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The life and death of a subglacial lake in West Antarctica

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ABSTRACT

Over the past 50 years, the discovery and initial investigation of subglacial lakes in Antarctica have highlighted the paleoglaciological information that may be recorded in sediments at their beds. In December 2018, we accessed Mercer Subglacial Lake, West Antarctica, and recovered the first *in situ* subglacial lake-sediment record—120 mm of finely laminated mud. We combined geophysical observations, image analysis, and quantitative stratigraphy techniques to estimate long-term mean lake sedimentation rates (SRs) between 0.49 ± 0.12 mm a^{-1} and 2.3 ± 0.2 mm a^{-1}, with a most likely SR of 0.68 ± 0.08 mm a^{-1}. These estimates suggest that this lake formed between 53 and 260 a before core recovery (BCR), with a most likely age of 180 ± 20 a BCR—coincident with the stagnation of the nearby Kamb Ice Stream. Our work demonstrates that interconnected subglacial lake systems are fundamentally linked to larger-scale ice dynamics and highlights that subglacial sediment archives contain powerful, century-scale records of ice history and provide a modern process-based analogue for interpreting paleo–subglacial lake facies.

INTRODUCTION

More than 600 subglacial lakes have been identified beneath the Antarctic ice sheet, including 140 "active" lakes that fill and drain, modulating subglacial meltwater transport from the continental interior to coastal ocean (Livingstone et al., 2022). Geophysical evidence shows that sediment deposition occurs at beds of subglacial lakes (e.g., Peters et al., 2008; Smith et al., 2018); this sediment record has been hypothesized to provide a record of subglacial processes and ice-sheet history (Bentley et al., 2011; Yan et al., 2022). However, Antarctic subglacial lakes are among the least accessible features on Earth, leaving this hypothesis largely untested: the only documented subglacial lake sediment cores were retrieved from Whillans Subglacial Lake (SLW) and consisted of structureless diamict indistinguishable from those retrieved from non-lacustrine subglacial environments (Kamb, 2001).

We present unequivocal evidence that lake sediment deposition occurs in Mercer Subglacial Lake (SLM), located 63 km south of SLW beneath the West Antarctic Ice Sheet.

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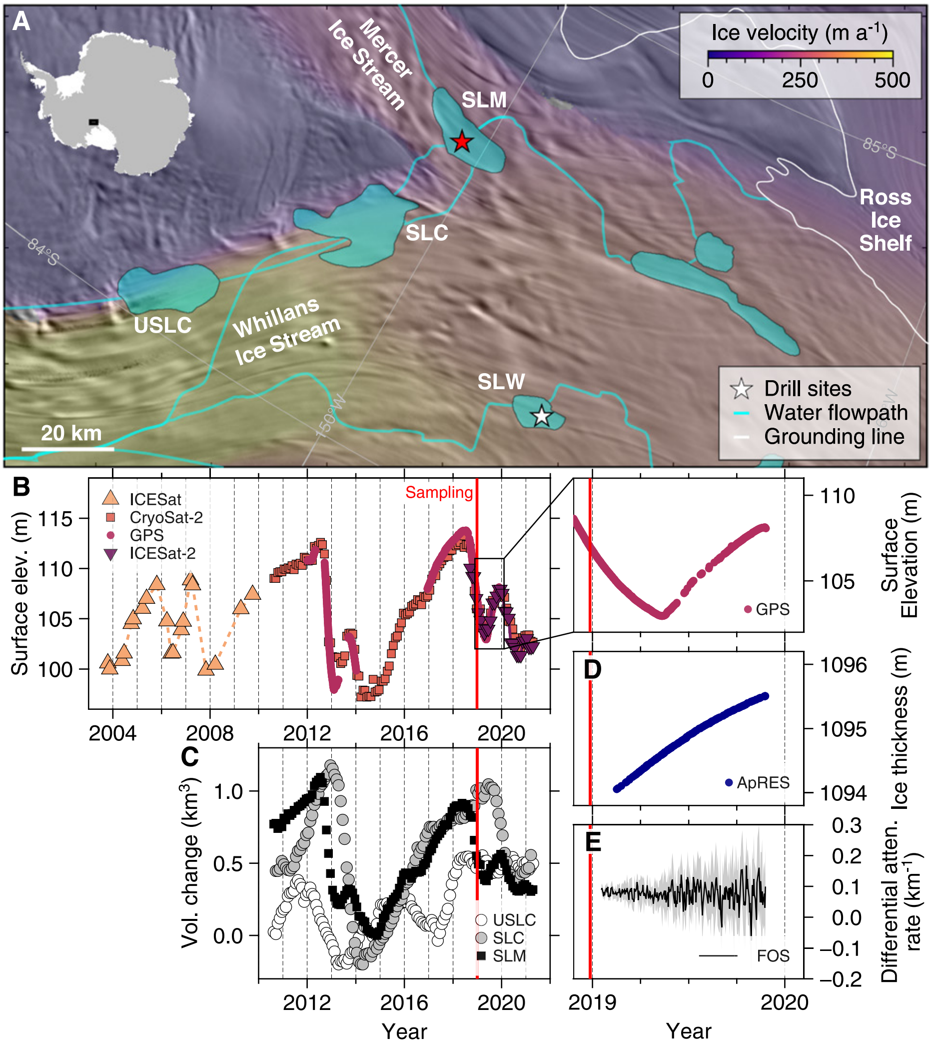

