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Antarctic subglacial lake exploration: first results and future plans

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Introduction

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After more than a decade of planning, three attempts were made in 2012–2013 to access, measure *in situ* properties and directly sample subglacial Antarctic lake environments. First, Russian scientists drilled into the top of Lake Vostok, allowing lake water to infiltrate, and freeze within, the lower part of the ice-core borehole, from which further coring would recover a frozen sample of surface lake water. Second, UK engineers tried unsuccessfully to deploy a clean-access hot-water drill, to sample the water column and sediments of subglacial Lake Ellsworth. Third, a US mission successfully drilled cleanly into subglacial Lake Whillans, a shallow hydraulically active lake at the coastal margin of West Antarctica, obtaining samples that would later be used to prove the existence of microbial life and active biogeochemical cycling beneath the ice sheet. This article summarizes the results of these programmes in terms of the scientific results obtained, the operational knowledge gained and the engineering challenges revealed, to collate what is known about Antarctic subglacial environments and how to explore them in future. While results from Lake Whillans testify to subglacial lakes as being viable biological habitats, the engineering challenges to explore deeper more isolated lakes where unique microorganisms and climate records may be found, as exemplified in the

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Lake Ellsworth and Vostok missions, are considerable. Through international cooperation, and by using equipment and knowledge of the existing subglacial lake exploration programmes, it is possible that such environments could be explored thoroughly, and at numerous sites, in the near future.

1. Introduction

While Antarctic subglacial lakes were discovered over 40 years ago [1], our appreciation of them as extreme yet viable habitats for life coincided with reports that Lake Vostok, buried beneath 4000 m of ice, may contain a diverse group of microorganisms [2,3]. We now know that over 400 subglacial lakes exist scattered across the Antarctic continent [4] (figure 1). Some subglacial lakes, like Lake Vostok, are confined within topographic valleys, allowing substantial volumes of water to pool. Lakes that lie in these topographical valleys may have resisted changes in ice-sheet configuration over glacial cycles, making them features that have existed since the continent became glaciated. This longevity allows speculation that they contain a sedimentary record of past ice and climate change spanning hundreds of thousands of years [6]. Other subglacial lakes are located across flat topography, where the water is shallower and where the lake basin and overlying ice sheet are unlikely to contain subglacial water over long periods. Indeed, some of these subglacial lakes have been shown to exhibit rapid losses/gains in volume possible only through episodic discharges of lake water [7,8]. We also appreciate subglacial lakes as modulators of water to the beds of fast-flowing ice streams [9,10], as components of extensive sedimentary wetland systems [11,12] and as analogues to extraterrestrial settings [13,14]. Clearly, Antarctic subglacial lakes represent a diverse and relatively unexplored range of aquatic environments [15], the investigation of which requires considerable scientific planning, engineering development and logistical support [16].

The first discussions on subglacial lake exploration took place as a series of four international meetings, focusing on Lake Vostok as the main target (Cambridge, UK, 1994, examining the information later published in Kapitsa *et al.* [2]; St Petersburg, Russia, 1998; Washington DC, USA, 1998; and Cambridge, UK 1999). To aid this initial planning, the Scientific Committee on Antarctic Research (SCAR) formed a group of specialists to promote and coordinate international discussions on subglacial lake exploration. Between 2000 and 2009, this committee provided a forum to encourage the international exchange of scientific knowledge and engineering plans. A fifth international meeting (Grenoble, France, 2006) considered the exploration of subglacial lakes within the context of the International Polar Year (2007–2008), building a template from which three major subglacial exploration missions were developed. The details of these programmes were shared and debated at the sixth international meeting (an AGU Chapman Conference, Baltimore, MD, USA, 2010; [17]), including specifics on how such investigation could be undertaken in a scientifically clean and environmentally responsible manner [18,19]. Following this meeting, SCAR drafted a ‘code of conduct’ on Antarctic subglacial lakes exploration, ratified at the 2011 Antarctic Treaty Consultative Meeting (Buenos Aires, Argentina). By 2011, the stage was finally set, after more than 15 years of planning and discussions, for three discrete subglacial lake exploration missions to take place.

