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Subglacial lakes and their changing role in a warming climate

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Abstract:

Subglacial lakes store ancient climate records, 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 total): 675 from Antarctica (59 newly-identified in this study), 64 from Greenland, 2 beneath Devon Ice Cap, 6 beneath Iceland's ice caps, and 26 from valley glaciers. We use this inventory to evaluate subglacial lake environments, dynamics, and their wider impact on ice flow and sediment transport. Lake behaviour is conditioned by their unique subglacial setting and the hydrologic, dynamic and mass balance regime of the overlying ice mass. We predict that in regions where climate warming causes ice-surface steepening there will be 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 due to development of efficient subglacial drainage. Future subglacial lake research requires new drilling technologies, and the integration of geophysics, satellite monitoring and numerical modelling, which will provide new insight into their wider role in a changing Earth system.

Key Points

- First global inventory of 773 subglacial lakes: 675 from Antarctica (59 newly identified here), 64 from Greenland, 6 from Iceland, 2 beneath Devon Ice Cap and 26 from valley glaciers.
- 80% of lakes are stable, implying closed systems, or that inflow and outflow is approximately balanced; the remainder are active lakes with 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 compared with Antarctica.
- Larger active subglacial lakes recharge at a faster rate than smaller lakes, suggesting an underlying control on lake refilling associated with lake size.
- Where climate warming causes ice-surface steepening lakes become less likely, 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, microbes and nutrients.

Introduction

Subglacial lakes under ice sheets and glaciers (Fig. 1) impact multiple components of the Earth system. Lakes provide viable habitats for microbial communities^{2,3} that might have followed unique evolutionary trajectories and serve as analogues for putative extra-terrestrial ecosystems⁴. Water transfer through subglacial lakes modulates basal hydrology^{5–9} and biogeochemical fluxes^{3,10}, and can cause ice-flow variations on sub-decadal time scales^{11–14}. Lake drainage transports large volumes of water and sediment downstream^{15,16}. Lake sediments contain archives of ice sheet history and climate change¹ similar to ice core records. In Antarctica, water crossing the *grounding line* into sub-ice shelf cavities⁶ can alter ice-ocean interactions^{17–20} and can modify ocean circulation²¹. Sudden outburst floods onto the glacier foreland form outwash plains (sandurs) and present a major hazard to infrastructure²².

Subglacial lakes occur when subglacial meltwater collects in local minima of *basal hydrologic potential*, due 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^{42,43} came from unusually strong, sharp, continuous and smooth basal reflections detected in airborne *radio-echo sounding* (RES) surveys in the late 1960s. However, lake inventories were not significantly expanded until further RES investigations in the 1990s and 2000s^{44,45}, while seismic surveying revealed thick water columns^{32,46,47}. Between 2005 and 2008 a new class of “active” lakes was discovered through satellite measurements of ice-surface elevation from Envisat/ERS-2 radar and ICESat laser altimetry^{4,48,49}. Active subglacial lakes can drain along subglacial flow-paths for hundreds of kilometres, and form connected networks^{50,51}.

Jökulhlaups in Iceland provide the longest record of subglacial lake activity, having been reported since the Middle Ages and investigated by ground expeditions and aerial reconnaissance since the early 20th Century³⁶. Icelandic subglacial lakes form by melting of ice via geothermal heat enhanced by volcanism and influxes of surface meltwater. During lake

98 drainage their overlying ice-surface depressions lower rapidly and slowly recover afterwards
 99 as the lake refills^{22,37–39}. Elsewhere, small outburst floods have been caused by drainage of
 100 large or multiple water-filled subglacial cavities from valley glaciers^{40,41}.

101
 102 Over the last decade, subglacial lakes have been discovered under other ice masses, for
 103 example, in Greenland^{52–54} and the Canadian Arctic⁵⁵. In Greenland, the first putative
 104 subglacial lake was inferred from a flat ice-surface elevation anomaly⁵⁶. Since then,
 105 interrogation of airborne RES data^{52–54} and identification of ice-surface elevation changes
 106 from satellite altimetry and high-resolution time-stamped Digital Surface Models
 107 (DSMs)^{15,54,57,58} confirmed their widespread existence under this ice sheet. The two subglacial
 108 lakes identified beneath Devon Ice Cap exist at temperatures well below the pressure-melting
 109 point and likely consist of hypersaline water⁵⁵.

110
 111 In this Review, we construct the first global inventory of subglacial lakes, enabling lake
 112 characteristics and dynamics to be classified. We frame subglacial lake character and function,
 113 and their impact on ice flow, subglacial drainage, sediment transport and biogeochemical
 114 fluxes as dependent on the hydrologic, dynamic and mass balance regime of the ice mass
 115 above. Using space-time substitution, a conceptual model is proposed for how subglacial
 116 lakes, and their influence on the broader environment, will change in a warming world.

117 **Background**

118 *Detecting and characterising subglacial lakes*

119 Identification and characterisation of subglacial lakes and their dynamics has largely relied on
 120 remote geophysical observations^{12,43,54,59–61} (Fig. 2a), due to the challenge of directly
 121 accessing and cleanly sampling water and sediments beneath thick ice⁶². Whillans Subglacial
 122 Lake^{1,63–65} and Mercer Subglacial Lake⁶⁶, West Antarctica (~600 m and 1100 m ice thickness)
 123 and western Skaftá Lake⁶⁷ and Grímsvötn⁶³, Iceland (~400 and 300 m ice thickness) have been
 124 cleanly accessed, while Lake Vostok, East Antarctica (~4000 m ice thickness) was drilled, but
 125 samples were contaminated⁶⁸. In the French Alps, the geometry and water level of a small
 126 subglacial lake under Glacier de Tête Rousse (76 m ice thickness) was successfully accessed
 127 and monitored using boreholes and sonar⁶⁹.

128
 129
 130 Recent innovations in RES have improved detection and characterisation of subglacial water.
 131 Increased radar system bandwidth and signal sensitivity have improved the detection,
 132 resolution and fidelity of radar reflections⁷⁰. Swath radar technology, enabling (pseudo) 3D
 133 imaging of bed topography and englacial layers^{71,72}, can better resolve basal roughness,
 134 hydrological routing and basal melt/freeze-on. Using scattering characteristics of returned
 135 bed echoes such as the specular content⁷³, trailing bed echoes⁷⁴, the bed echo coherent
 136 index^{75,76} and bed-echo variability⁷⁷ has advanced quantitative identification of subglacial
 137 water and the understanding of subglacial drainage systems^{73,78–80}. Finally, there have been
 138 improvements in the automatic detection of subglacial lakes^{29,54,81} including utilisation of
 139 machine learning algorithms⁸¹. Despite enhancements in radar technology, some dynamic
 140 lakes may not have particularly smooth ice-water interfaces, making interpretation of
 141 specular content problematic.

142
 143 While radar sounding can measure lake extent, seismic reflection surveys are necessary to
 144 reveal water column thickness and structure of lake sediments^{32,47,60,82,83}. Active seismic

145 surveys using innovative survey design and analysis (e.g., acoustic impedance or Amplitude
146 Versus Angle) can confirm the presence of a subglacial lake and characterize lake floor
147 properties (i.e., hard bedrock vs. sediment, till porosity)^{47,60}. Other geophysical methods,
148 gravimetry for deeper structure, and electromagnetic (EM) approaches, can reveal the
149 geological and hydrological setting surrounding subglacial lakes^{84–86}.

150
151 Satellite observations of ice-surface displacement derived from Interferometric Synthetic
152 Aperture Radars (InSAR) on ERS-2⁵, Radarsat⁸⁷ and the Advanced Land Observing Satellite
153 (ALOS)⁸⁸, together with elevation measurements from satellite radar and laser altimeters on
154 ERS-2⁵, Envisat⁵¹, ICESat⁴⁹ and CryoSat-2^{6,88–90} have proved crucial in detecting indirect
155 subglacial lake activity, and for estimating their change in volume. In particular,
156 improvements in the accuracy, coverage and record length of the new generation of polar
157 orbiting altimeters, starting with CryoSat-2 in 2010, is enabling a transition from opportunistic
158 studies to operational, near-real-time monitoring of subglacial lake activity⁶. Most recently,
159 Sentinel-3 (2016 onwards) and ICESat-2 (2018 onwards) have been used to monitor subglacial
160 lake activity^{91,92} (Fig. 2b). Sentinel-3 provides frequent (27-day) temporal sampling and – as
161 an operational mission – guarantees long-term continuity of measurements. ICESat-2 with its
162 40 m along-track spacing and sub-decimeter precision^{93,94} provides unprecedented spatial
163 and temporal sampling of subglacial lake activity⁹⁵ (Fig. 2b).

164
165 While monitoring active (10 km)-scale Antarctic lakes by satellite altimeters is well
166 established, the discovery of numerous smaller (<1 km) lakes in Greenland⁵⁴ presents an
167 observational challenge. Recent, exploratory work utilised timestamped DSMs (e.g.
168 ArcticDEM, REMA and TanDEM-X), generated from super high resolution (1-10 m)
169 stereoscopic optical imagery^{96,97}, or single pass radar interferometry. These data can detect
170 detailed patterns of surface deformation associated with lake volume changes, with high
171 vertical precision^{15,58}. Small lakes (<2 km) beneath valley glaciers have also been identified
172 using InSAR to measure ice-surface elevation changes⁹⁸.

173 174 *Subglacial lake distribution and hydrology*

175 Subglacial lakes have been predicted^{8,105–107} and identified^{54,55,98,108} in diverse settings.
176 Previous inventories have focused on lakes beneath individual ice masses. The last inventory
177 of Antarctica in 2012 contained 379 subglacial lakes¹⁰⁸, while 60 subglacial lakes were
178 identified beneath the Greenland Ice Sheet in 2019 based on an ice-sheet-wide survey and
179 the published literature⁵⁴. Despite a long history of research into Iceland subglacial lakes<sup>22,37–
180 39,67,109–111</sup>, there is no formal complete inventory.