Figure 1. (A) Map of the Mercer Subglacial Lake (SLM) region at the confluence of Mercer and Whillans Ice Streams in West Antarctica. SLM (red; this study) and Whillans Subglacial Lake (SLW) drill sites are marked with stars. Hypothesized water flow paths (cyan lines) suggest that water flows from Upper Conway Subglacial Lake (USLC) to Conway Subglacial Lake (SLC) and into SLM. (B) Surface-elevation time series at the SLM drill site from multi-mission satellite altimetry and continuous GPS stations. Highlighted panel shows GPS surface elevation for the year after SLM sampling (vertical red line). (C) USLC, SLC, and SLC subglacial water volume-change estimates during the CryoSat-2 (European Space Agency satellite) period showing connections and time lags between lakes. (D) Ice thickness from autonomous phase-sensitive radio-echo sounding (ApRES) observations. (E) Differential attenuation rate within fiber-optic sensors (FOS) in the lake column for the year after SLM sampling.

We demonstrate a tight coupling between the initiation of deposition in SLM and regional ice-stream variability, wherein stagnation of Kamb Ice Stream reorganized ice flow of adjacent ice streams (Catania et al., 2012) and led to SLM formation 180 ± 20 a before core recovery (BCR) based on our most likely sedimentation rate (SR) estimate. Subglacial lakes modulate ice-flow velocity (e.g., Stearns et al., 2008), impact location and timing of freshwater and nutrient-rich discharge into the Southern Ocean (Carter and Fricker, 2012), and interact with deeper, more expansive subglacial groundwater systems (Gustafson et al., 2022). Therefore, establishing the life cycle of these features remains crucial for quantifying transport of carbon (Vick-Majors et al., 2020), nutrients (Hawkings et al., 2020), and dissolved gases (Michaud et al., 2017) within and beyond the subglacial system.

REGIONAL SETTING

The downstream confluence of Mercer and Whillans Ice Streams hosts a widespread, active subglacial hydrologic network (Fricker et al., 2007). Interconnected chains of subglacial lakes, including SLM and SLW (Fig. 1A), temporarily store water for months to decades before episodic drainage events release water downstream (e.g., Smith et al., 2009). Based on updated lake surface-elevation time series, SLM completes a fill-drain cycle every 4–6 a (Fig. 1B) with a clear connection to the activity of two lakes upstream: Conway Subglacial Lake (SLC) and Upper Conway Subglacial Lake (USLC) (Fig. 1C; Carter et al., 2013).

