A 60-year international history of Antarctic subglacial lake exploration

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Abstract: In January 2013, the US WISSARD programme measured and sampled Lake Whillans, a subglacial water body at the edge of West Antarctica, in a clean and environmentally sensitive manner, proving the existence of microbial life beneath this part of the ice sheet. The success of WISSARD represented a benchmark in the exploration of Antarctica, made possible by a rich and diverse history of events, discoveries and discussions over the past 60 years, ranging from geophysical measurement of subglacial lakes to the development of scientific hypotheses concerning these environments and the engineering solutions required to test them. In this article, I provide a personal account of this history, from the published literature and my own involvement in subglacial lake exploration over the last 20 years. I show that our ability to directly measure and sample subglacial water bodies in Antarctica has been made possible by a strong theme of international collaboration, at odds with the media representation of a scientific 'race' between nations. I also consider plans for subglacial lake exploration and discuss how such collaboration is likely to be key to success of future research in this field.

There has been much written about the history of scientific discovery in Antarctica, revealing how science, exploration and geopolitics have been closely intertwined since the late nineteenth century (e.g. Naylor *et al.* 2008). Scientific advances in Antarctica can be attributed to major periods of collaboration and cooperation, such as during the four International Polar Years (IPYs 1882–83, 1932–33, 1957–58 and 2007–08). The 1957–58 IPY was regarded as a huge success and prompted the further integration of scientific discussion through the establishment of the Scientific Committee on Antarctic Research (SCAR) and, following this, the Antarctic Treaty. SCAR works to coordinate and facilitate international cooperation in Antarctic science and to provide the Antarctic Treaty with scientific evidence, which allows international oversight on matters such as environmental protection and adherence to the Treaty's other rules. Thus, Antarctic science, particularly large programmes that require considerable logistical support and technological development over many years, often develops as a consequence of scientific planning, multinational collaboration and international scrutiny. One example of such research is the exploration of Antarctic subglacial lakes, bodies of water at the bed of the ice sheet, which SCAR has acted to facilitate over the past 20 years, and which culminated in field programmes to measure and sample three individual lakes in 2012/13: Lake Vostok, led by a Russian team; Lake Ellsworth, led by the British; and Lake Whillans, led by the USA. A recurring theme of the media interest surrounding these programmes was the notion of a scientific 'race' between apparently competing nations, each attempting to be the first to discover the secrets that lie within these dark, cold and isolated environments (e.g. *The Guardian*, 14 February 2012 headline, 'Antarctic lake race sees scientists dash for life's secrets in subglacial world'). So, which is true? Has Antarctic subglacial lake exploration been a model of noble internationalism in polar science, or have individual nations, and scientists, been in it for themselves? To answer this question, I provide a personal view of the history of subglacial lake exploration, from which one can retrospectively understand whether it has been helped, or not, by an international approach to scientific discovery and whether any individual nation has had, or can have, the ability to independently 'race' with another.

Subglacial lake identification, measurement and distribution

Shortly after the end of the Second World War, Australian physicist Gordon Robin, through his PhD investigations as part of the Norwegian–British–Swedish expedition to Dronning Maud Land in East Antarctica, perfected the use of seismic sounding to measure ice thickness (Robin 1958). Seismic

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waves (e.g. sound) travel well through dense ice, but are attenuated by soft firn and snow at the surface. Consequently, to increase the signal-to-noise ratio, boreholes (*c.* 50 m deep) need to be drilled – one for the charge and one for the receiver(s). The experiment is simple: a small explosion sets off a sound wave, which travels down to the ice base, where it is reflected and subsequently recorded by the receiver. The two-way travel time is noted and converted into distance as the speed of sound in ice is known reasonably well. Thus, a measure of ice thickness is possible using a simple seismic reflection test, adapted for harsh polar field conditions by Robin. While the process of data acquisition is time consuming (two boreholes for each data point, meaning that a single datum would take at least a day to record), by aligning measurements along a survey line a profile of ice-sheet thickness, and therefore bed topography, could be derived. In this way, the first two-dimensional cross-section measurements of the Antarctic ice sheet and its subglacial landscape were obtained.

The mission statement of the third IPY (also known as the International Geophysical Year) was 'to observe geophysical phenomena and to secure data from all parts of the world; to conduct this effort on a coordinated basis by fields, and in space and time, so that results could be collated in a meaningful manner'. This inclusive approach led to several exploratory scientific missions across Antarctica, using the seismic techniques described by Robin a few years earlier. Two overland traverses were most notable: a US expedition crossing West Antarctica, involving a young glaciologist from the University of Wisconsin named Charles Bentley, and a Russian survey from the coast to the centre-point of East Antarctica (the Pole of Relative Inaccessibility), which had among its party Andrei Kapitsa from Moscow State University. The data collected by these surveys transformed our knowledge of the continent, proving it to be a single landmass, showing the ice to be several kilometres thick (at Vostok Station, for example, it was measured as *c.* 3.7 km) and, in large parts of West Antarctica, revealing the bed to be over a kilometre below sea-level.