2. Lake exploration programmes

In February 2012, Russian ice-core drillers punctured into the surface of Lake Vostok, accessing a subglacial lake for the first time [20]. Upon penetrating the lake, water flooded rapidly into the borehole as hydraulic equilibrium was reached. The water froze during the ensuing winter and was re-cored the following summer season, allowing a sample of frozen lake surface water to be recovered. The analysis of this sample is discussed in reference [21]. Ten months later, in December 2012, UK scientists attempted to access Lake Ellsworth, a deep-water lake at the centre

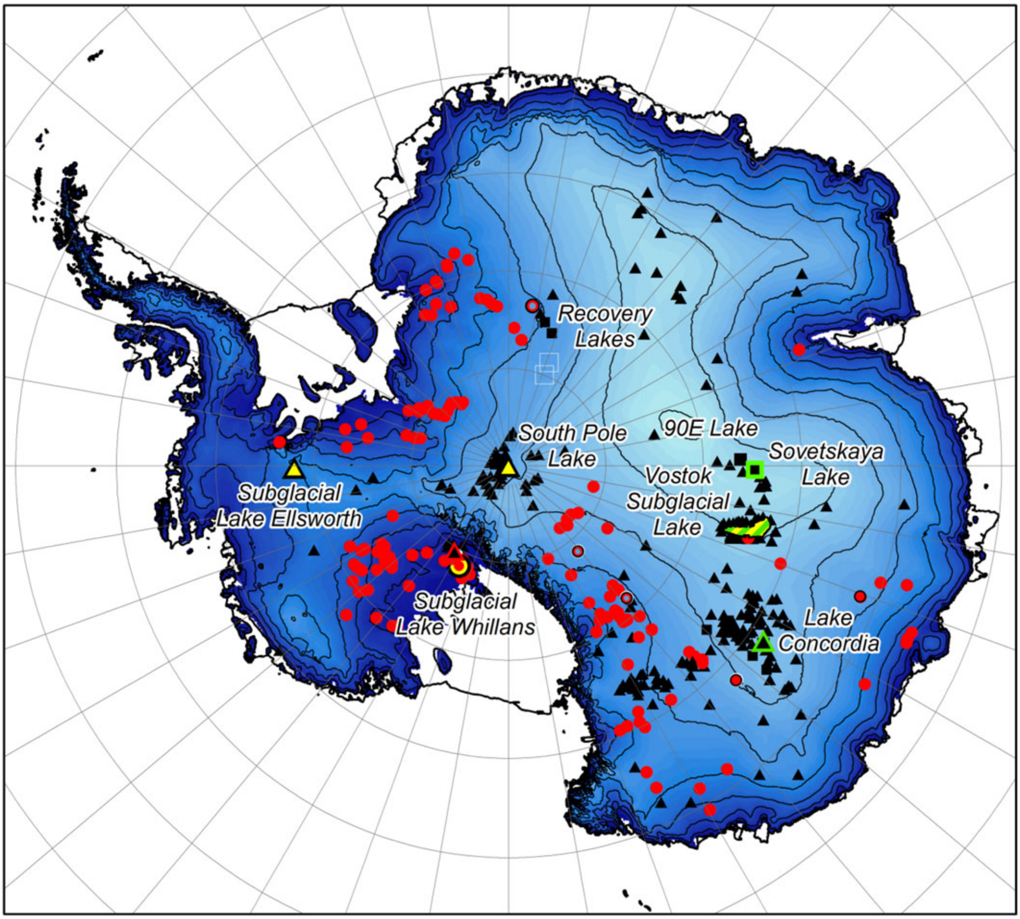

Figure 1. The locations of Antarctic subglacial lakes (adapted from reference [5]). Colours/shapes denote the type of investigations undertaken at each site: Black/triangle, radio-echo sounding; yellow, seismic sounding; green, gravitational field mapping; red/circle, surface height change measurement; square, shape identified from ice surface feature. Lake Vostok, far the largest subglacial lake, is shown in outline. (Online version in colour.)

of West Antarctica, using a purpose-built clean access hot-water drill [22]. The mission had to be called off, however, when the drill experienced a series of equipment and operational failures [23]. One month later, in January 2013, a US team using a clean hot-water drill, successfully accessed, measured and sampled the water and sediment within Lake Whillans, a relatively shallow 'active' lake on the edge of West Antarctica. The first results from this mission revealed an active biota beneath the Antarctic ice sheet [24,25].