181
182 Subglacial lake locations and volumes are determined by the subglacial hydrology, which
183 results from subglacial water production and the surface and bedrock topography. The
184 distribution and production rate of subglacial water is controlled by the insulation and
185 pressure of the overlying ice sheet⁹⁹, geothermal heat (an extreme example is sub-ice
186 volcanism in Iceland²²), frictional heat generated by fast-flowing ice streams or outlet
187 glaciers⁹⁹, and surface water injections¹⁰⁰ (Fig. 1). The flow and storage of subglacial water is
188 governed by basal hydrologic potential¹⁰¹: The ice-surface gradient is ~10x as important as
189 the bedrock gradient in controlling hydrologic potential and is therefore likely a first order
190 control on lake genesis and stability¹⁰²; lake formation in bed depressions is favoured where
191 ice surfaces and basal slopes are flatter¹⁰¹. However, this does not account for spatio-

temporal variations in subglacial water pressure. Lake drainage occurs when the hydropotential seal is broken¹⁰³ or when water leakage from the basin produces efficient syphons¹⁰⁴.

Subglacial lake inventory

We constructed a new global inventory of subglacial lakes, based on lakes identified and published in the peer-review literature prior to June 2021, supplemented with 59 newly-identified lakes in Antarctica, from interrogating archived RES data collected between 2002-2019 (see Supplementary Information). The new lakes range from 170-9720 m in length (median: 1320 m) with 46 clustered in the subglacial Gamburtsev Mountains of East Antarctica beneath ice ~3000 m thick. We define a subglacial lake as any discrete water body at the base of an ice mass²⁵, without presuming a minimum area or depth. With this definition, lakes exist across a wide range of lengthscales²⁶; from small (~1 m) water bodies in basal cavities²⁷ to large (> 100 km) lakes that strongly influence ice dynamics by producing flat ice surfaces²⁸, and from shallow (<~1 cm) water patches connected by saturated sediments^{29,30} to deep (~100s m) lakes with their own internal circulation³¹⁻³⁵. Although no minimum subglacial lake size is presumed, the smallest lakes in the inventory are on the order of 0.0001 km³.

Using these criterion, we tallied 773 total lakes, including 675 from Antarctica, 64 from Greenland, 2 beneath Devon Ice Cap, 6 beneath the ice caps of Iceland, and 26 from valley glaciers (Fig. 3 and Supplementary Information). The resulting ~80% increase in the number of Antarctic subglacial lakes since the last inventory¹⁰⁸, largely due to new analyses of RES datasets^{45,106,112}, is still an order of magnitude fewer than predicted¹⁰⁷. Although ~90% of inventoried lakes are beneath the Antarctic Ice Sheet, this partly reflects their larger size, making them easier to identify¹⁰⁸, and the bias towards Antarctic surveys.

Subglacial lake setting and behaviour

Our inventory indicates a range of lake settings and behaviours, including: isolated, stable subglacial lakes with a large size range beneath Devon Ice Cap and the interiors of Antarctica and Greenland; large (median: 0.12 km³) but slowly (over months) cascading lake drainage beneath Antarctic ice streams; an order of magnitude smaller subglacial lakes 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 (on the order of 0.0001 km³) beneath valley glaciers that drain rapidly (<hour to days) (Figs. 3-4).

Stable lakes

Over 80% of subglacial lakes in our inventory are not active (i.e., 'stable' lakes in Fig. 3), which implies they are closed systems, or that inflow and outflow is approximately balanced. These predominantly RES-detected lakes occur where hydrological catchments are small¹⁰⁷ and basal melt rates are low or absent⁵⁵. 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 lakes¹¹³⁻¹¹⁵, including some >100 km long (e.g. Lake PEL¹¹⁶ and Lake Vostok^{28,113}). Large clusters of stable lakes occur beneath thick ice (>~3000 m) 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 Devon Ice Cap are 7.0 and 8.2 km in length and occur in

239 a similar setting to most stable lakes in Antarctica, beneath the central ice divide in bedrock
 240 troughs⁵⁵. In Greenland, RES-detected lakes tend to occur away from the relatively flat and
 241 cold bed beneath the ice sheet's interior, and are typically <2 km long, with the largest known
 242 lake 5.9 km long⁵⁴. Cluster of relatively large lakes occur in the East Greenland subglacial
 243 mountain chain with another cluster of smaller lakes in northern Greenland where the bed
 244 relief is subdued (Fig. 3a).

245 *Active lakes*

246 Active lakes in our inventory (Figs. 1, 3) have been predominantly identified, and their
 247 volumes quantified, from ice-surface elevation changes⁴⁹ and their outburst floods¹¹⁷.
 248 Because ice mechanics, ice-flow dynamics, and basal traction also influence the surface
 249 expression of lake drainage¹¹⁸, lake volume can be overestimated by altimetry¹¹⁹ and some
 250 ice-surface changes might not necessarily be due to subglacial lake activity^{6,102,120}. Despite
 251 these caveats, our inventory indicates that active lakes generally occur closer to ice margins
 252 than stable lakes. They also have large upstream hydrological catchments and/or form in
 253 areas where meltwater is abundant, either due to frictional melting beneath ice streams and
 254 outlet glaciers (e.g., Antarctica¹²¹), elevated geothermal heating (e.g., Iceland²²) and/or
 255 surface meltwater inputs (e.g., Greenland⁵⁷).

256
 257
 258 In Antarctica, surface-elevation histories of 140 active lakes show a median volume change of
 259 $\sim 0.12 \text{ km}^3$ per lake during drainage, which is an order of magnitude greater than for active
 260 lakes in Greenland, and three orders of magnitude larger than flood volume estimates of
 261 valley glaciers. This variation might partly reflect a bias in detection approaches as smaller
 262 lakes have yet to be identified in Antarctica. Most Icelandic subglacial lakes are similar in size
 263 to the active lakes in Greenland; an exception is Lake Grímsvötn, which drains up to $\sim 5 \text{ km}^3$
 264 of water because of a thick ice dam and high geothermal heat flux over a wide subglacial
 265 area^{22,39}.

266
 267 Our inventory includes 26 valley glaciers where outbursts from small subglacial water bodies
 268 have been recorded, including 20 in the European Alps^{24,40,117,122}. Transient storage in water-
 269 filled cavities is probably common to most glaciers^{123–127} but their small volume makes it
 270 difficult to detect their location and differentiate outbursts from background runoff.
 271 Identified outbursts of 10^{-4} to 10^{-5} km^3 of water might therefore represent high-magnitude
 272 low-frequency events^{128,129}. Although the sample size is small, glaciers with known outbursts
 273 tend to be relatively steep⁴⁰, consistent with the idea that faster sliding causes greater
 274 cavitation¹²⁴.

275 *Patterns of subglacial lake activity*

276 For lakes with at least one complete fill-drain cycle on record ($n = 36$), we identified five
 277 distinct patterns of ice-surface elevation change (Fig. 4a) based on the ratio of filling (ice
 278 surface uplift) and draining (ice surface subsidence) durations, as follows:

- 280
- 281 • Pattern 1: slow filling and rapid drainage (ratio > 1);
- 282 • Pattern 2: similar rates of filling and drainage (ratio ~ 1);
- 283 • Pattern 3: rapid filling and a longer period drainage (ratio < 1);
- 284 • Patterns 4 and 5: extended (multi-year) periods of quiescence, at a high stand and low
- 285 stand, respectively.

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Patterns 1, 3 and 4 are the most distinctive, while the difference between patterns 2 and 5 is less clear. For many 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 predictable⁷. Drainage of active subglacial lakes is variable^{6,15,22,129,130} and does not necessarily result in complete emptying²².

In Iceland, all lakes exhibit Pattern 1, with Grímsvötn draining every 1-10 years²² (roughly depending on ice dam thickness¹¹⁰) (Fig. 4a). Rapid drainage of these lakes can either take the form of exponentially rising discharge, consistent with drainage via subglacial channels^{39,103,131,132} and linearly rising discharge triggered by rapid subglacial lake refilling, flotation of the ice dam, or initial drainage as a sheet flood^{22,109,133}. This second drainage style is thought to explain rapid discharge (<1 hour) of water from subglacial cavities^{40,129}.

The fill-drain patterns of active lakes in Greenland (n = 7) and beneath valley glaciers (n = 26) are not well constrained due to limited data. In Greenland, three active lakes have extended high stands (Pattern 4), which suggests an external threshold controlling lake drainage initiation¹⁶. 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 drainage⁴¹ through seasonally-modulated fill-drain cycles in smaller lakes^{98,130}, or late summer drainage of larger lakes^{15,57}. Diurnal to seasonal drainage of water filled cavities is hypothesised to occur in response to meltwater driving unstable expansion of intervening orifices^{124,134,135} allowing them to connect^{136,137} and empty rapidly down subglacial channels^{41,129}.

In Antarctica, we observed all five drainage patterns⁷, likely reflecting 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^{7,138}. For example, the quiescent phase of lakes characterised 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^{7,104}, which includes both distributed and efficient drainage and changes in catchment scale water pressure¹³⁹. GlaDS 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^{7,104}.

Lake discharge and recharge relationships

Despite uncertainty in lake volumes derived from ice-surface elevation changes¹¹⁹, 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 relationship¹⁴⁰ between flood peak discharge and volume for marginal ice-dammed lakes, and is consistent with Nye’s theory of lake drainage via subglacial channels, which predicts that $b=1$ for any set of geometrically similar lakes¹⁴¹. This suggests that drainage of active lakes in Greenland and Antarctica predominantly occurs through subglacial channels^{7,142}. For a given V , Q_m is one to two orders of magnitude higher — and the flood duration proportionally shorter — for lakes in Greenland and Iceland compared with Antarctica (Fig. 4b); Antarctic lakes typically take

333 tens of months to drain, while lakes in Greenland and Iceland drain in days to weeks. This
334 difference is consistent with jökulhlaup theory in that the hydrologic gradient strongly
335 influences the drainage time scale^{21,141}. Steeper ice surfaces, and hence higher hydrologic
336 gradients, in Iceland and near the Greenland Ice Sheet margin produce greater subglacial lake
337 discharges of shorter duration than the shallower ice-surface slopes of Antarctica.
338 Conceivably, lakes beneath steep valley glaciers might drain even faster for a given lake
339 volume, but we lack observations to test this hypothesis.

340
341 The recharge rate of subglacial lakes also displays a consistent power-law relationship with
342 lake volume where different lake populations have similar recharge rates (Fig. 4c). Larger
343 lakes recharge faster than smaller lakes, indicating an underlying control on lake refilling
344 associated directly or indirectly with lake size. Although this relationship is not fully
345 understood, and recharge rates for smaller lakes is more uncertain as they are more difficult
346 to observe, we suggest that larger lakes are more likely to form in larger catchments
347 associated with greater meltwater input. A similar scaling relationship is found between the
348 area of subaerial lakes and their catchments¹⁴³.