In the early 1960s UK physicist Stan Evans and Robin, by now Director the Scott Polar Research Institute (SPRI) in Cambridge, began experiments to understand the electrical properties of cold ice and how VHF radio waves could be used to measure ice thickness. VHF radio waves (50–150 MHz) travel well through cold ice (<−10°C) but reflect off boundaries of large dielectric contrast (such as at the bed). Radio-echo sounding (RES), as it was known (essentially ice-penetrating radar), was able to chart ice thickness, therefore, in an analogous way to seismic sounding. The major advantage of RES over seismic sounding was that it did not require the drilling of boreholes and could be deployed on a moving platform to obtain cross-section information during transit. The most significant innovation by Evans and Robin was to consider how RES could be mounted and used effectively on aircraft. In the late 1960s their Cambridge team, supported by funding and logistics from the US Antarctic Research Program, demonstrated the use of airborne RES with instant and revolutionary success.

Using RES on an aircraft, the rate and quality of data acquisition improved enormously. When previously it had taken at least a day to get a data point, it now took less than a second and with equal accuracy (an improvement of 5 orders of magnitude). Where it had taken a season to build a transect, it now took a single sortie; and where a profile of the ice sheet may have been constructed with a few dozen seismic data-points, now it could be put together with many thousands of RES reflections. Early RES trial flights, using a Super Constellation L-1049 aircraft, were targeted at the very centre of the East Antarctic ice sheet, where Russian traversing had covered a decade before. In so doing, Robin and his team proved that continental-wide coverage by aircraft mounted with RES was feasible, and the data were remarkable. So followed one of the key decades in Antarctic glaciological and continental discovery.

Systematic profiling of the Antarctic ice sheet took place in four field seasons: 1971/72, 1974/75, 1977/78 and 1978/79. Over the decade, further advances in RES equipment were made, primarily through physicist Preben Gudmundsen from the Technical University of Denmark, and navigation was improved (the early flights used 'dead reckoning', which was replaced by an Inertial Navigation System or 'INS'). The aircraft of choice by now was a reliable long-range Hercules C130 transporter, supplied by the US Navy. Thus, a US–UK–Danish collaboration surveyed about 40% of East Antarctica and 80% of West Antarctica, defining the subglacial landscape for the first time and making profound discoveries about the continent and the way that ice flowed over it (Drewry 1983). For example, the first subglacial lake was discovered from data collected on one of the first long-range survey flights in 1969. An unusually flat subglacial radio-echo surface beneath the Russian base at Sovetskaya Station in central East Antarctica was received and attributed to a 'thick layer of water beneath the ice' (Robin *et al.* 1970). Shortly afterwards, the first inventory of 17 subglacial lakes was documented from East Antarctic RES data (Oswald & Robin 1973; Fig. 1). Lake Vostok, the gigantic subglacial lake in East Antarctica, was detected by RES in December 1974 (Robin *et al.* 1977), although its true extent was not established at this time. These early discoveries showed the bed of the Antarctic Ice Sheet to be wet in many places, that water could be stored in 'lakes'