Ice flow in this area has switched between active streaming (>10^2 m a^{-1}) and stagnation (<10^1 m a^{-1}) throughout the last millennium (e.g., Catania et al., 2012), hypothesized to be driven by changes in subglacial water routing (Alley et al., 1994). Inferences of coupling between large-scale dynamics and subglacial water systems have been largely limited to analysis of advected surface features (e.g., Marsh et al., 2016). As WIS continues to slow at 1.9%–2.7% a^{-1} (Siegfried et al., 2016), resulting ice thickness perturbations are expected to alter the hydrologic system (e.g., Winberry et al., 2014). The time scales over which these changes occur are unknown because our observational record is limited to modern satellite missions since 2003 (Siegfried and Fricker, 2021).

SUBGLACIAL LAKE ACCESS AND OPERATIONS

We cleanly (i.e., minimizing all aspects of contamination and disturbance of the subglacial environment) accessed SLM in December 2018 by melting an ~0.4-meter-diameter borehole through 1087 m of overlying ice at 84.64029°S, 149.50134°W (Priscu et al., 2021). Our updated lake activity time series (2003–2021) based on multi-mission satellite altimetry and GPS data (Fig. 1B) indicated SLM had just entered a draining phase at time of access with surface height 14.9 ± 0.3 m above lowstand.

SLM borehole science operations included *in situ* observations, sediment coring, and installation of a fiber-optic mooring for long-term temperature observation. We focus on a 0.49-meter-long sediment core collected with a multicoring device modified for use in a narrow borehole (Michaud et al., 2016). See the Supplemental Material[1] for complete operations and analysis descriptions.

IN SITU SUBGLACIAL LAKE OBSERVATIONS

Camera imagery and temperature and conductivity profiling were combined to estimate a water-column thickness at SLM of 15 m (Priscu et al., 2021); this *in situ* measurement is consistent with our estimate of the drill site's

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[1] Supplemental Material. Supplemental Figures S1–S3 and Table S1, and extended information about our GPS, satellite altimetry, ApRES, distributed temperature sensing, and sediment core statistical methods. Please visit https://doi.org/10.1130/GEOL.S.22120316 to access the supplemental material, and contact editing@geosociety.org with any questions. All code and data required for reproducing the figures in this study are available via GitHub (Siegfried et al., 2023a) and Zenodo (Siegfried et al., 2023b).

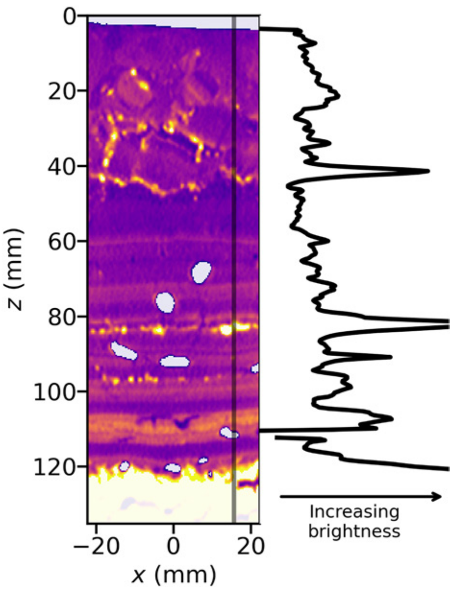

Figure 2. Computed tomography (CT) image slice of upper laminated lake sediment package from Mercer Subglacial Lake (West Antarctica) sediment core. Top 130 mm of core image is presented on a linear brightness color scale. Example brightness trace for the location marked by the vertical line is shown at right showing six large peaks. Lower diamict unit is masked along with clasts and voids. See Figure S3 (see footnote 1) for all CT slices used to estimate an optimal sedimentation rate and the impact of clast and void filtering.

surface height above lowstand at time of access. SLM surface-elevation anomalies (±4 m) for the subsequent year were an order of magnitude larger than ice thickness change (+0.54 m) as indicated by autonomous phase-sensitive radio-echo sounding (ApRES) (Fig. 1D), suggesting our surface-elevation time series (Fig. 1B) can be interpreted as water-column thickness changes between the ice base and underlying sediments.