349 **Subglacial lakes and ice dynamics**

350 Observations of the influence of subglacial lake activity on ice flow are limited^{10,11,13,15,90,144–}
351 ¹⁴⁶. Most of our understanding stems from numerical models^{103,147,148} and observations of
352 subglacial water drainage from ice marginal lakes^{149,150} and surface meltwater inputs to the
353 bed¹⁵¹.

354
355
356 Subglacial lake drainage can impact ice flow by altering basal water pressure and thus basal
357 traction¹⁴⁴ (Fig. 5). The size of this impact depends on whether, and to what extent, lake
358 discharge exceeds the hydrologic capacity of the existing subglacial drainage system. If lake
359 discharge is relatively small and enters an efficient (high hydrologic capacity) subglacial
360 drainage system, the ice velocity response will be limited¹⁴⁴ (Fig. 5). We expect these
361 conditions in regions with significant seasonal surface melt and steep subglacial hydrologic
362 potential, for example in Greenland and beneath valley glaciers^{54,130}.

363
364 Lake discharge that exceeds the hydrologic capacity of the existing subglacial drainage system
365 will cause a transient increase in basal water pressure and enhanced basal sliding¹⁴⁸ (Fig. 5).
366 Initial acceleration will be larger with a greater water pressure perturbation, for example
367 during higher lake discharge, or in a less efficient drainage system. Once discharge falls below
368 the drainage system's hydrologic capacity, water pressure decreases and high-pressure water
369 drains from connected areas of the bed, increasing basal traction and reducing sliding over a
370 large area¹⁴⁴. This behaviour is expected for lake drainages beneath relatively thin ice with
371 steeper hydrologic potential gradients, where subglacial channels are more likely to form and
372 take longer to close due to lower creep closure rates. For example, eight days after the 1996
373 drainage of Lake Grímsvötn began, downstream ice velocity had increased by 200% over an 8
374 km wide area around the subglacial flood path¹⁴⁴. This increase was followed by a 50%
375 deceleration in ice flow, which did not fully recover for 4 years¹⁴⁵. A similar pattern on a
376 shorter timescale has been observed¹⁶ in west Greenland, where, in the month following
377 drainage of a subglacial lake 6 km from the terminus of Isunnguata Sermia, mean ice velocity
378 reduced by ~25%.

379

380 Subglacial lake drainages beneath Thwaites Glacier, West Antarctica produced muted (<3%)
 381 ice-flow accelerations of several-days¹⁴⁶. During a 2012 drainage event, a 2% increase in
 382 velocity was followed by a ~3% deceleration over 6 months. In East Antarctica, drainage of
 383 two lakes beneath Byrd Glacier with a mean discharge of $70 \text{ m}^3 \text{ s}^{-1}$ increased ice flow by up to
 384 10% over the 75 km long glacier trunk between December 2005 and February 2007¹¹. Five
 385 years of continuous Global Positioning System data on Whillans and Mercer ice streams in
 386 West Antarctica revealed net ice-flow enhancement associated with a cascading lake drainage
 387 event¹⁴. This enhancement comprised three episodic ice flow accelerations of up to 4% over
 388 the two-year duration of flow enhancement but no subsequent slow-down to below the pre-
 389 drainage event ice velocity. Multi-year but more muted ice flow enhancement compared to
 390 observations in Iceland¹⁴⁴ are consistent with lower subglacial lake discharges of longer
 391 duration in Antarctica (Fig. 4b). As Antarctic ice streams are typically characterised by
 392 abundant subglacial water and saturated sediments^{152–154} lake drainages may have a limited
 393 additional impact on basal friction. Subdued deceleration on the falling limb of the lake
 394 drainage hydrograph is possible for several reasons. First, although theoretically possible^{7,142},
 395 formation of low-pressure channels is less likely due to shallow hydrologic potential gradients,
 396 which limit the generation of turbulent heat, and heat loss to colder overlying ice. Second,
 397 any low-pressure channels which form during peak discharge might have limited extent¹⁴²
 398 and are likely to be rapidly shut down once discharge wanes, limiting their ability to capture
 399 high-pressure water from adjacent connected areas.

400
 401 The net long-term impact of subglacial lakes on ice velocity depends on the balance of
 402 reduced motion (compared to ice motion in the absence of lakes) during lake filling¹⁴,
 403 enhanced motion during lake drainage, and reduced motion following the development of
 404 efficient downstream drainage, which might in some cases go below long-term average
 405 values. These effects depend on evolving and interrelated parameters such as lake filling rate,
 406 lake discharge, ice thickness and temperature, subglacial hydrologic gradient, and the
 407 hydrologic capacity of existing subglacial drainage. A universal association between subglacial
 408 lake activity and ice motion therefore seems unlikely; indeed, while one study¹³ suggests a
 409 net long-term reduction in ice motion can result from lake filling and drainage, another¹⁴
 410 found that a two-year period of lake filling, followed by a two-year period of lake drainage
 411 resulted in a positive velocity anomaly compared to long-term average.

412

413 **Landscape impact**

414 Subglacial lake drainages can erode, transport and deposit large volumes of sediment sub-,
 415 en-, and proglacially. Observations from contemporary subglacial lake outburst floods show
 416 evidence of mechanical erosion of subglacial sediments^{155–157}, rapid deposition of *eskers* and
 417 fracture fills within the ice mass^{158,159}, the construction of large outwash plains^{15,160–163} and
 418 proglacial debris flows on steeper slopes^{41,129}. In Iceland, repeated outburst floods are
 419 thought to dominate sediment supply to the proglacial foreland and contribute to the
 420 formation of substantial sandurs^{164,165}. Former subglacial lake drainage event(s) have been
 421 inferred from large (10^2 - 10^3 m wide) palaeo-channels cut into the bed^{166–172}, which can funnel
 422 ice flow and influence ice dynamics¹⁷³. For example, estimated peak discharge is 1.6 - 2.2×10^6
 423 $\text{m}^3 \text{ s}^{-1}$ for the Labyrinth, an outburst flood landscape in the McMurdo Dry Valleys,
 424 Antarctica¹⁶⁷, which is ~2 orders of magnitude greater than the largest subglacial lake floods
 425 observed today.

426

427 Sediment erosion and transport during lake drainage is thought to be roughly proportional to
 428 discharge^{161,174}, although modulated by substrate, sediment availability, and the flood route
 429 and hydrograph shape^{157,175}. In particular, rapidly-rising (linear increase in discharge)
 430 subglacial lake outburst floods in Iceland cause significant landscape modification¹⁶¹. For
 431 example, the 1996 jökulhlaups from Grímsvötn drained 3.2 km³ of water within 40 hours, had
 432 a peak discharge of 4 x 10⁴ m³ s⁻¹, and flooded the entire outwash plain²². The sediment yield
 433 was ~1.8 x 10⁸ m³, equating to 0.3 m (65,700 m ka⁻¹) of erosion across the glacier bed impacted
 434 by floodwaters^{164,176,177}. This erosion compares to average glacial erosion rates for Vatnajökull
 435 Ice Cap of ~0.32 m ka⁻¹¹⁷⁸.

436

437 Similar rapid drainages from lakes beneath valley glaciers^{41,122} (<hours to days) and the
 438 Greenland Ice Sheet¹⁶ (<1 month) also result in substantial geomorphic change. Small
 439 outburst floods caused by release of subglacial water stored in cavities beneath South
 440 Tahoma Glacier on Mount Rainier, Washington, typically transform into debris flows as they
 441 incorporate proglacial sediment on the valley slopes^{117,129,179}. Between 1967 and 1994 at least
 442 23 outburst events have occurred, resulting in significant incision of sediment and stagnant
 443 ice in the upper catchment (>20 mm a⁻¹), and aggradation of up to 10⁷ m³ sediment in the
 444 downstream valley¹⁷⁹. The 2015 outburst of a small (<1 km²) subglacial lake close to the
 445 margin of Isunguata Sermia, western Greenland, flooded the foreland, aggrading the
 446 proglacial channel by up to 8 m close to the outlet.

447

448 The geomorphic impact of Antarctic subglacial lake drainages is constrained by large
 449 bedrock^{168,169,171} palaeo-channels, active¹⁸⁰ and palaeo¹⁸¹ sediment channels, and eroded or
 450 restricted landform growth at the grounding line (e.g. grounding zone wedges)¹⁸¹. Larger
 451 Antarctic subglacial lakes (Fig. 3b), with longer duration drainage might enable the transport
 452 of more sediment if there is an abundant supply¹⁸². However, gradual leakage of water from
 453 Antarctic lakes⁸ and the lower mean discharge (Fig. 4b) suggest they might be less effective
 454 geomorphic agents than lakes in other settings.

455

456 **Subglacial ecosystems**

457 Subglacial lacustrine systems store, transform and export carbon and nutrients^{9,183}. Although
 458 these fluxes are poorly understood due to limited direct observations, dissolved elements and
 459 sediments in subglacial discharge and any turbulent mixing resulting from discharge
 460 dynamics, can enhance primary productivity in downstream environments such as proglacial
 461 lakes, fjords and the polar oceans¹⁸⁴. The hydrological and glaciological context of subglacial
 462 lakes influence *in situ* geochemical conditions which, in turn, control the metabolic regime
 463 and distinct genomic adaptations of resident microorganisms. To date only four active
 464 subglacial lakes have been directly sampled for microbial analyses^{1,63,66,67} (Fig. 3). However,
 465 these limited samples retrieved directly from subglacial lake water and sediments confirm the
 466 presence of active microbial communities¹⁸⁵.

467

468 Subglacial lacustrine ecosystems (Fig. 6) must contend with permanent darkness, high
 469 pressures and low temperatures. In the case of hypersaline lakes, cells must also manage salt
 470 stress. The absence of sunlight requires that microorganisms harness energy from
 471 thermodynamically favourable and predictable chemical reactions known as “*redox*”
 472 *reactions*¹⁸⁶ with primary production via *chemosynthesis*^{1,2,63,187,188}. A wide range of materials
 473 provide electrons for reduction in the subglacial setting, including geological sources such as

474 bedrock minerals, either *in situ* or scoured during lake drainage and refill, reduced compounds
475 such as sulphur from geothermal fluids, or biological sources such as the by-product of
476 microbial sulphate reduction or *methanogenesis*. Organic matter might be transported from
477 the surface or available from 'legacy' ecosystems overridden by advancing ice sheets
478 including marine or terrestrial *necromass* as well as any labile organic matter in underlying
479 sediments^{189,190}. Any available oxygen in the subglacial environment would be rapidly
480 consumed through microbial oxidation of reduced substrate, including organic matter or
481 inorganic compounds such as sulphide, ammonia, methane or Fe(II). Given sufficient electron
482 donors and no new input of oxygen, subglacial systems will be driven to anoxia, conditions in
483 which some microorganisms can respire using diverse alternate electron acceptors, with
484 predictably decreasing energetic yield. Evidence for iron reducers, denitrifiers, sulphate
485 reducers and methanogens, which respire Fe(III), nitrate, sulphate and carbon dioxide,
486 respectively, have all been observed in subglacial lake settings^{1,191–193}.