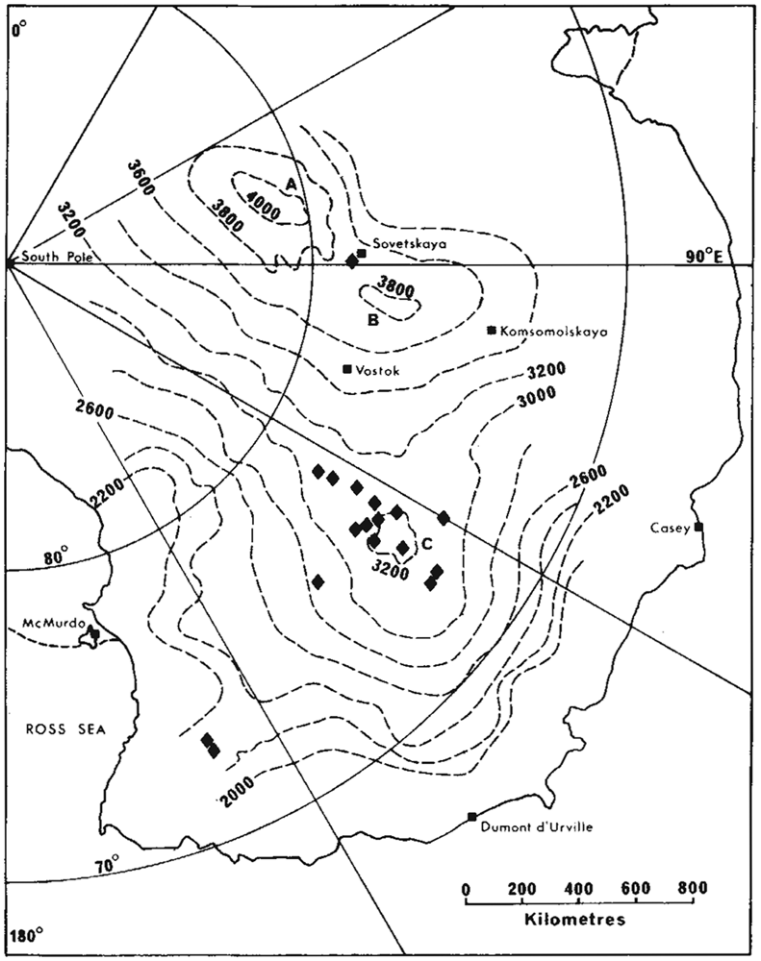

Fig. 1. The inventory of 17 Antarctic subglacial lakes, 1973. Taken from Oswald & Robin (1973).

and that the distribution of subglacial lakes was widespread across the surveyed regions of the continent.

Although subglacial lakes were undeniably discovered using RES by Robin and his team, the first mention of 'lakes' in Antarctica was made by a Russian pilot (Robinson 1960) who, as part of an experiment to determine ice-surface landmarks to aid flight orientation, identified 'oval depressions with gentle shores' on the ice surface. Although these features were referred to as 'lakes' by pilots who observed them, such as Robinson, there was no connection made between these features and water beneath the surface.

It is interesting to note that, despite the published discovery of subglacial lakes in the 1970s, hardly any research was conducted on them during the 1980s. This was almost certainly due to the cessation of long-range surveying of the ice sheet at the expense of targeted smaller-scale observations (Turchetti *et al.* 2008). This changed, however, in the early 1990s with the introduction of satellite observations of ice-surface altimetry, such as by the European Remote Sensing satellite (ERS-1). Ridley *et al.* (1993) analysed ERS-1 data from East Antarctica, and noticed a remarkably flat surface at and to the north of Vostok Station. This surface, which pilots may have observed in the 1950s, coincides remarkably well with RES evidence of a large subglacial lake established by Robin *et al.* (1977), and delineates the outline of the lake beneath (the ice surface above large subglacial lakes is flat owing to the frictionless contact between ice and water at the ice-sheet base). The combination of satellite and RES data confirmed that this lake, Lake Vostok, was over 240 km long and more than 50 km wide. These data also showed the existence of the lake directly beneath

Vostok Station, where Kapitsa and others had collected seismic ice thickness measurements around 30 years previously.

It thus became apparent that the old seismic data may contain a previously unidentified signal of the lake floor given that, unlike radio waves, sound waves travel well in water. To see if this was the case, SCAR convened a meeting at SPRI in 1994 with members of the early exploration programmes including, among others, Robin and Kapitsa. At the meeting, it was agreed that Kapitsa and Robin would work together in analysing the seismic data, drawing in a number of others, including the Russian glaciologist Igor Zotikov, who had previously worked on determining the temperature distribution of ice masses. This international collaboration led to the discovery that Lake Vostok, hidden beneath *c.* 4 km of ice, had a water depth of over 500 m (Kapitsa *et al.* 1996), making it one of the world's top 10 largest freshwater lakes. Consideration of the glacial history of East Antarctica suggested that the lake may have been in continual existence for as long as thick ice cover had occupied the continent, up to 14 million years ago. Unlike previous publications on subglacial lakes during the 1970s, Kapitsa *et al.* (1996), which featured on the front cover of *Nature* magazine, was met by worldwide media attention and considerable new scientific interest, particularly from the microbiological community, which instantly regarded the lake as an extreme yet viable habitat for life, cut off from the rest of the planet for sufficient time to allow novel adaptations to have developed (Ellis-Evans & Wynn-Williams 1996).

