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A wide variety of unique environments beneath the Antarctic ice sheet

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It is 20 years since subglacial Lake Vostok in central East Antarctica was found to be one of the world's largest freshwater bodies (Kapitsa et al., 1996). It was hypothesized to be both an ancient, extreme yet viable environment for microbial life, and a recorder of past climate change. Testing these hypotheses is possible with direct measurement and sampling, but *in-situ* examination is challenging because of the thick ice to drill through, the necessary cleanliness required of the experiment, and the extreme polar conditions in which to operate. In this issue of *Geology*, Michaud et al. (2016, p. 347) report on water and sedimentary material collected in January 2013 from Lake Whillans, a component of the hydrological system beneath Whillans ice stream in West Antarctica. They reveal the water comprises melted basal ice and a small proportion of seawater, the concentration of which increases with sediment depth, making it unique among known subglacial environments within and outside of Antarctica. Here, to place the Lake Whillans work in context, I discuss the range of Antarctic subglacial lake environments, showing the continent to contain an assortment of systems in which novel physical, chemical, and biological processes may take place.

DISCOVERY OF ANTARCTIC SUBGLACIAL LAKES

Subglacial lakes are prevalent in Antarctica because ice is a good insulator of heat, allowing the ice bed to reach the pressure melting temperature under geothermal heating, provided the ice is thick enough. Water flows under gravity and the pressure of ice, and collects in hydrological sinks governed by topography and the ice-surface slope. Subglacial lakes were discovered in the late 1960s using ice-penetrating radar; radio-wave reflections from an ice-water interface are flat, bright and smooth, and distinct from those off the surrounding bed. Because radio waves are absorbed in water, measuring subglacial lake depths requires seismics. Satellite altimetry can identify subglacial lake surfaces, as an ice sheet is often noticeably flat over them owing to the change in ice-flow dynamics between grounded and floating ice. Satellite elevation time series data can reveal lakes that "actively" issue or receive water (Wingham et al., 2006). Analysis of combinations of such data have led to the documentation of over 400 subglacial lakes (Wright and Siegert, 2012; Siegert et al., 2016), more than a hundred of which are components of a dynamic hydrological system (Smith et al., 2009; Siegert et al., 2014a).

PHYSIOGRAPHICAL SETTINGS OF SUBGLACIAL LAKE ENVIRONMENTS

Diversity among subglacial lakes can be characterized in a number of ways (Wright and Siegert, 2011), including (1) size, from the >240-km-long, >1-km-deep Lake Vostok (Siegert et al., 2011), to very small and likely shallow (<1 m deep) lakes; (2) location, from lakes at the ice-sheet center that vary in size, to those close to the ice-sheet edge that are always relatively small; (3) hydrological system, from heavily isolated lakes that contain ancient water, to those integral to widespread basal water-flow and that may be ephemeral; (4) topographic and geological settings, from lakes contained within well-defined valleys (Bell et al., 2006), to those over broad flat sediment; (5) ice-sheet dynamics, from those at the slow-flowing ice-sheet center to lakes linked to enhanced ice flow (Siegert and Bamber, 2000); and (6) ice thickness, from those buried by >3 km of ice at the ice-sheet center, to those under thinner ice toward the margin. Lake Whillans and Lake Vostok represent end-members of this classification.

It is clear that not all subglacial lakes are alike. Deep-water lakes occupying topographic valleys beneath the ice-sheet center are more likely to be ancient systems that are robust to glacial-interglacial ice-sheet changes, making them well suited as both extreme and isolated habitable environments (in which novel biophysical adaptations may have developed over millions of years), and as recorders of climate change, possibly providing direct evidence for deglaciation in Antarctica. In contrast, while lakes near the ice-sheet edge are less likely to be ancient, and their sediments more likely modified by grounded ice, their water will provide information on conditions across a wider subglacial catchment.

SUBGLACIAL LAKE EXPLORATION

As direct measurement and sampling of subglacial lakes is conceptually and logistically challenging, identification of the most appropriate location for such work is important. For Lake Vostok, the existence of an ice core at Vostok Station (at the lake's southern end) made it ideal as a Russian research target (Lukin and Bulat, 2011). Similarly, for United States colleagues, the proven logistical capacity at Whillans ice stream made Lake Whillans a preferred location (Fricker et al., 2011). In the United Kingdom, the identification of a third site, Lake Ellsworth (Siegert et al., 2012)—a 14-km-long, deep-water lake in central West Antarctica—was made using objective criteria (Siegert, 2002) showing how it could address both hypotheses.