487

488 Active lakes along continental margins, such as Whillans Subglacial Lake (Fig 6a) may
489 accumulate solute-rich porewaters generated by upstream basal melt. The formation of steep
490 chemical, physical and biological gradients at lake water-sediment interfaces can influence
491 microbial abundance and productivity¹⁹⁴. Accumulated solutes and recycled organic matter
492 can provide nutrients for energy-yielding metabolisms and cellular biosynthesis. Data from
493 Whillans Subglacial Lake (Fig 6a), indicate that ammonium ions are an important energy
494 source for biosynthesis^{2,195}, and taxa related to N-cycling microorganisms, for example, the
495 betaproteobacterium "*Candidatus Nitrotoga arctica*", are abundant^{1,196}. This group is known
496 to mediate the oxidation of nitrite to nitrate, an important step in *nitrification*¹⁹⁷. Sediment-
497 water interfaces, where ions diffuse upwards into the water column^{1,198}, create a niche for
498 enhanced microbial activity and higher rates of dark carbon fixation³. Transitioning into lake
499 sediments, microbially-mediated methane¹⁹¹ and sulphur oxidation¹⁹² are key processes.

500

501 Active subglacial lakes below Vatnajökull Ice Cap, Iceland (Fig 6b), provide a redox gradient of
502 oxygenated glacial melt and reducing geothermal fluid, which can also support
503 *chemolithotrophic* communities¹⁸⁸. Microbial assemblages in western Skaftá Lake, for
504 example, utilize sulphide, sulphur or hydrogen as electron donors and oxygen, sulphate or
505 CO₂ as electron acceptors^{63,67}. Similarities in the microbial community between distinct lakes
506 below Vatnajökull suggest a subsurface hydrological connectivity that can seed these
507 transient lakes with cellular biomass and nutrients discharged in jökulhlaups¹⁸⁸, which
508 ultimately impacts downstream biological communities including fishing grounds¹⁹⁹.

509

510 Greenland's active subglacial lakes (Fig 6c) are largely thought to be filled by the rapid
511 injection of surface melt via moulins⁵⁷, which would provide oxygen and photosynthetically
512 derived organic matter, supporting aerobic metabolism. This seasonal delivery could create
513 physical turbulence, scouring legacy organic material as drainage systems expand²⁰⁰. Aerobic
514 respiration would eventually exhaust the supply of oxygen, driving the system to anoxia as
515 winter temperatures freeze out fresh surface melt. Although Greenland subglacial lakes have
516 yet to be directly accessed, multiple lines of evidence suggest microbial methane production,
517 an anaerobic process, occurs at its bed^{201–203}. In fact, Greenland lakes may be quite diverse
518 with recent evidence suggesting hypersaline or geothermally heated systems²⁰⁴, with both
519 scenarios shaping microbial communities.

520

521 Significantly less is known about the deep, closed-basin lakes under the thick (>1 km) interior
522 of ice sheets, although they are also anticipated to host ecosystems, due to possible
523 geothermal stirring of nutrients³¹ and oxygen derived from sediments and/or the ice above.
524 Samples of accretion ice above Lake Vostok contained 10s-100s of DNA-containing cells per
525 ml of melt water²⁰⁵ and while these numbers are low compared to Whillans Subglacial Lake,
526 which contained ~100,000 cells in the same volume, uncontaminated samples from Lake
527 Vostok water remain elusive⁶⁸. Regardless, water column samples collected at a discrete
528 depth might not be representative of water body dynamics, as subglacial lakes can be
529 thermally unstable³, driving internal mixing³¹. Hypersaline lakes beneath Devon Ice Cap⁵⁵
530 present an intriguing end-member system, where microbes must survive in high solute
531 concentrations.

532

533 **Future evolution of subglacial lakes**

534 This Review has identified a range of subglacial lake behaviours (Fig. 7) providing a proxy for
535 how their role might evolve in the future under changes in local conditions. This includes large
536 stable lakes beneath ice mass interiors, slowly cascading lake drainage beneath Antarctic ice
537 streams (Fig. 7a), faster draining smaller lakes beneath the Icelandic ice caps and ablation
538 zone of the Greenland Ice Sheet (Fig. 7b-c), and water-filled cavities that drain rapidly beneath
539 valley glaciers (Fig. 7c). This progression coincides with steeper ice-surface slopes, thinner ice,
540 and enhanced meltwater inputs. Similar temporal changes are expected as climate warming
541 causes ice mass loss, recession and thinning^{206,207}, increased surface²⁰⁸ and basal²⁰⁹ (due to
542 faster ice flow and surface melt inputs) melting, inland expansion of ablation areas^{210,211}, and
543 ice acceleration, for example, due to thinning and loss of buttressing ice shelves^{212,213}.

544

545 In general, subglacial lakes are predicted to be less abundant beneath smaller ice masses as
546 recession produces steeper mean surface slopes (higher hydrologic gradients) reducing the
547 potential for hydrologic minima^{102,105}. Thus, as ice masses shrink, the relative area of the bed
548 occupied by subglacial lakes should decrease (Fig. 7). This decrease is consistent with the
549 reduction in water volume stored in Icelandic ice-dammed lakes since the early 20th Century
550 as their ice dams lower in response to climate warming²² and the drainage of a subglacial lake
551 beneath Crane Glacier, Antarctic Peninsula, due to ice-surface steepening following ice shelf
552 collapse¹². Warming of ~1.8°C in Greenland²¹⁴ is predicted to lead to irreversible mass loss
553 over multi-millennia, while 2-3°C warming in Antarctica^{215,216} is likely to cause substantial
554 grounding-line retreat and the collapse of major marine drainage basins in West Antarctica²¹⁷.
555 Thus, ice-surface steepening due to grounding line retreat and loss of ice shelves is likely to
556 trigger lake drainage and reduce the potential for subglacial ponding. In general, East
557 Antarctic Ice Sheet decline is predicted to be initiated at ~6-7°C warming and will likely be
558 dominated by the melt-elevation feedback^{215,216,218}. Here, subglacial lakes are likely to remain
559 relatively stable over multi-millennia timescales, and might even increase in number around
560 the margin due to enhanced surface melt and its input to the bed.

561

562 Although we predict a general decline in lake abundance and total water volume as large ice
563 masses shrink, spatial heterogeneity in subglacial lake distribution beneath the Antarctic and
564 Greenland ice sheets (Fig. 3) suggests this pattern is complicated by local factors including
565 bed roughness, basal thermal regime and geothermal heat flux¹⁰⁷ (Fig. 7). Rough beds can
566 promote cavitation¹²⁵, and have more topographic depressions for subglacial water storage.
567 For example, lakes are clustered within the Ellsworth Subglacial Highlands¹¹² and subglacial

568 Gamburtsev Mountains⁴⁵ in Antarctica. These lakes, particularly associated with deep
569 tectonic troughs (e.g. Lake Vostok)¹¹⁴, are more likely to withstand ice sheet changes. Basal
570 thermal regime controls the availability of water to form lakes and will change in response to
571 ice sheet evolution²¹⁹ and reorganisation of water or ice flow^{220–222}. Currently, there are
572 abundant large, stable lakes beneath the warm interior of Antarctica whereas the near
573 freezing interior of Greenland is largely devoid of lakes⁵⁴ (Fig. 3). Increases in the aerial extent
574 and intensity of basal melt beneath the Greenland Ice Sheet²⁰⁹ could facilitate inland
575 expansion of new subglacial lakes. Any increase in saturated sediments would facilitate
576 enhanced rock-water interactions liberating solutes for microbial processes. Thinning of ice
577 overlying subglacial magma systems – such as those beneath the West Antarctic Ice Sheet²²³,
578 Iceland²²⁴ and Chile²²⁵ – could stimulate volcanic activity^{226–228}, resulting in more numerous
579 and active lakes.

580

581 Mountain glaciers are undergoing widespread recession and thinning in response to climate
582 warming²²⁹. However, the link between climate and subglacial storage beneath these smaller
583 ice masses is poorly constrained and likely to be strongly influenced by local factors. For
584 example, debris covered glaciers are undergoing a reduction in surface gradient caused by a
585 down-glacier increase in debris thickness that focuses the highest rates of surface lowering in
586 the mid-ablation zone²³⁰. This change in gradient might enhance storage of subglacial water
587 in these glaciers. The storage capacity of subglacial cavities¹²⁵ will also control the distribution
588 and extent of ponding at the bed and is likely to be a key mechanism beneath mountain
589 glaciers (Fig. 7c). Cavitation is expected to be greatest on rough and steep beds and where
590 basal sliding is high^{124,134}. Thus, steep valley glaciers on rough beds could have an abundance
591 of small, seasonally draining subglacial lakes⁴⁰ which could become more common as melt
592 inputs increase basal sliding. Finally, the susceptibility of a glacier to surging has been linked
593 to increased basal water storage beneath longer (and shallower) glaciers and between cold-
594 dry and warm-temperate climate extremes²³¹.

595

596 Larger, stable lakes tend to be located beneath or near ice sheet divides where surface slopes
597 are generally low while hydrologically active lakes occur closer to ice margins where the
598 hydrologic gradient is steeper (Fig. 3). Hence an evolution from ice sheet centre to margin
599 dictates lake formation and associated hydrological processes. Ice masses with steeper
600 hydrologic gradients (Fig. 7a-b), produce higher subglacial lake discharges of shorter duration
601 (Fig. 3b)^{21,141} and ice surface melt and rainfall inputs to the bed can trigger^{122,129} or modulate
602 drainage^{57,130}. For example, outburst floods from beneath South Tahoma Glacier usually occur
603 during hot or rainy weather in summer or early autumn, and the probability of an outburst
604 increases with temperature¹²⁹. As surface melt intensifies and expands inland²¹⁰ and where
605 ice-margin retreat and ice shelf loss causes hydrologic gradients to steepen, we expect more
606 vigorous lake activity over a greater proportion of the bed (Fig. 7). In particular, ablation zone
607 expansion could create new drainage pathways, facilitating the drainage of formerly isolated
608 lakes beneath ice mass interiors, such as Greenland⁵⁴. Although subglacial lakes are currently
609 isolated from surface processes in Antarctica, recent evidence of water penetrating to the
610 bed of grounded ice in the Peninsula²³² hints at a future with increasing coupling between
611 supraglacial and basal hydrology near the grounding line as surface melt intensifies²¹⁰.
612 Atmospheric warming of ~3°C could trigger widespread collapse of large ice shelves fringing
613 Antarctica^{216,218} resulting in steepening of ice-surface slopes¹². The stability of Antarctic ice
614 shelves is therefore likely to play a key role in controlling any shift to more rapid lake drainage.