The actual writing of the paper by Kapitsa *et al.* (1996) was a challenging process, owing mainly to the different views between Kapitsa, Robin and Zotikov on who was the first to discover subglacial lakes. Robin argued that his team were the first to publish evidence of subglacial lakes, which was undeniable. However, Kapitsa claimed that his 1961 PhD thesis included the first mention of subsurface water (referred to as 'meltwater lenses') in Antarctica. Zotikov disagreed with Kapitsa, however, because his analysis lacked appreciation of ice-sheet thermal dynamics (Zotikov 1963) and was, consequently, unsubstantiated. Kapitsa had obtained the seismic data, however, and within those data was the evidence of basal water. Unfortunately, Kapitsa had not spotted the lake-floor reflections, never considered the seismic data to contain information other than ice thickness and so never published on it. He often referred to his failure to tie his ideas on basal water with the seismic data as a scientific regret. At one point in the writing process, this disagreement resulted in the abandonment of the paper until a precise wording of Kapitsa's early ideas was eventually accepted by all three. Thus, in the paper it states, 'owing mainly to the high noise level, seismic shooting studies … produced no evidence … of the meltwater lenses beneath the ice sheet that had been suggested by Kapitsa on morphological grounds' (Kapitsa *et al.* 1996). This seminal paper was saved, therefore, by an important degree of international scientific diplomacy.

The establishment of the geographical scale of Lake Vostok in 1996, and speculative ideas on its potential contents, was supplemented in the same year by a second inventory of 77 Antarctic subglacial lakes (Fig. 2), which was collated from a reanalysis of the 1970s RES data collected by Robin's team 20 years earlier (Siegert *et al.* 1996). The revised inventory demonstrated that scientific interest in subglacial lakes need not necessarily be restricted to Lake Vostok, the physical conditions in that lake, and therefore the environment to support life, probably being similar in many other subglacial water bodies. Nine years later, as more RES data were collected by the USA, UK, Russia and Italy, the inventory of subglacial lakes grew to 145 (Siegert *et al.* 2005; Fig. 3).

Then, another remarkable finding was made. Analysis of ERS-1 altimetric time-series data revealed an area of the central East Antarctic ice sheet to have reduced in elevation by more than 3 m, far in excess of the instrumental error, over 14 months between 1997 and 1999. During the same period, three areas of the ice sheet more than 200 km away rose up by more than a metre. Given that the regions of uplift coincided with the positions of known subglacial lakes at the mouth of a major subglacial valley known as the Adventure Trench, and that the area of subsidence was located at the head of this trench, the measurements were interpreted as evidence of an outburst of subglacial lake water, flowing over 200 km along the axis of the trench into a series of other lakes (Wingham *et al.* 2006). This discovery revealed a previously unappreciated highly active basal hydrology in Antarctica, and demonstrated that, far from being totally isolated, some subglacial lakes could be connected over large distances through a hierarchical hydrological chain (Siegert *et al.* 2007). Further analysis of satellite interferometry (Gray *et al.* 2005) and laser altimetry revealed more evidence for basal water flow and subglacial lake outbursts, particularly beneath Whillans Ice Stream (Fricker *et al.* 2007; 2016), leading to an inventory of 130 so-called 'active' subglacial lakes (Smith *et al.* 2009). Combined with lakes detected from newly acquired RES data, these active lakes pushed the tally within the fourth version of the inventory of Antarctic subglacial lakes to 381 (Wright & Siegert 2011, 2012; Fig. 4), scattered throughout the continent, confirming wet-based conditions over around half the ice sheet. Following subsequent discoveries, by 2016 the tally of known, discrete subglacial lake locations stood at 402 (Siegert *et al.* 2016*a*).