Two profiles of water-column temperature and conductivity collected during borehole science operations revealed it to be well mixed, with uniform temperature (−0.74 ± 0.01°C), uniform conductivity (287.2 ± 1.1 μS cm^{-1}), and negligible water velocity (<1 cm s^{-1}) (Priscu et al., 2021). Although we were unable to calibrate our fiber-optic distributed temperature sensing for precise temperature retrievals (see the Supplemental Material for methods), analysis of differential attenuation within the optical fiber indicated uniform water-column temperature through April 2019 and non-uniform water column temperature beginning May 2019 (Fig. 1E). This timing coincides with the switch from SLM draining to filling (Fig. 1B), suggesting a significant change in the water column as SLC drainage temporarily increased SLM's water volume during the SLM drainage phase (Carter and Fricker, 2012; Fig. 1C).

SEDIMENT CORE ANALYSIS

We collected multicores from SLM that captured the sediment-water interface and recovered the first laminated sedimentary sequence from contemporary subglacial Antarctica. Core handling and transit disturbed fine-scale structure in the top 45 mm, but preservation of laminations in the lower 75 mm suggests the total laminated lake sediment thickness is 120 ± 2 mm. This low-density (1.24 ± 0.02 g cm^{-3}), clast-poor (0.13 ± 0.22 > 2 mm clasts per 25 cm^{3} sediment) mud (>80 vol%) overlays a massive clast-rich muddy diamict (Fig. S1 in the Supplemental Material) characteristic of other Siple Coast subglacial sediment cores (Kamb, 2001).

Using computed tomography imaging, we identified planar interlaminated clay and silt couplets ($N = 6$–7 by visual inspection) as observed in grayscale values reflecting grain-size change (Reilly et al., 2017) (Fig. 2). Spectral analysis of grayscale values along vertical traces through the undisturbed portion identified significant (≥90% probability) cycles with greatest power at periods of 12 mm and 4.1 mm (Fig. 3A; Fig. S2; Table S1). We interpret the rhythmically laminated mud in our core ("rhythmites" hereafter) as sediment deposition in contemporary SLM.

DISCUSSION

Rhythmite Depositional Processes

We considered various subglacial processes, which act over time scales spanning several orders of magnitude, that could produce rhythmite deposition in SLM: (1) large-scale stick-slip motion of WIS (hourly); (2) subglacial lake fill-drain cycles (sub-annual to decadal); and (3) ice-stream stagnation-reactivation cycles (centennial). Sediments recovered from SLW (Hodson et al., 2016) and elsewhere across the region (Kamb, 2001) did not recover rhythmites, ruling out subglacial processes 1 and 3 given that these processes occur across the Siple Coast. We propose that the lake depositional environment changes significantly during SLM fill-drain cycles, including large changes in water-column thickness (Fig. 1B) and structure (Fig. 1E); these contrasts may provide the conditions needed to produce the observed rhythmites. Therefore, we interpret the rhythmites as an archive of past multi-year fill-drain events of SLM.

Physical interpretation of the rhythmite sequence requires understanding the sediment sources and depositional processes driving observed variability in SLM sedimentation. We considered three separate, interrelated processes affected by fill-drain dynamics (Fig. 4):

(1) Source-sediment differences due to upstream subglacial lake dynamics, which would suggest SLM rhythmites represent dynamics of and pre-sorting in (Schroeder et al., 2019) SLC (Fig. 4A).

(2) Drainage-channel erosion between lakes (Carter et al., 2017), which would suggest SLM rhythmites include remobilized subglacial diamict from between SLC and SLM (Fig. 4B).