615

616 Large melt inputs into a subglacial lake can trigger flotation of the ice dam, causing a sheet
617 flood with a rapidly rising discharge²² and mobilisation of large volumes²² of
618 sediment^{164,176,177}. These catastrophic drainages might become more frequent with large and
619 rapid surface melt and rainfall inputs²³³ and ice dam thinning, providing a potential hazard to
620 downstream populations and infrastructure in glaciated mountain regions (Fig. 7c). The
621 increased erosive capacity may also (partially) remove sediment deposits contained within
622 lakes reducing their potential as climate archives. The link between deglaciation and drainage
623 periodicity is less clear. In Iceland periodicity has been related to ice dam thickness¹¹⁰.
624 However, there is no clear difference in drainage periodicity between lakes in Iceland and
625 Antarctica⁷, which is supported by the consistent power-law relationship between recharge
626 rate and lake size in different settings (Fig. 4c), suggesting a more complex relationship.

627

628 This conceptual model allows us to consider how future evolution of subglacial lake drainage
629 (Fig. 7) will impact the environment and ice dynamics. Increased lake activity is likely to
630 enhance the hydrological and biogeochemical connectivity between lakes and their
631 surroundings¹⁸⁸ locally enhancing transport of sediment, solute and nutrients to downstream
632 ecosystems^{9,183} and water across the grounding line of marine-terminating glaciers⁶. The
633 regional impact of lakes drainages on ecosystems is likely to shift through time as drainage
634 direction is highly sensitive to small changes in ice sheet geometry^{105,234}. Increased routing of
635 water through lakes coupled with steepening ice-surface slopes will impact melt-refreeze
636 patterns at the ice-water interface potentially disrupting lake stratification and circulation
637 patterns, with implications for the lake ecosystem and sediment deposition¹. Enhanced
638 nutrient mixing might promote microbial productivity throughout the water column, however
639 large discharge of sediments could reduce light penetration in proglacial waters inhibiting
640 photosynthetic production. Large, episodic surface meltwater inputs into subglacial lakes⁵⁷
641 ¹²⁹ provide a supply of oxidants, sediment, microbes and labile organic matter, which might
642 seasonally enhance oxic processes (Fig. 6c). Conversely, scoured beds, reduced time for rock-
643 water interactions and dilution by supraglacial meltwaters could inhibit some subglacial
644 biogeochemical activity, but the overall impact is uncertain because we have yet to access
645 and sample the full range of lake environments. Increased discharge of subglacial lake water
646 at marine terminating glaciers or ice streams can modify freshwater budgets and nutrient
647 supply within sub-ice-shelf cavities and the wider ocean^{6,21}. This pattern will likely be
648 modulated by the environment into which the water discharges and circulation in the sub-ice
649 shelf cavity or fjord.

650

651 Subglacial lake drainage across grounding lines can enhance plume-driven frontal ablation^{235–}
652 ²³⁷, impacting ice margin/ shelf stability^{6,20}. Embayments at subglacial lake outflow points⁶,
653 and surface depression and crevassing of ice above the grounding line following the 2003
654 drainage of Subglacial Lake Engelhardt, West Antarctica²⁰ demonstrate the potential of lake
655 drainage events to enhance frontal ablation. An expanding ablation zone will increase the
656 chances of lake drainage entering an existing, efficient subglacial drainage system¹⁴⁴ and thus
657 having a limited impact on ice dynamics. However, higher discharge floods of shorter duration
658 (Fig. 4b) are more likely to exceed the existing downstream hydrologic capacity, resulting in
659 large initial ice-flow enhancements¹⁴⁴, followed by a reduction in ice flow as channels develop
660 and discharge falls below the system's hydrologic capacity (Fig. 7)^{15,145}. More extensive and

661 long-lived efficient subglacial drainage will increase the probability that the ‘fill-drain’ cycle of
 662 a subglacial lake causes net reduction in ice flow.

663

664 **Outlook**

665 We have presented a new global inventory of 773 subglacial lakes: 675 in Antarctica, 64 in
 666 Greenland, 2 under Devon Ice Cap, 6 in Iceland, and 26 under valley glaciers. Due to existing
 667 data availability our inventory is heavily skewed towards Antarctica (Fig. 3), yet hydrological
 668 predictions suggest there are many thousands of unobserved subglacial lakes^{105–107}.
 669 Therefore, future efforts should aim to expand the identification and characterisation of lakes
 670 below valley glaciers, ice caps and in Greenland. In particular, for mountain glaciers, the
 671 sudden drainage of lakes poses a hazard to downstream populations^{125,238}, thus, a better
 672 understanding of water storage and drainage beneath glaciers in vulnerable areas and how
 673 the risk might change due to climate warming should be a priority. Improvements in spatial
 674 and temporal coverage and resolution of satellites^{6,88,91,95}, increased availability of high-
 675 resolution multi-temporal DSMs^{97,239} coupled with lake detection automation⁸¹ and machine
 676 learning²⁴⁰ will likely allow these gaps to be filled, particularly for lakes that are smaller and
 677 traditionally more difficult to detect^{54,58,241}. Future satellite missions, including ESA’s
 678 Copernicus Polar Ice and Snow Topography Altimeter (CRISTAL)^{88,90} and ESA’s P-band Biomass
 679 Earth Explorer²⁴², will help to identify and monitor long-term changes in subglacial lakes. An
 680 orbiting radar sounder could also provide unprecedented spatial and temporal coverage of
 681 Earth’s cryosphere, as well as a homogenous sampling of the ice sheet at a uniform radar
 682 frequency and quality^{243,244}.

683

684 Another challenge is to improve our understanding of subglacial lake fill-drain cycles.
 685 Subglacial lakes exhibit diverse drainage patterns (Fig. 4a), but only 36 lakes have
 686 observations spanning at least one complete cycle; longer-term records of how they respond
 687 to changes in climate are restricted to Iceland²² and some valley glaciers⁴¹. Operational, near-
 688 real-time monitoring of subglacial lake activity from polar orbiting satellites is already
 689 providing improvements in the coverage and length of observational records. Integration of
 690 remote observations and numerical modelling has potential for characterising the timing,
 691 volumes and processes associated with lake drainage and refilling. For example, application
 692 of passive seismology (Fig. 2a), which monitors acoustic vibrations caused by turbulent
 693 subglacial water flow²⁴⁵, would allow for continuous monitoring of subglacial lake dynamics,
 694 and the evolving hydrologic properties²⁴⁶ of water inflow and outflow. Satellite and
 695 geophysical observations can, in turn, be used to constrain and force catchment-scale
 696 numerical ice sheet models^{7,247} to analyse fill-drain characteristics, and their coupling with
 697 the wider hydrological system and overlying ice. A longer-term (centennial to millennial)
 698 perspective on past lake drainages and their role in topographic evolution beneath retreating
 699 ice sheets can be gleaned from geological landform analysis and sediment records^{170,181,248},
 700 and the inclusion of sediment dynamics in subglacial hydrology models^{249,250}.

701

702 Coupling between lake volume and ice motion is currently poorly constrained, and requires
 703 data with high temporal resolution, ideally gapless acquisition over one or more fill-drain
 704 cycles, and broad spatial coverage to quantify the downstream dynamic effect of lake
 705 discharge. Coupled subglacial hydrology and ice dynamic modelling can utilize these data to
 706 determine the primary drivers on ice motion. Efforts must focus on constraining the initial
 707 ice dynamic response and net long-term impact of subglacial lake drainages for a range of

708 discharge magnitudes and glaciological settings. Recent (e.g. ESA's Sentinel-1 constellation)
709 and planned (e.g., NASA-ISRO SAR (NISAR)) SAR-imaging satellite missions with high spatial
710 resolution (2.7-22 m) and short repeat cycles (6 to 12 day) will improve the likelihood of
711 obtaining high quality ice motion and surface topography data from image cross-correlation
712 and (Differential) Interferometric Aperture Radar²³⁹ even for ice masses that experience
713 significant surface melting or snowfall. Coupling of subglacial and ice dynamics models will
714 allow analyses of physical drivers of lake stability and future lake behaviour.

715
716 Direct access into subglacial lakes representing the range of hydrologic, dynamic and mass
717 balance regimes is needed to understand the factors that control metabolic productivity and
718 taxa diversity of resident microbial communities. Biogeochemical measurements from a
719 range of subglacial conditions will inform global carbon budgets and support predictions of
720 how climate change may alter the function of these ecosystems. Replicate samples from
721 subglacial lakes can inform the stability of communities and pace of ecosystem change.
722 Because discharge from subglacial lakes likely has important implications for downstream
723 ecosystems, continuing to identify and characterize discharge points, particularly at marine-
724 terminating systems, is critical. Advances in automated underwater vehicles, which can scan
725 larger areas along coastal margins, particularly along underexplored grounding zones, will be
726 required.

727
728 Drilling capabilities that enable clean, direct access into subglacial lakes are essential for
729 advancing our understanding of resident microbial communities. Recently, hot water drills
730 have been designed with systems that filter and irradiate melt water used in drilling^{251,252}.
731 Further development of these systems for logistical efficiency and increased automation,
732 coupled with progress in thermal probe technologies²⁵³ that enable *in situ* measurements and
733 acquisition of samples for microbial analysis^{254,255}, will be crucial for exploring deep subglacial
734 lakes^{253,255}.