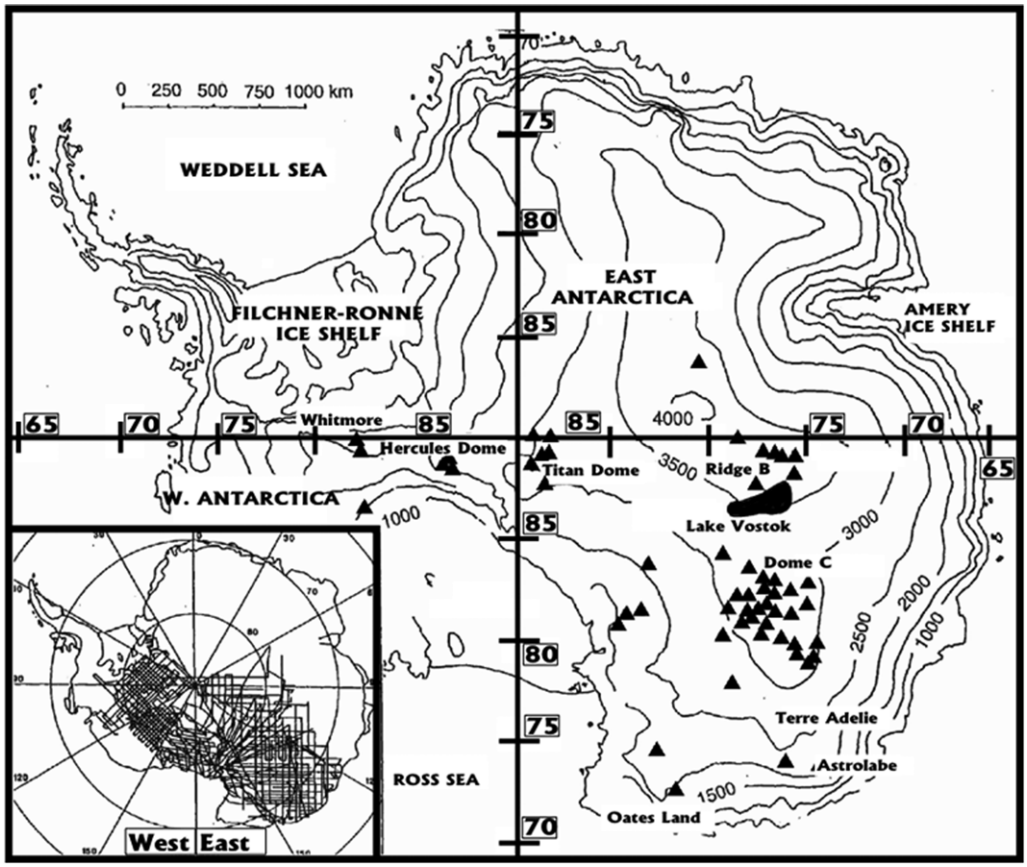

Fig. 2. The inventory of 77 Antarctic subglacial lakes, 1996. Taken from Siegert *et al.* (1996).

Scientific interest in Lake Vostok and the coordinating role of SCAR

As a consequence of a fragmented 30 year period of investigation between the mid-1960s and 1990s, and the data collected by Russian, British, US and European scientists, by 1996 subglacial lakes had been discovered in Antarctica and their viability as habitats for life had begun to provoke scientific interest among a multidisciplinary and international community. With Lake Vostok as a focus of attention, and with direct exploration of the lake in the minds of many, a new field of investigation began to emerge in which microbiologists, geologists and glaciologists discussed the nature of the science they might hope to realize from direct measurement and sampling of the water and, indeed, how such research would be logistically possible and technically feasible.

Two international meetings were held in 1998 to initiate plans for the exploration of Lake Vostok. The first, in Washington, DC was led by Robin Bell from Columbia University, and involved mainly US scientists, including participation from NASA, and a few from the UK and elsewhere. This was followed quickly by a Russian-led meeting, hosted at the Arctic and Antarctic Research Institute in St Petersburg by Valery Lukin, again involving some overseas scientists but without significant US participation. It quickly became apparent to those in SCAR that the developing plans were in danger of being fragmented between Russia and the USA at this early stage. For this reason, it convened a third meeting in 1999 in Cambridge (led by Cynan Ellis-Evans from the British Antarctic Survey, BAS) to build international consensus on how exploration of Lake Vostok (and other subglacial lakes, although despite attempts they were rarely given the same attention) could be achieved, and how international collaboration could support the ambitions. For those few present at all three meetings, three things became clear: (1) that drilling into the lake and acquiring direct measurement and sampling in a clean way was necessary to test whether life existed in the