(3) Changes in SLM water-column thickness driving changes in water velocity, which would suggest SLM rhythmites represent local lake dynamics that cause removal of fine sediments near lowstand or a change in relative position of the sediment source (Fig. 4C).

We propose that coupled dynamics between SLC and SLM (i.e., sedimentation processes 1 and 2) were a key factor that drove rhythmite deposition because this interpretation also accounts for the lack of rhythmites in nearby SLW (Hodson et al., 2016), a more isolated active subglacial lake with no lake immediately upstream (Fig. 1A).

Statistical Estimation of Lake Age

We estimated the time at which SLM formed by linking the satellite altimetry record (Fig. 1B) and sediment core laminae frequency (Fig. 3A). The contact at 120 ± 2 mm in the sediment core delineates a sharp contrast between lake sediments and underlying diamict (Fig. 2), marking the geologically rapid transition from

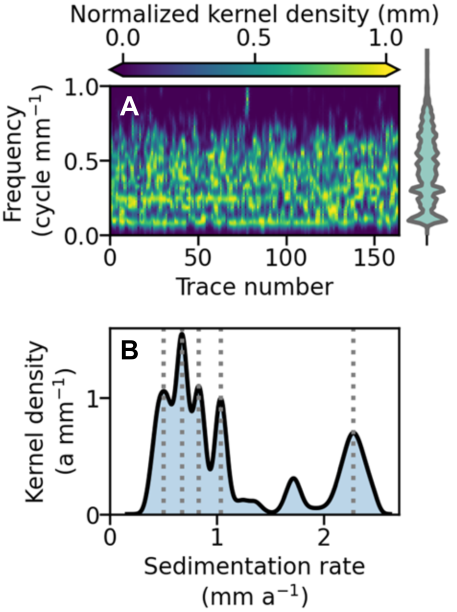

Figure 3. (A) Kernel density estimates of significant frequencies (in cycles mm^{-1}) for each vertical brightness trace through the undeformed section of lake sediments in filtered core imagery. Significant frequency determination based on robust red noise multi-taper spectral analysis (Mann and Lees, 1996). Violin plot shows kernel density estimate of all traces with peak density at 0.082 and 0.24 cycle mm^{-1} (vertical scale on same *y*-axis). (B) Distribution of sedimentation rates (SRs) estimated through Monte Carlo analysis that combines Mercer Subglacial Lake cyclicity derived from satellite altimetry (Fig. 1B) and laminae frequency (A). Vertical dotted lines highlight five most likely optimal SR.