In February 2012, Lake Vostok became the first subglacial lake to be penetrated using ice coring. Because drilling fluid is lighter than water, upon lake entry, water rushed into the borehole and froze. Subsequent re-coring of this ice produced a lake sample (Bulat, 2016). In December 2012, attempts to deploy a purpose-built, clean hot-water drill to access Lake Ellsworth failed owing to technical issues with the equipment (Siegert et al., 2014b). A month after, in January 2013, U.S. scientists successfully drilled into Lake Whillans using a clean hot-water drill, acquiring samples that are yielding new insights into conditions at the ice base (Mikucki et al., 2016; Michaud et al., 2016).

DIVERSITY OF ENVIRONMENTS

That the subglacial environment of Whillans ice stream contains seawater will not surprise glaciologists who know the ice flow is intricately linked with ocean tides; the tides influence basal sediment mechanical properties (Winberry et al., 2011). What may be more interesting is the observed increase in the proportion of seawater with sediment depth, suggesting interplay between tides and the movement of water beneath the ice-bed interface. While Antarctic groundwater is a grossly understudied area, it may well be important to Whillans ice stream dynamics (Christoffersen et al., 2014), adding a further reason to understand subglacial environments where ice-ocean interactions may occur.

The situation at Lake Whillans, beneath ~800 m of ice, is both fascinating and likely non-representative of other subglacial lakes; at the time of drilling, the water depth was only ~5 ft. The lake itself is known to be heavily affected by inflows and discharges, meaning it is probably unlikely to represent a stand-alone ecosystem. Hence, while significant scientific and technical advances have been made at Lake Whillans, the hypotheses that have driven subglacial lake research over the last two decades remain untested.

Lake Vostok is an ultimate research target, as it is ancient and because biodiversity scales with size. Here, and in other isolated deep-water lakes, measurement and sampling of the water column will determine its chemical and physical stratification, the degree of mixing, and the spatial concentrations of living organisms. Because the lake is so large, one sampling point is insufficient to understand it as a system. While Russian scientists plan to continue using the ice core to sample the lake, clean hot-water drilling will be needed to develop the exploration further. Given the substantial technical, logistical, and physical challenges in ground-based research in interior East Antarctica, it is likely this experiment will be perfected elsewhere. Indeed, despite the setbacks to the exploration of Lake Ellsworth, it remains well suited both to advancing the technology and to testing the two basic hypotheses. Subglacial lakes are not the only form of aqueous environment in Antarctica, however. Sedimentary basins have been identified where groundwater may permeate. A hypothesis that they contain stores of methane due to biogeochemical processes (Wadham et al., 2012) is also testable with direct measurement and sampling.

SUMMARY

Antarctica contains a wide variety of subglacial environments that we have only just begun to explore. The first results from Lake Whillans have led to fascinating discoveries. While evidence for the input of seawater to the Lake Whillans system makes it unique among known subglacial environments (Michaud et al., 2016), it also begs further questions on how water is exchanged between the ice sheet and the ocean. Despite advances, the two major hypotheses of subglacial lake exploration remain untested. Lake Vostok remains an ultimate target of research but it is likely the science will be progressed elsewhere. Lake Ellsworth is a good candidate, but others are emerging, as is interest from nations such as China and South Korea. Indeed a potentially deep-water mega-lake has been inferred to exist near a logistics hub of the Chinese Antarctic program (Jamieson et al., 2016).

The past decade has seen the science of subglacial lake exploration move forward steadily. We now know how to explore these pristine environments cleanly and without disturbance. While the exploration of a deep-water subglacial lake could happen within a decade, a full understanding of the complex environment beneath the Antarctic ice will take much longer. This pioneering area of science remains in its infancy.

REFERENCES CITED

Bell, R.E., Studinger, M., Fahnestock, M.A., and Shuman, C.A., 2006, Tectonically controlled subglacial lakes on the flanks of the Gamburtsev Subglacial Mountains, East Antarctica: Geophysical Research Letters, v. 33, p. L02504, doi:10.1029/2005GL025207.

Bulat, S.A., 2016, Microbiology of the subglacial Lake Vostok: First results of borehole-frozen lake water analysis and prospects for searching for lake inhabitants: Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences, v. 374, p. 20140292, doi:10.1098/rsta.2014.0292.

Christoffersen, P., Bougamont, M., Carter, S.P., Fricker, H.A., and Tulaczyk, S., 2014, Significant groundwater contribution to Antarctic ice streams hydrologic budget: Geophysical Research Letters, v. 41, p. 2003–2010, doi:10.1002/2014GL059250.

Fricker, H.A., et al., 2011. Siple Coast Subglacial Aquatic Environments: The Whillans Ice Stream Subglacial Access Research Drilling Project, *in* Siegert, et al., eds., Subglacial Antarctic Aquatic Environments: American Geophysical Union Geophysical Monographs v. 192, p. 199–219, doi:10.1029/2010GM000932.

Jamieson, S.S.R., Ross, N., Greenbaum, J.S., Young, D.A., Aitken, A.R., Roberts, J.L., Blankenship, D.D., and Siegert, M.J., 2016, A large subglacial lake and canyon system in Princess Elizabeth Land, East Antarctica: Geology, v. 44, p. 87–90, doi:10.1130/G37220.1.