735
736 Geophysical innovations will reveal more about the physical properties of subglacial lakes and
737 how they change through time. Autonomous phase-sensitive radio-echo sounding (ApRES)²⁵⁶⁻
738 ²⁵⁸ can determine vertical strain in the ice, glean information on the ice-dynamic response
739 to lake filling and draining, and basal melt/freeze rates, providing critical input data for water
740 circulation models. Next-generation full-waveform inversion techniques for interpreting
741 active-source seismic observations²⁵⁹ provide more precise constraints on the structure of
742 subglacial water systems, particularly for regions with thin water cavities and/or sediment
743 layers²⁶⁰. EM approaches provide constraints on the pore-water properties of water-
744 saturated subglacial sediment packages and the salinity of lake waters. Developments in time-
745 lapse geophysical monitoring, innovations in miniaturisation, autonomy, cost reduction, and
746 power savings for geophysical sensors⁷⁰, as well as integration of different geophysical
747 approaches (e.g. EM and seismic exploration to derive lake salinity^{84,261}) with numerical
748 modelling of lake hydrology³¹ will refine the spatial and temporal resolution of our
749 understanding of subglacial lakes. Together, these developments will provide a more holistic
750 understanding of how subglacial lakes interact with the wider hydrological system, including
751 poorly resolved components such as the flow of water within sediments and rocks²⁶².

752 753 **Summary**

754 The storage of water under ice masses is widespread and occurs in a range of settings²⁶ and
755 climatic regimes. This diversity has resulted in a wide spectrum of subglacial lake
756 environments, behaviours and impacts. Our global inventory of 773 lakes suggests this
757 diversity is related to the characteristics of overlying ice masses and the topography and
758 material of the ice bed. Grounding-line retreat²¹⁵ and ice shelf loss of the West Antarctica Ice
759 Sheet^{216,218} may result in fewer and smaller lakes that drain more rapidly. As melt intensifies
760 and expands further inland due to climate warming (e.g., in Greenland²⁰⁸) more subglacial
761 lakes might become coupled to surface melt and rainfall inputs, increasing the number of
762 active lakes and the potential for catastrophic drainages. Beneath small ice caps and valley
763 glaciers data on subglacial lakes is limited (Fig. 3) and the impact of local controls (e.g., bed
764 roughness) and glacial processes (e.g. debris covered glaciers) is likely to result in significant
765 variations in their response to warming.

766
767 Increased lake activity will drive large initial ice-flow enhancements followed by a reduction
768 in ice flow as channels develop and discharge falls below the system's hydrologic capacity.
769 More extensive and long-lived efficient subglacial drainage will increase the probability that
770 a fill-drain cycle of a subglacial lake will lead to a net reduction in ice flow. As hydrological
771 connections are made between lakes, their subglacial surroundings, and the ice surface,
772 fluxes of sediment, solute and nutrients will be temporarily stored and then released
773 downstream, modulating the nourishment of downstream subglacial and proglacial
774 ecosystems and providing conditions for both aerobic and anoxic processes. The future of
775 subglacial lake investigation is likely to be driven by innovations in geophysical techniques and
776 drilling technologies, and advances in our ability to monitor subglacial lake activity and ice
777 motion in near-real-time from satellites and *in situ* instrumentation. Integrated programmes
778 that bring together complimentary techniques and numerical modelling are likely to lead the
779 way in advancing our understanding of the current and future role of subglacial lakes.

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796

797 **Author Contributions:**

798 SJL led the project and assembled the authorship team. SJL produced the global subglacial
799 lake inventory with input from all authors. YL, RJS and KW identified the additional new
800 Antarctic subglacial lakes included in the global inventory and wrote the Supplementary

801 Materials section. The section on lake discharge-recharge relationships came from
 802 discussions between SJL, FN and AJS. KW produced Figure 1; SJL produced Figures 3, 4 and 5,
 803 with help from FN and AJS; JM produced Figure 6; AR and SJL produced Figure 7; and MS, HAF
 804 and AR contributed Figure 2. All authors contributed to writing and editing of the manuscript
 805 prior to submission.

806

807 **Competing Interests:**

808 The authors declare no competing interests.

809

810 **Glossary**

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

812 **Basal hydrologic potential.** *Total head determined by bed topography, weight of the overlying*
 813 *ice, and basal drainage characteristics.*

814 **Jökulhlaup.** *Glacial outburst flood from a subglacial or proglacial lake.*

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

817 **Equilibrium Line Altitude.** *The elevation at which the accumulation and ablation of ice are in*
 818 *balance over a given time period (typically, one year).*

819 **Esker.** *A slightly sinuous ridge of glaciofluvial sediments (e.g. gravels) that record the former*
 820 *drainage of meltwater under, in or on top of ice masses.*

821 **Cold based ice.** *Ice below freezing at the ice-bed interface and thus frozen to the underlying*
 822 *substrate*

823 **Redox reactions.** *chemical reactions where a molecule becomes reduced and another becomes*
 824 *oxidized.*

825 **Chemosynthesis.** *the fixation of single carbon molecules into organic biomass using energy*
 826 *from the oxidation of inorganic electron donors.*

827 **Methanogenesis.** *a metabolic process that yields energy for microbial growth while releasing*
 828 *methane.*

829 **Necromass.** *organic material consisting of or derived from dead organisms*

830 **Nitrification.** *the oxidation of reduced nitrogen compounds to nitrite or nitrate.*

831 **Chemolithotrophic.** *the metabolic oxidation of inorganic compounds to yield energy and fix*
 832 *single-carbon compounds into organic biomass*

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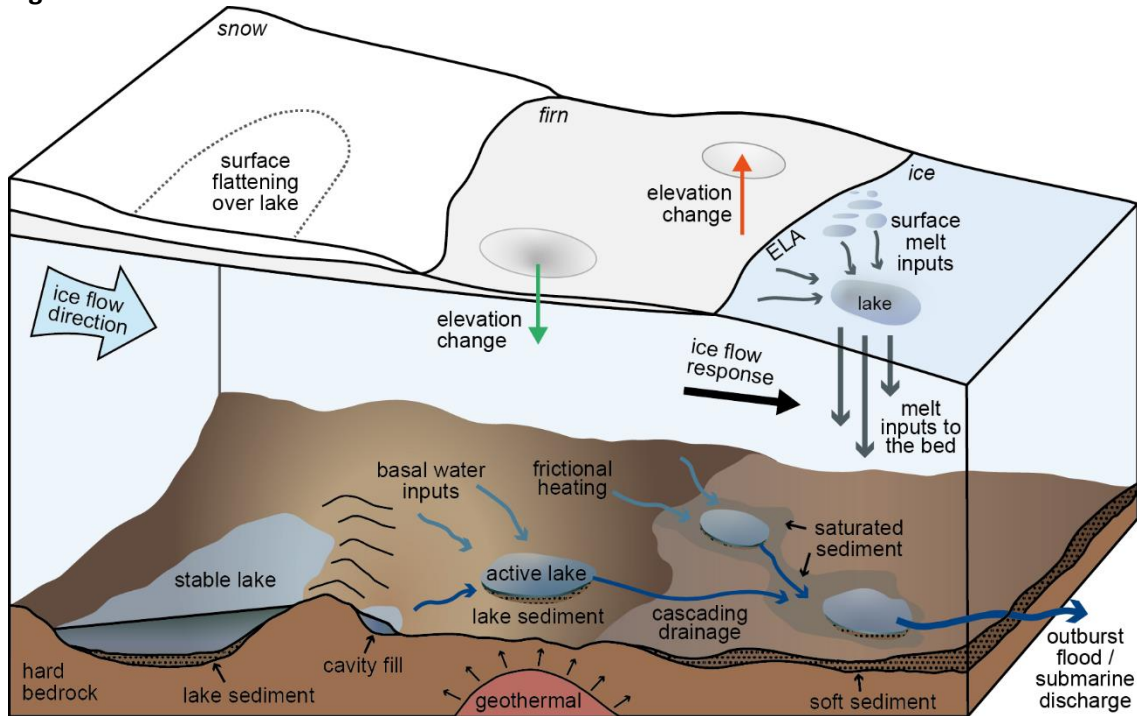
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1451 **Figures**