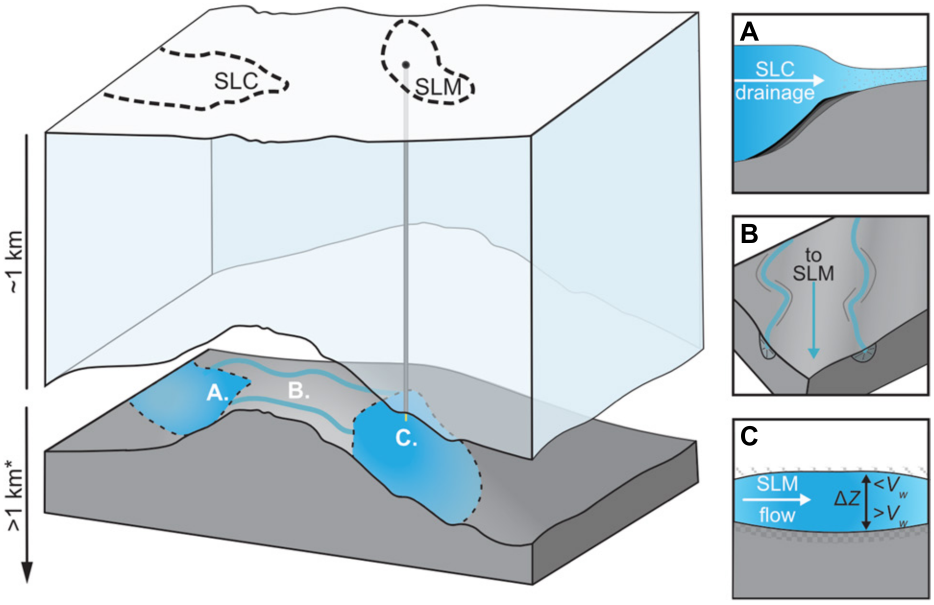

Figure 4. Cartoon depiction of Mercer Subglacial Lake (SLM) and Conway Subglacial Lake (SLC) in West Antarctica with a cross-section of ice surface, bed topography (Morlighem et al., 2020), total sediment thickness (marked with asterisk; Gustafson et al., 2022) along the water flow path between SLC and SLM, and possible depositional processes. (A) Sediments are pre-sorted in SLC and eroded and transported to SLM during SLC drainage. (B) Drainage channels are eroded between SLC and SLM, remobilizing subglacial diamict. (C) Water column thickness changes (Δ*Z*) result in changes in water velocity (V_w), which removes fine sediments during drainage.

a sub-ice-stream environment to the modern depositional lake. To estimate a long-term average SR for the lake sediment package, we employed statistical techniques developed for geological records that contain cyclicity associated with depositional processes (in this case, fill-drain cycles) but lack adequate chronological constraints (Meyers and Sageman, 2007). Our resulting distribution of possible (i.e., able to reject our null hypothesis) SRs, obtained through Monte Carlo simulation (Fig. 3B) and the observed 4–6 a fill-drain cycle frequency (see the Supplemental Material for methods), range from 0.49 ± 0.12 mm a^{-1} to 2.3 ± 0.2 mm a^{-1}. This SR range suggests that SLM formed between 53 and 260 a BCR. Based on the most consistently identified long-term average SR of 0.68 ± 0.08 mm a^{-1} (Fig. 3B), we estimate SLM formation occurred 180 ± 20 a BCR.

Timing of SLM formation coincides with a known large-scale ice-stream reorganization: Kamb Ice Stream stagnated and upper WIS narrowed through inward shear-margin migration 182 a BCR (Catania et al., 2012). Ongoing WIS thickening (e.g., Smith et al., 2020) and deceleration (e.g., Beem et al., 2014) imply that complete stagnation may occur in the coming decades due to basal freezing (e.g., Joughin et al., 2005). If Kamb Ice Stream thickening and deceleration enabled SLM initiation 180 a BCR, then continued WIS stagnation will likely force the demise of SLM as a subglacial lake: the dynamic, high-volume water system beneath WIS will devolve toward a low-volume lake system along ice-stream margins similar to that beneath the currently stagnated Kamb Ice Stream trunk (Kim et al., 2016). The entire life cycle of SLM—from its formation 180 a BCR to its future disappearance—would then span ~200–250 a. Quantifying this active subglacial lake time scale allows us to contextualize the periodicity of carbon and nutrient transfer between the subglacial and marine environments and provides us a metric by which subglacial hydrologic processes may be included in future models. Our work fingerprinting the genesis of subglacial rhythmites provides a means to connect modern subglacial processes to similarly laminated subglacial lake deposits found in the geologic record (e.g., Kuhn et al., 2017; Remmert et al., 2022).

CONCLUSIONS

Recovery and statistical analysis of lake sediments from contemporary subglacial Antarctica provided a constraint on the time scale of Antarctic subglacial lake activity prior to the satellite observational record. This result allowed us to infer a fundamental paleoglaciological connection between regional ice-stream variability and subglacial hydrology 180 ± 20 a BCR and provides strong evidence for a tight coupling between ice-stream stagnation processes and the onset of dynamic subglacial water systems in Antarctica. Future use of surface geophysical data combined with direct sediment sampling of additional subglacial lakes will further refine our process-scale understanding of critical biogeochemical cycles associated with the Antarctic ice sheet and surrounding Southern Ocean.

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