These three national missions collectively provided a wealth of new knowledge on what can be achieved with successful measurement and sampling of subglacial lakes, and the engineering pitfalls that must be avoided in accessing deeper lake environments cleanly. Indeed, as in many areas of science, the lessons learned through mission failure [26] are likely to be as important to the future development of subglacial lake exploration as the first scientific results.

3. SCAR horizon scan and the future of Antarctic subglacial exploration

In 2014, SCAR commenced a formal scientific horizon scanning exercise to identify the top 80 questions that Antarctic researchers aim to answer by 2035 [27]. Following this exercise the Council of Managers of National Antarctic Programmes (COMNAP) began a matching exercise, to understand the logistics and engineering challenges that answers to each question will require.

The Royal Society Theo Murphy Meeting at Chicheley Hall (30–31 March 2015) formed a unique opportunity to collectively provide input into the COMNAP process, to assist the development of future subglacial exploration missions. To this end, attendees completed a questionnaire relating to their scientific ambitions and preferred programme arrangements required to meet them. The result, albeit from a subset of a much larger community, yielded an interesting degree of close agreement on the one hand, and contrasting views on the other hand, relating to specific aspects of subglacial exploration. A summary of the findings from this questionnaire exercise is provided below.

Attendees were first asked to list which of the horizon scan questions they plan to address. The top four answers were as follows (numbers refer to the order of questions as in Kennicutt *et al.* [27]):

#26. How does subglacial hydrology affect ice sheet dynamics, and how important is this linkage?
#27. How do the characteristics of the ice sheet bed, such as geothermal heat flux and sediment distribution, affect ice flow and ice sheet stability?
#34. How will the sedimentary record beneath the ice sheet inform our knowledge of the presence or absence of continental ice?
#47. How do subglacial systems inform models for the development of life on Earth and elsewhere?

Collectively, these questions demonstrate the multidisciplinary nature of the research that can be gained from subglacial lake exploration using a combination of geophysical survey, clean subglacial lake access measurement and sampling, down borehole measurement and sediment drilling; all of which have considerable logistical and engineering requirements.

A second set of questions related to the location where research is thought best conducted in terms of scientific deliverables and logistical ease. Although there were numerous responses for subglacial lakes Vostok, Ellsworth and Whillans, the largest number of respondents commented that a variety of settings was required to fully answer the questions, and not restricting only to subglacial lakes. Indeed, clean sampling of sedimentary material away from subglacial lakes was described by several attendees as being an interesting way of answering the top four questions. That the community did not focus on one particular lake, indicates that there is no single agreed ‘best suited’ lake for exploration at this stage. Only by the exploration of multiple subglacial targets, across the Antarctic continent, can the full diversity of these systems at the ice sheet bed be comprehended.

The third set of questions concerned the technological advances needed for measurement and sampling, lake access and cleanliness and environmental stewardship. Given that numerous lake exploration probes have already been designed, built and tested [28]), the majority of responses focused on equipment not yet configured, such down borehole monitoring systems, long-term *in situ* measurement, and the deep sampling of benthic sediments. On lake access, the consensus was far clearer; that clean, reliable deep-ice hot-water drilling is required. In terms of cleanliness, most respondents commented that procedures for clean subglacial lake access have now been developed using hot-water drilling. Some remarked that procedures and protocols for monitoring cleanliness of boreholes, and devices passed within them, need to be further established (see reference [29]).

The final set of questions focused on whether international collaboration is required to undertake subglacial lake exploration in future and, if it is, what the nature of such collaboration should be. While some level of cross-national collaboration was almost unanimously regarded as being desirable, only half the responses thought it essential. Although some favoured the idea of a single major international programme, financially supported by several nations, the majority of respondents spoke to the advantages of retaining a multiple target approach. Instead of a single managed programme, international collaboration should be enhanced through academic and knowledge exchanged between programmes, and through sharing of samples to ensure reproducibility of results. With the emphasis on informal cooperation rather than on managed collaboration, there was an agreement that SCAR can, and should, retain a role in promoting and coordinating subglacial lake exploration research.