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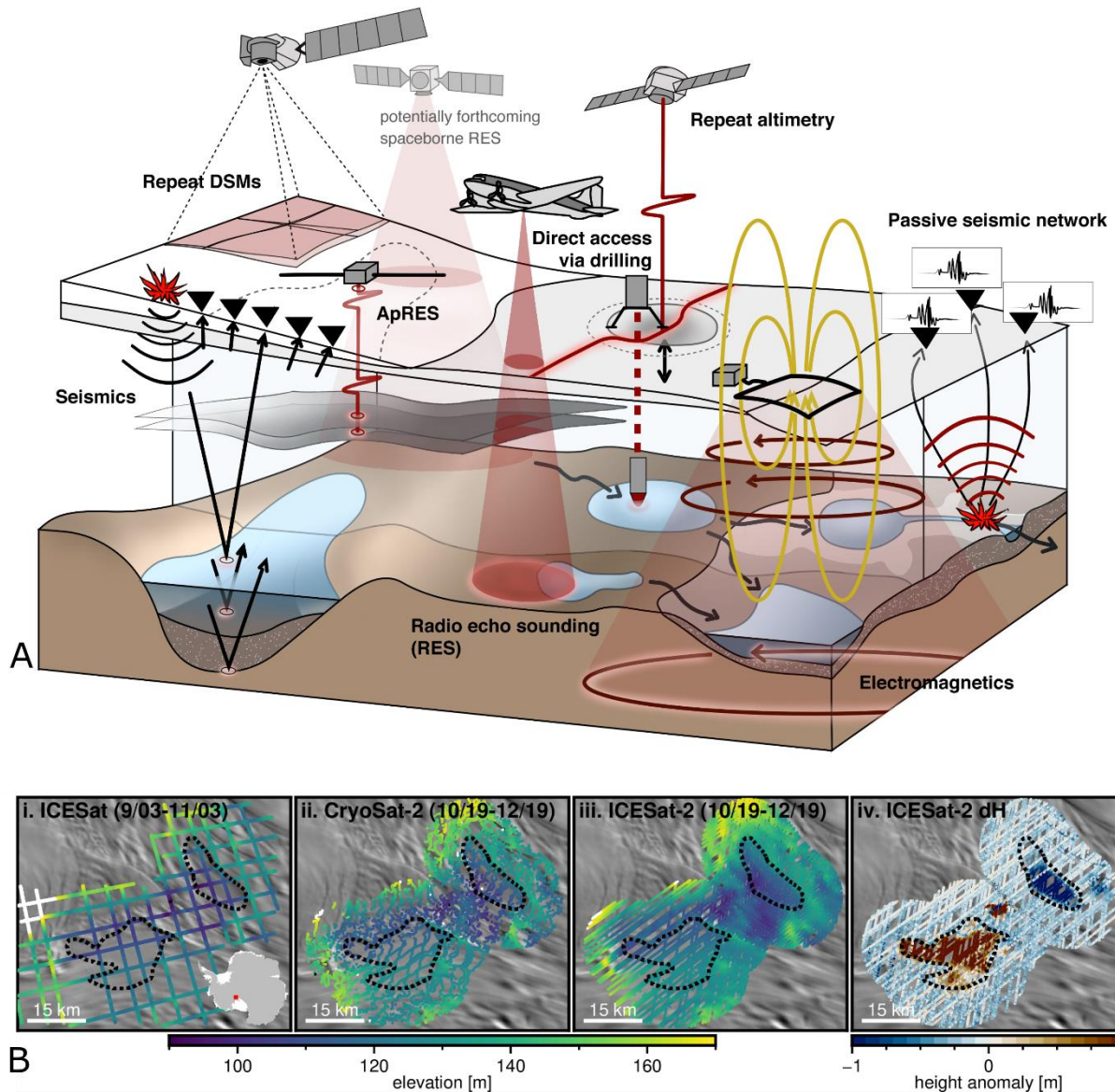
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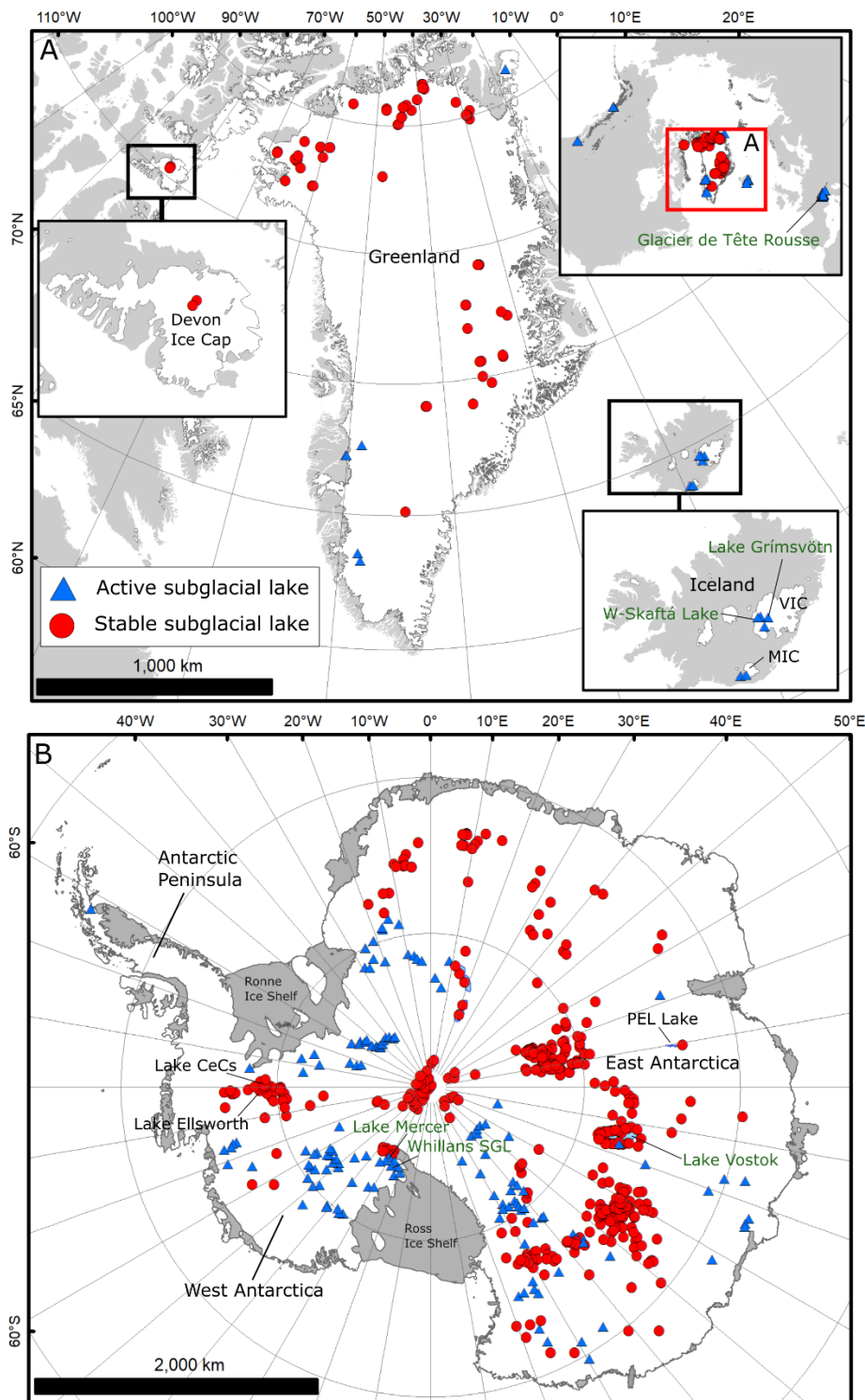
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Figure 1. Different settings of subglacial lakes and their links with other parts of the hydrological system of an ice sheet or a glacier. Lakes can range from stable systems trapped in topographic (and hydrologic potential) depressions towards the 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), localised 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.



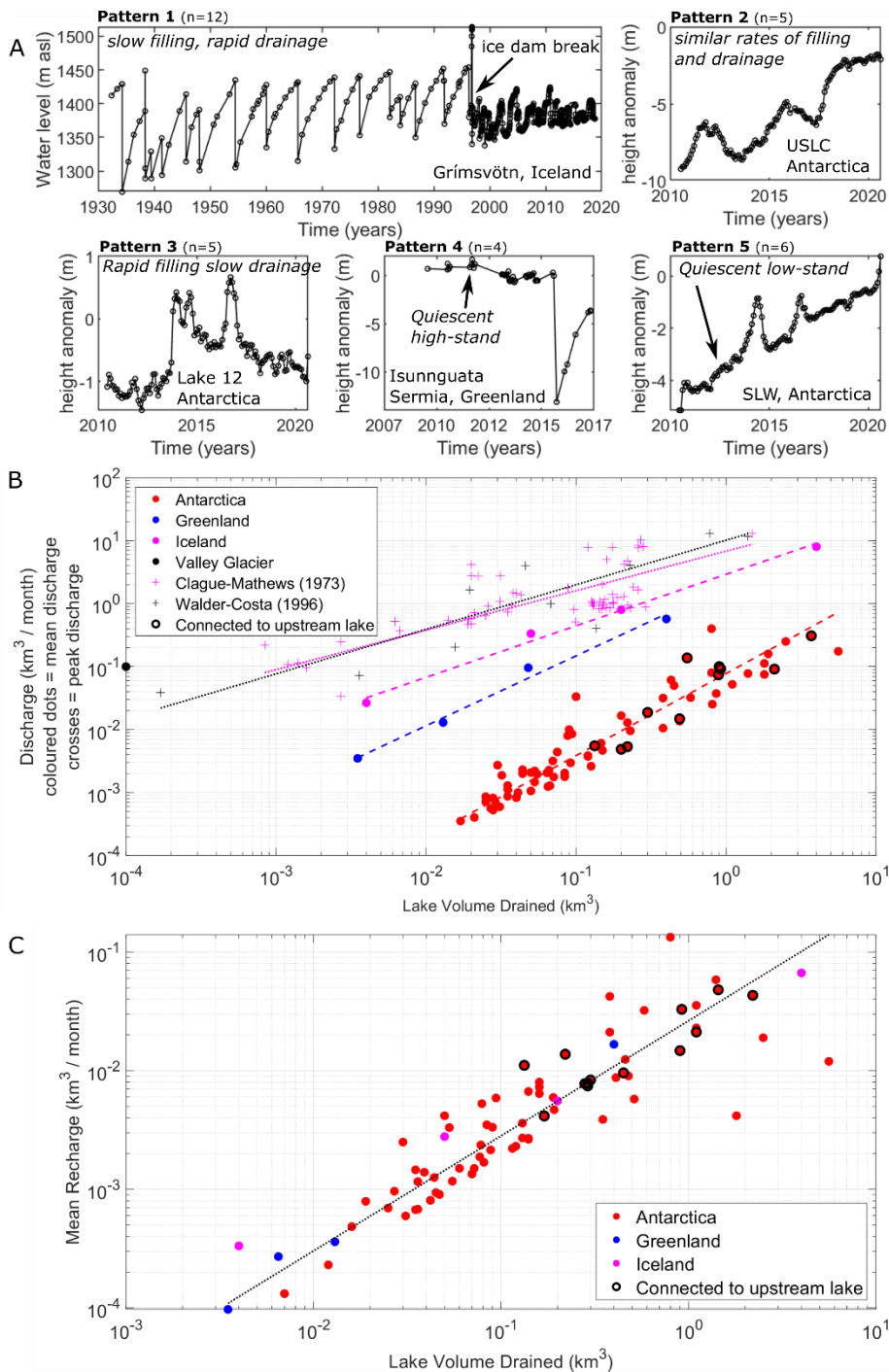
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Figure 2. Recent advances and future potential for investigating subglacial lake dynamics. A. Schematic of the range of different geophysical techniques and satellites for identifying subglacial lakes, probing their environment and monitoring their dynamics. B. Comparison between altimetry coverage of active subglacial lakes in Antarctica. Ice surface elevation measurements for three months of (i) ICESat global Antarctic and Greenland ice sheet altimetry (GLA12), (ii) CryoSat-2 synthetic aperture radar interferometric (SARIn) mode, and (iii) ICESat-2 land ice height (ATL06) data coverage over Conway Subglacial Lake and Mercer Subglacial Lake, West Antarctica. Inset map shows location of panels in Antarctica. (iv) ICESat-2 ATL06-derived ice-surface height anomaly for May 2019. Figure adapted from Siegfried & Fricker (2021)⁹².