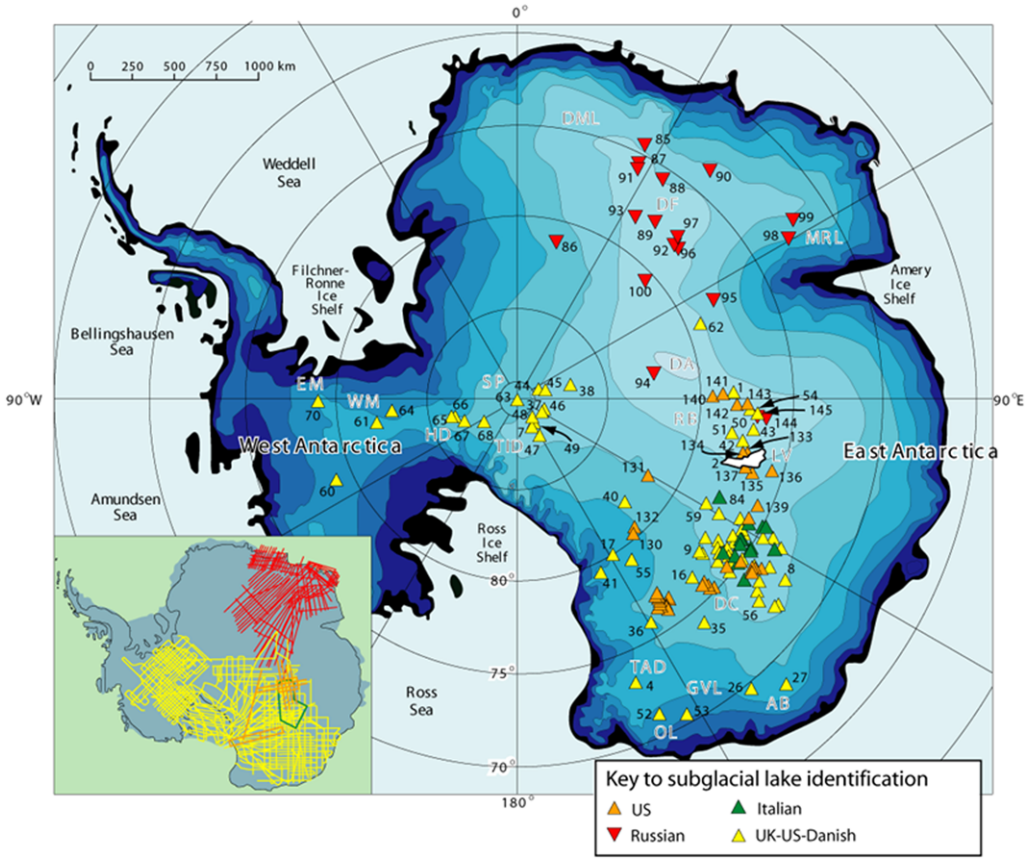

Fig. 3. The inventory of 145 Antarctic subglacial lakes, 2005. Yellow lakes are those identified from SPRI data, green lakes are from the Italian dataset, pink lakes were located in US RES data and red lakes were identified from Russian data. The inset illustrates the coverage of RES data used in the inventory (note that the US and Italian surveys comprise multiple RES transects within boxed areas). Abbreviations to place names are as follows: AB, Astrolabe Subglacial Basin; DA, Dome A; DC, Dome C; DF, Dome F; DML, Dronning Maud Land; EM, Ellsworth Mountains; GVL, George V Land; HD, Hercules Dome; LV, Lake Vostok; MRL, Mac Robertson Land; OL, Oates Land; RB, Ridge B; SP, South Pole; TAD, Talos Dome; TID, Titan Ice Dome; WM, Whitmore Mountains. Taken from Siegert *et al.* (2005).

lake; (2) that such an experiment had to be conducted cleanly; and (3) that no equipment existed to meet these requirements. It was also apparent that the physical conditions of none of the 145 known subglacial lakes (i.e. the size and shape and physiographical setting) were understood in sufficient detail to constrain an exploration plan.

In 1999, to enable the purposeful development of scientific objectives and their delivery, SCAR commissioned an international 'group of specialists' to encourage the sharing of data and plans between individual nations, including the acquisition of geophysical data. Within this framework of SCAR support, a series of advances in our knowledge of Lake Vostok and other subglacial lakes was made. First, Italian geophysicists made the first airborne RES survey of Lake Vostok for 20 years (Tabacco *et al.* 2002). In the Austral summer of 1999–2000, 12 new RES transects were collected, including a continuous line along the 240 km axis of the lake, which confirmed the conclusion of Kapitsa *et al.* (1996) of a large, continuous lake, with margins defined by the satellite-derived flat ice surface. This survey was followed in the 2000–2001 season by 20 000 km worth of line geophysical data, collected by the US Support Office for Aerogeophysical Research, defining both the lake margin in finer (<10 km) resolution (Studinger *et al.* 2003*a*) and its geological setting (Studinger *et al.* 2003*b*).

By around the same time Russian geophysicists had collected a series of ground-based measurements, including seismic data, revealing the shape