4. Summary

In 20 years, Antarctic subglacial lake exploration has developed from seminal thought, to conceptual design and programme development, and finally to the first exploratory missions. The most successful, the direct sampling of Lake Whillans, revealed a surprisingly high diversity of microorganisms in the water column and sediments beneath the West Antarctic Ice Sheet. While this finding is significant, many unanswered questions remain, including the functional role of life across lakes with different hydraulic retention times, and the climate records that are held in their sedimentary floors. Russian plans to use the deep ice-core facility at Vostok Station to recover more information at Lake Vostok may well yield answers. It is unlikely that ice-coring equipment can be used at every lake location owing to the scale of the facility needed, the length of time (and expense) to drill to more than 3000 m, and the need for an organic-based borehole drilling fluid, which has consequences for environmental stewardship. Instead, deep, clean hot-water drilling is required. Unfortunately, the first attempt to use such a drill, at Lake Ellsworth, was unsuccessful. Much has been learned from the experiences of the three programmes, and because of this we now, collectively, have a much better idea on how to commence the exploration of one of the planet's last natural frontiers. It is entirely feasible that regular access to a variety of subglacial lakes, fully answering a number of questions from the SCAR horizon scan, will have taken place by 2035.

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References

1. Oswald GKA, Robin G de Q. 1973 Lakes beneath the Antarctic ice sheet. *Nature* **245**, 251–254. (doi:10.1038/245251a0)
2. Kapitsa AP, Ridley JK, Robin G de Q, Siegert MJ, Zotikov IA. 1996 Large deep freshwater lake beneath the ice of central East Antarctica. *Nature* **381**, 684–686. (doi:10.1038/381684a0)
3. Priscu JC *et al.* 1999 Geomicrobiology of sub-glacial ice above Lake Vostok, Antarctica. *Science* **286**, 2141–2144.
4. Siegert MJ, Ross N, Le Brocq AM. 2016 Recent advances in understanding Antarctic subglacial lakes and hydrology. *Phil. Trans. R. Soc. A* **374**, 20140306. (doi:10.1098/rsta.2014.0306)
5. Wright AP, Siegert MJ. 2012 A fourth inventory of Antarctic subglacial lakes. *Antarct. Sci.* **24**, 659–664. (doi:10.1017/S095410201200048X)
6. McKay RM, Barrett PJ, Levy RS, Naish TR, Golledge NR, Pyne A. 2016 Antarctic Cenozoic climate history from sedimentary records: ANDRILL and beyond. *Phil. Trans. R. Soc. A* **374**, 20140301. (doi:10.1098/rsta.2014.0301)
7. Wingham DJ, Siegert MJ, Shepherd A, Muir AS. 2006 Rapid discharge connects Antarctic subglacial lakes. *Nature* **440**, 1033–1036. (doi:10.1038/nature04660)
8. Smith BE, Fricker HA, Joughin IR, Tulaczyk S. 2009 An inventory of active subglacial lakes in Antarctica detected by ICESat (2003–2008). *J. Glaciol.* **55**, 573–595. (doi:10.3189/002214309789470879)
9. Siegert MJ, Bamber JL. 2000 Subglacial water at the heads of Antarctic ice-stream tributaries. *J. Glaciol.* **46**, 702–703.
10. Bell RE, Studinger M, Shuman CA, Fahnestock MA, Joughin I. 2007 Large subglacial lakes in East Antarctica at the onset of fast-flowing ice streams. *Nature* **445**, 904–907. (doi:10.1038/nature05554)