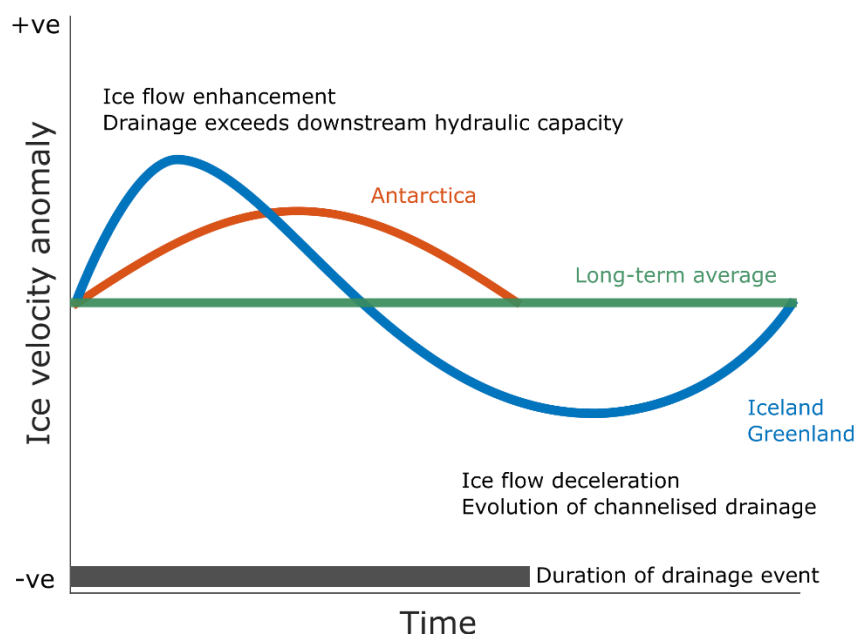
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Figure 3. Global inventory of subglacial lakes. Red circles represent stable lakes identified from RES and blue triangles represent active lakes that have been observed to drain at least once. The extent of larger lakes (e.g. lakes PEL and Lake Vostok) are defined by blue polygons. VIC = Vatnajökull Ice Cap; MIC = Mýrdalsjökull Ice Cap. SGL = subglacial lake. Lakes 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. Top-right inset of subglacial lakes identified in the northern Hemisphere shows the location of A (red box).



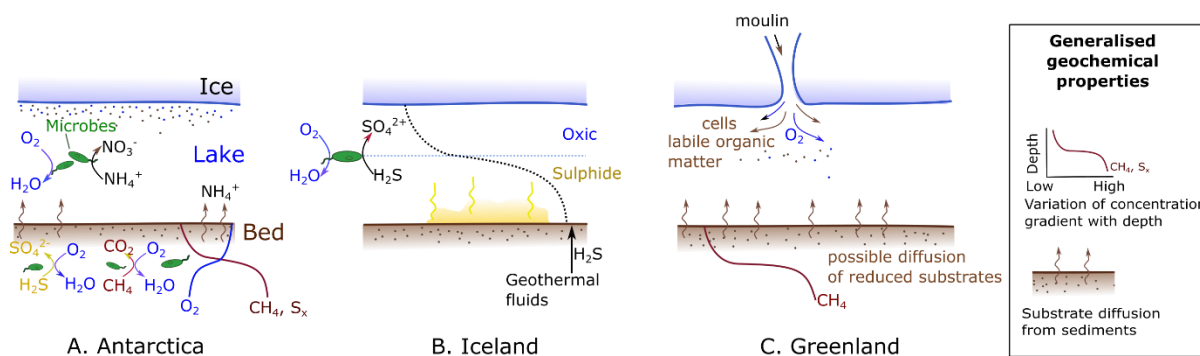
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Figure 4. Fill-drain cycles and the relationship between lake volume and recharge/discharge. A. Examples of different fill-drain patterns of subglacial lakes identified from ice-surface elevation changes. This is based on lakes with at least one complete fill-drain cycle. USLC = Upper Subglacial Lake Conway; SLW = Whillans Subglacial Lake. B. Mean water discharge versus total water volume drained, for drainage events from subglacial lakes and ice-marginal lakes. Dashed lines plot orthogonal distance regression fits for different lake populations. The volume of water drained from each subglacial lake has been derived from ice-surface elevation change (see main text for caveats with using this method). Crosses represent data for ice-marginal lakes draining through subglacial channels^{140,263}; the respective discharge values are peak discharges. Black outlines highlight drainage events fed by the drainage of an upstream subglacial lake. C. Mean recharge rate of different subglacial lakes plotted against lake volume change, as estimated from ice-surface elevation change (dashed line = orthogonal distance regression).



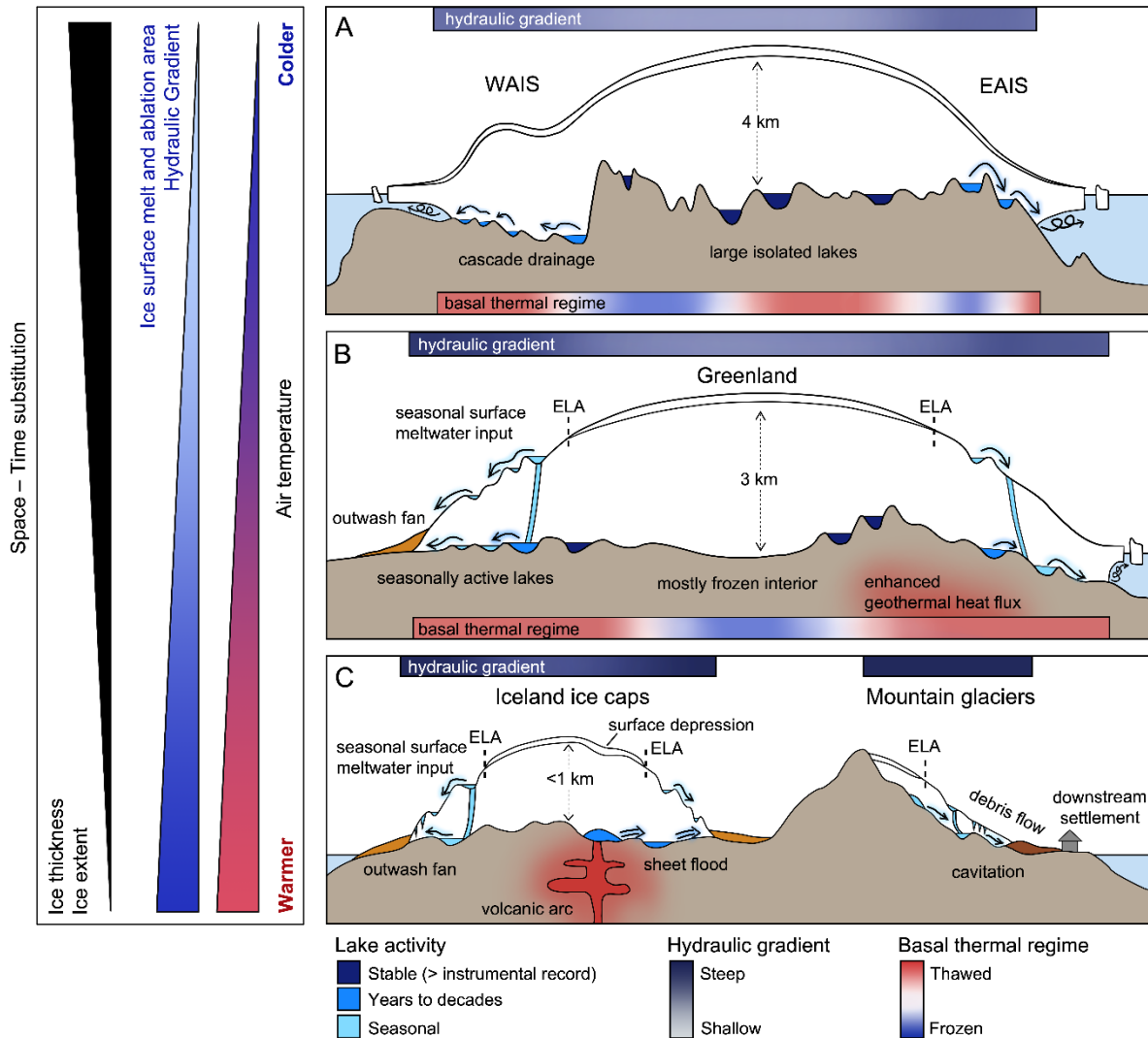
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Figure 5. Conceptual model of the influence of subglacial lake activity on ice flow. For a given subglacial lake drainage event, the ice-flow response will depend on whether, and to what extent, lake discharge exceeds the hydrologic capacity of the 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 hydrologic 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.



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Figure 6. Generalized examples of microbial redox reactions across a range of lake settings. In the absence of sunlight, these systems derive primary production via 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. We highlight three example lake settings. In active Antarctic lakes such as Whillans Subglacial Lake (A), basal ice interacts with the surface water column, but, in general, these lakes lack surface connectivity, which restricts oxygen resupply and delivery of photosynthetically derived nutrients within glacial melt. Icelandic lakes formed from active hydrothermal systems under ice (B) 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, sulphur oxidizing microbes dominate. In an active Greenland lake (C) recharge from surface meltwater via moulins can deliver significant volumes of supraglacial materials, including photosynthetically derived organic matter that would influence redox gradients. The inset key indicates that relative changes in concentration of a particular substrate.



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Figure 7. Space-time substitution using spatial variations in the behaviour of subglacial lakes beneath modern ice masses to assess the impacts of climate warming on their future distribution, geometry and activity. A-C are conceptual models of the hydrological systems of Antarctica (A), Greenland (B) and smaller ice masses such as ice cap and valley glaciers (C). Antarctica is dominated by very large stable lakes close to ice divides with active lakes that drain slowly (months to years) tending to occur beneath ice streams closer to the ice margin. Greenland is largely devoid of lakes in the near-frozen interior. Stable lakes are typically found above the ELA, with active lakes, recharged by surface water, found at or below the ELA and associated with higher discharges than Antarctica (draining in days to weeks). Subglacial lake discharges are similar in Iceland (days to weeks), with lakes influenced by subglacial volcanism and occasionally experiencing large sheet floods due to rapid lake refilling. Valley glaciers are associated with small lakes that can drain rapidly (<hour to days) and are modulated by surface melt and rainfall inputs. Note that the space aspect has large gaps (e.g., Antarctica is much larger than Greenland, and Greenland is much larger than the ice caps of Iceland) and little is known about how changes 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 they will become more active. Beneath smaller ice masses (e.g. valley glaciers) changes in lake abundance will be strongly controlled by local factors. Warming is likely to enhance the potential for surface coupling (e.g. melt and rainfall inputs), resulting in higher overall discharges of shorter duration, and more frequent sheet

1542 floods. The reduction in ice overburden pressure might also stimulate volcanic activity, resulting in
1543 enhanced basal melting and lake formation. ELA = Equilibrium Line Altitude; WAIS = West Antarctic
1544 Ice Sheet; EAIS = East Antarctic Ice Sheet.