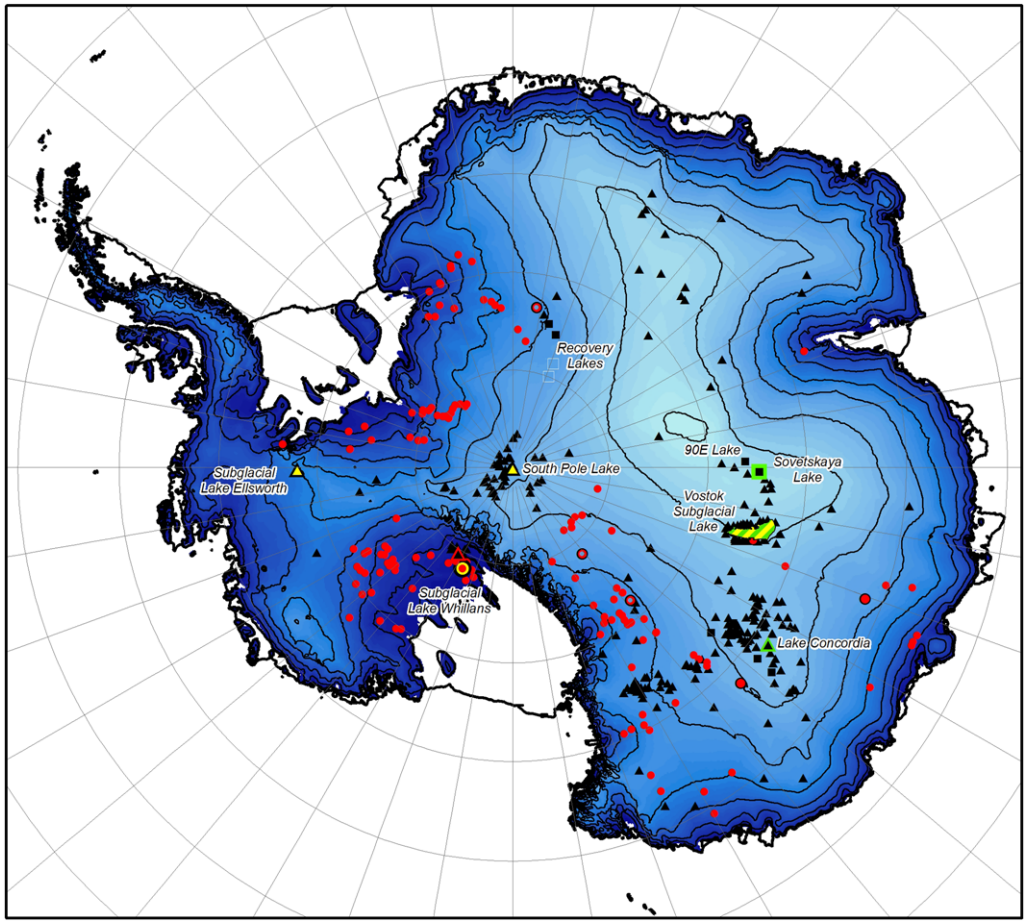

Fig. 4. The inventory of 381 Antarctic subglacial lakes, 2012. Colours/shapes indicate the type of investigations undertaken at each site: Black/triangle, RES; yellow, seismic sounding; green, gravitational field mapping; red/circle, surface height change measurement; square, shape identified from ice surface feature. Lake Vostok is shown in outline. Taken from Wright & Siegert (2012).

of the lake cavity and confirming the water depth to be more than 1 km at its centre (Masolov *et al.* 2001; Siegert *et al.* 2011*a*). These advances in the physiography of Lake Vostok allowed several teams to utilize numerical modelling to comprehend the likely physical conditions within the lake, including temperature, salinity, density and the flow of water (Wüest & Carmack 2000; Williams 2001; Siegert *et al.* 2001; Mayer *et al.* 2003).

Further SCAR involvement and project development

When in 1996 it was confirmed that Vostok Station was located over the southern edge of Lake Vostok, it became instantly apparent that the base of the Vostok ice core, which had recovered a unique record of Earth's atmospheric composition dating back 420 000 years (Petit *et al.* 1999), was only *c.* 150 m from the roof of the lake. Studies of the basal units of the ice core, expecting to take the climate record further back, revealed virtually no gas content, however. Rather than being formed by ice accumulating at the surface, this gas-poor ice was formed instead by lake water freezing to the ice sheet underside, creating over 200 m of 'accreted ice' at the ice sheet base. Thus, the ice core had collected a frozen sample of lake water (Jouzel *et al.* 1999). The accreted ice was distributed to several teams, as part of a Russian, French and US understanding, and was quickly processed for biogeochemical signatures. In the same volume of *Science* magazine that published evidence of the accretion

came two further papers revealing evidence in the accreted ice for microbial life, some of which was culturable (Karl *et al.* 1999; Priscu *et al.* 1999). One problem with the accreted ice samples was that their extraction from the ice sheet involved their being subjected to the ice-core antifreeze (in this case kerosene). As the samples were not obtained cleanly, and were thus potentially contaminated, the findings of life within the accreted ice were open to challenge. Considerable, sometime acrimonious, debate on the fidelity of the accretion ice microbial content followed, but with the realization that these disagreements would be redundant if and when direct, clean samples of the water were acquired.

