydrology and ice dynamics models will allow analyses of physical drivers of lake stability and future lake behaviour.

Direct access into subglacial lakes that represent the range of hydrological, dynamic and mass balance regimes is needed to understand the factors that control metabolic productivity and taxa diversity of resident microbial communities. Biogeochemical measurements from a range of subglacial conditions will inform global carbon budgets and support predictions of how climate change might alter the function of these ecosystems. Replicate samples from subglacial lakes can provide information about the stability of communities and pace of ecosystem change. Because discharge from subglacial lakes probably has important implications for downstream ecosystems, continuing to identify and characterize discharge points, particularly at marine-terminating systems, is critical. Advances in automated underwater vehicles, which can scan large areas along coastal margins, particularly along underexplored grounding zones, will be required.

Drilling capabilities that enable clean, direct access into subglacial lakes are essential for advancing our understanding of resident microbial communities. Recently, hot water drills have been designed with systems that filter and irradiate the melt water used in drilling[248,249]. Further development of these systems for logistical efficiency and increased automation, coupled with progress in thermal probe technologies[250] that enable in situ measurements and acquisition of samples for microbial analysis[251,252], will be crucial for exploring deep subglacial lakes[250,252].

Geophysical innovations will reveal more about the physical properties of subglacial lakes and how they change over time. Autonomous phase-sensitive radio-echo sounding (ApRES)[253–255] can determine vertical strain in the ice, which provides information on the ice-dynamic response to lake filling and draining, and basal melt–freeze rates, which provide critical input data for water circulation models. Next-generation full-waveform inversion techniques for interpreting active-source seismic observations[256] provide more precise constraints on the structure of subglacial water systems, particularly for regions with thin water cavities and/or sediment layers[53]. Electromagnetic approaches provide constraints on the porewater properties of water-saturated subglacial sediment packages and the salinity of lake waters. Developments in time-lapse geophysical monitoring, innovations in miniaturization, autonomy, cost reduction, and power savings for geophysical sensors[60], and integration of different geophysical approaches (such as electromagnetic and seismic exploration to derive lake salinity)[75,257] with numerical modelling of lake hydrology[107] will refine our understanding of subglacial lakes. Together, these developments will provide a more holistic picture of how subglacial lakes interact with the wider hydrological system, including poorly resolved components such as the flow of water within sediments and rocks[258].

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Author contributions
S.J.L. led the project and assembled the authorship team. S.J.L. produced the global subglacial lake inventory with input from all authors. Y.L., R.J.S. and K.W. identified the additional new Antarctic subglacial lakes included in the global inventory and wrote the Supplementary Data. The section on lake discharge–recharge relationships came from discussions between S.J.L., F.S.L.N. and A.J.S. K.W. produced Fig. 1; S.J.L. produced Figs. 3, 4 and 5, with help from F.N. and A.J.S.; J.A.M. produced Fig. 6; A.R. and S.J.L. produced Fig. 7; and M.S., H.A.F. and A.R. contributed to Fig. 2. All authors contributed to the writing and editing of the manuscript prior to submission.

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