11. Priscu JC, Tulaczyk S, Studinger M, Kennicutt II MC, Christner BC, Foreman CM. 2008 Antarctic subglacial water: origin, evolution and ecology. In *Polar lakes and rivers* (eds W Vincent, J Laybourn-Parry), pp. 119–135. Oxford, UK: Oxford University Press.
12. Wadham *et al.* 2012 Potential methane reservoirs beneath Antarctica. *Nature* **488**, 633–637. (doi:10.1038/nature11374)
13. Bulat SA, Alekhina IA, Marie D, Martins J, Petit JR. 2011 Searching for life in extreme environments relevant to Jovian's Europa: lessons from subglacial ice studies at Lake Vostok (East Antarctica). *Adv. Space Res.* **48**, 697–701. (doi:10.1016/j.asr.2010.11.024)
14. Cockell CS *et al.* 2011 Subglacial environments and the search for life beyond the Earth. In *Subglacial Antarctic aquatic environments* (eds M Siegert, C Kennicutt, B Bindschadler), pp. 129–148. AGU Geophysical Monograph 192. Washington, DC.
15. Wright A, Siegert MJ. 2011 The identification and physiographical setting of Antarctic subglacial lakes: an update based on recent geophysical data. In *Subglacial Antarctic aquatic environments* (eds M Siegert, C Kennicutt, B Bindschadler), pp. 9–26. AGU Geophysical Monograph 192. Washington, DC: American Geophysical Union.
16. Kennicutt MC, Siegert MJ. 2011 Subglacial aquatic environments: a focus of 21st century antarctic science. In *Subglacial Antarctic aquatic environments* (eds M Siegert, C Kennicutt, B Bindschadler), pp. 1–8. AGU Geophysical Monograph 192. Washington, DC.
17. Siegert MJ, Kennicutt M, Bindschadler R (eds). 2011 *Antarctic Subglacial aquatic environments*, 246p. AGU Geophysical Monograph 192, Washington, DC, USA: American Geophysical Union.
18. US National Research Council. 2007 Exploration of Antarctic subglacial aquatic environments. In *Committee on the principles of environmental stewardship for the exploration and study of subglacial environments, Polar Research Board, Division of Earth and Life Sciences* (*2007*). National Research Council of the National Academies. Washington, DC: The National Academies Press. 152 p.
19. Doran PT, Vincent WF. 2011 Environmental protection and stewardship of subglacial aquatic environments. In *Subglacial Antarctic aquatic environments* (eds M Siegert, C Kennicutt, B Bindschadler), pp. 149–156. AGU Geophysical Monograph 192. Washington, DC: American Geophysical Union.
20. Lukin VV, Vasiliev NI. 2014 Technological aspects of the final phase of drilling borehole 5G and unsealing Vostok Subglacial Lake, East Antarctica. *Ann Glaciol* **55**, 83–89. (doi:10.3189/2014AoG65A002)
21. Bulat SA. 2016 Microbiology of the subglacial Lake Vostok: first results of borehole-frozen lake water analysis and prospects for searching for lake inhabitants. *Phil. Trans. R. Soc. A* **374**, 20140292. (doi:10.1098/rsta.2014.0292)
22. Siegert MJ *et al.* 2012 Clean access, measurement and sampling of Ellsworth subglacial lake: a method to explore deep Antarctic subglacial lake environments. *Rev. Geophys.* **50**, RG1003. (doi:10.1029/2011RG000361)
23. Siegert MJ, Makinson K, Blake D, Mowlem M, Ross N. 2014 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. *Ann. Glaciol.* **55**, 59–73. (doi:10.3189/2014AoG65A008)
24. Christner BC *et al.* 2014 A microbial ecosystem beneath the West Antarctic ice sheet. *Nature* **512**, 310–313. (doi:10.1038/nature13667)
25. Mikucki JA *et al.* 2016 Subglacial Lake Whillans microbial biogeochemistry: a synthesis of current knowledge. *Phil. Trans. R. Soc. A* **374**, 20140290. (doi:10.1098/rsta.2014.0290)
26. Makinson K *et al.* 2016 Clean subglacial access: prospects for future deep hot-water drilling. *Phil. Trans. R. Soc. A* **374**, 20140304. (doi:10.1098/rsta.2014.0304)
27. Kennicutt MC *et al.* 2014 Polar research: six priorities for Antarctic science. *Nature* **512**, 23–25. (doi:10.1038/512023a)
28. Mowlem M *et al.* 2016 Probe technologies for clean sampling and measurement of subglacial lakes. *Phil. Trans. R. Soc. A* **374**, 20150267. (doi:10.1098/rsta.2015.0267)
29. Pearce DA, Magiopoulos I, Mowlem M, Tranter M, Holt G, Woodward J, Siegert MJ. 2016 Microbiology: lessons from a first attempt at Lake Ellsworth. *Phil. Trans. R. Soc. A* **374**, 20140291. (doi:10.1098/rsta.2014.0291)