Kapitsa, A., Ridley, J.K., Robin, G. de Q., Siegert, M.J., and Zotikov, I., 1996, Large deep freshwater lake beneath the ice of central East Antarctica: Nature, v. 381, p. 684–686, doi:10.1038/381684a0.

Lukin, V., and Bulat, S., 2011. Vostok Subglacial Lake: Details of Russian Plans/Activities for Drilling and Sampling, *in*, Siegert, et al., eds., Subglacial Antarctic Aquatic Environments: American Geophysical Union Geophysical Monographs v. 192, p. 187–197, doi:10.1029/2010GM000951.

Michaud, A.B., Skidmore, M.L., Mitchell, A.C., Vick-Majors, T.J., Barbante, C., Turetta, C., van Gelder, W., and Priscu, J.C., 2016, Solute sources and geochemical processes in Subglacial Lake Whillans, West Antarctica: Geology, v. 44, p. 347–350, doi:10.1130/G37639.1.

Mikucki, J.A., et al., 2016: Antarctic subglacial lake exploration: First results and future plans: Philosophical Transactions of the Royal Society of London, A, v. 374, p. 20140290, doi:10.1098/rsta.2014.0466, doi:10.1098/rsta.2014.0290

Siegert, M.J., 2002, Which are the most suitable Antarctic subglacial lakes for exploration?: Polar Geography, v. 26, p. 134–146, doi:10.1080/789610135.

Siegert, M.J., and Bamber, J.L., 2000, Subglacial water at the heads of Antarctic ice-stream tributaries: Journal of Glaciology, v. 46, p. 702–703.

Siegert, M., Popov, S., and Studinger, M., 2011. Subglacial Lake Vostok: a review of geophysical data regarding its physiographical setting, *in* Siegert, et al., eds., Subglacial Antarctic Aquatic Environments: American Geophysical Union Geophysical Monographs v. 192, p. 45–60, doi:10.1029/2010GM000934.

Siegert, M.J., et al., 2012, Clean access, measurement and sampling of Ellsworth Subglacial Lake: A method to explore deep Antarctic subglacial lake environments: Reviews of Geophysics, v. 50, p. RG1003, doi:10.1029/2011RG000361.

Siegert, M.J., Ross, N., Corr, H., Smith, B., Jordan, T., Bingham, R., Ferraccioli, F., Rippin, D., and Le Brocq, A., 2014a, Boundary conditions of an active West Antarctic subglacial lake: Implications for storage of water beneath the ice sheet: The Cryosphere, v. 8, p. 15–24, doi:10.5194/tc-8-15-2014.

Siegert, M.J., Makinson, K., Blake, D., Mowlem, M., and Ross, N., 2014b, An assessment of deep-hot-water drilling as a means to undertake direct measurement and sampling of Antarctic subglacial lakes: Experience and lessons learned from the Lake Ellsworth field season 2012–13: Annals of Glaciology, v. 55, p. 59–73, doi:10.3189/2014AoG65A008.

Siegert, M.J., Ross, N., and Le Brocq, A., 2016, Recent advances in understanding Antarctic subglacial lakes and hydrology: Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences, v. 374, p. 20140306, doi:10.1098/rsta.2014.0306.

Smith, B.E., Fricker, H.A., Joughin, I.R., and Tulaczyk, S., 2009, An inventory of active subglacial lakes in Antarctica detected by ICESat (2003–2008): Journal of Glaciology, v. 55, p. 573–595, doi:10.3189/002214309789470879.

Wadham, J.L., et al., 2012, Potential methane reservoirs beneath Antarctica: Nature, v. 488, p. 633–637, doi:10.1038/nature11374.

Winberry, J.P., Anandakrishnan, S., Wiens, D.A., Alley, R.B., and Christianson, K., 2011, Dynamics of stick–slip motion, Whillans Ice Stream, Antarctica: Earth and Planetary Science Letters, v. 305, p. 283–289, doi:10.1016/j.epsl.2011.02.052.

Wingham, D.J., Siegert, M.J., Shepherd, A.P., and Muir, A.S., 2006, Rapid discharge connects Antarctic subglacial lakes: Nature, v. 440, p. 1033–1036, doi:10.1038/nature04660.

Wright, A., and Siegert, M.J., 2011, The identification and physiographical setting of Antarctic subglacial lakes: An update based on recent geophysical data, *in* Siegert, et al., eds., Subglacial Antarctic Aquatic Environments: American Geophysical Union Geophysical Monographs v. 192, p. 9–26, doi:10.1029/2010GM000933.

Wright, A.P., and Siegert, M.J., 2012, A fourth inventory of Antarctic subglacial lakes: Antarctic Science, v. 24, p. 659–664, doi:10.1017/S095410201200048X.

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