Given that the ice core was positioned so close to the lake ceiling, Russian scientists focused on using the technology to drill further down and into the lake, to recover direct water samples. National plans for subglacial lake exploration were, subsequently, starting to take shape, prompting SCAR to reform its 'group of specialists' into a formal 'scientific research programme' named Subglacial Antarctic Lake Environments (SALE), which had a remit to coordinate and plan the international exploration of these subglacial systems.

Around 2000, Lake Vostok was seen by many as a special focus for scientific investigation, given its huge size v. other known lakes (as evidenced by the discussion at the international meetings around that time). For some, this focus ignored the facts that the lake was hidden under particularly thick, cold ice, and was located at the very centre of the East Antarctic ice sheet – all of which would contribute to making its exploration more challenging than for other lakes. This focus also ignored the science that might be achieved through exploration of other subglacial lakes; the question of life in the lake water could potentially be answered by any of the lakes, for example. Given the likely significant cost of both the technological development and the fieldwork, it was appropriate to design an objective set of criteria to comprehend which of the Antarctic subglacial lakes was best suited to exploration in the first instance (Siegert 2002). Six criteria were drawn up as follows: (1) does the lake provide the greatest likelihood for attaining the scientific goals; (2) can the lake be characterized in a meaningful way (e.g. size, postulated structure); (3) is the lake representative of other lakes and settings; (4) is the geological/ glaciological setting understood; (5) is the lake accessible (what is the closest infrastructure); and (6) is the programme feasible within cost and logistical constraints? Siegert (2002) concluded that one of the relatively small (*c.* 10 km long) subglacial lakes, beneath the thinner, warmer ice in West Antarctica, would be best suited for the first clean direct exploration of a subglacial lake. The advantage that such a lake would have over lakes beneath relative thick, cold ice was that it made the prospect of using hot-water drilling, allowing potentially clean access to the lake, relatively feasible. This analysis was quickly followed by the SALE group's evaluation of the programme, and its timeframe, that would be needed for such exploration (Priscu *et al.* 2003), the discovery of Lake Ellsworth (which had not featured in the 1996 inventory) as a 'candidate for subglacial lake exploration' (Siegert *et al.* 2004) and the updated inventory of 145 lakes (Siegert *et al.* 2005). As a consequence, by 2005, Lake Vostok was no longer the prime focus of attention for many, although it remained key to Russian scientific plans given the infrastructure already in place at Vostok Station, and because the ice core borehole was so close to the surface of the lake.

In 2006, a fifth international meeting, organized by Jean-Robert Petit (a member of SALE), was held at Grenoble, France. Its purpose was to shift the discussion from the scientific drivers for subglacial lake exploration (as these had become clear from previous meetings) to the practical plans necessary to deliver an exploration programme. By this time, a UK team had established Lake Ellsworth as a preferred candidate for exploration, having funding in place to conduct a comprehensive geophysical investigation of the lake to determine its dimensions and physiographical setting. Hence, with Russian scientists maintaining interests in Lake Vostok, two separate programmes began to form. In the US, the National Academy of Sciences (NAS) undertook an independent assessment of the exploration of subglacial aquatic environments with the intention of defining a set of standards for responsible exploration of these systems (National Research Council 2007). SALE evaluated the report and accepted its findings, promoting cleanliness of any direct measurement and sampling experiment as paramount over other considerations. While it failed to offer a view of which technology was best suited to clean exploration, the NAS report made a clear and thoughtful critique of the various techniques available, including their potential pitfalls on this key issue, from which an individual could reach an objective understanding of the form of experiment needed.

As a consequence, and through discussions held previously by SALE, many concluded that hot-water drilling was the only feasible means by which 'clean' direct access to a subglacial lake environment could be achieved, with the notable exception of members of the Russian programme on Lake Vostok, whose focus remained on using the on-site ice-coring technology. The Russian position drew criticism from some (for example the Committee on Environmental Protection, CEP, of the Antarctic Treaty Consultative Committee, ATCM), over continued plans to use the kerosene-filled borehole to access Lake Vostok and, potentially, deploy instruments.

In 2007, following the identification of 'active' lakes within Whillans Ice Stream in West Antarctica, plans began to form surrounding the direct investigation of the one of the lakes, named Lake Whillans, the ice-sheet grounding zone downstream of the lake and the subglacial ice shelf environment. Hence, by the end of the first decade of the twenty-first century, three programmes had been initiated: a trilogy of US programmes on the Whillans ice stream system; the UK programme on Lake Ellsworth; and the Russian programme on Lake Vostok.

Plans for exploration

A ground-based geophysical survey of the Lake Ellsworth region, over two seasons in 2007–08 and 2008–09, revealed the lake to be buried beneath 3–3.3 km of ice, around 14 km long, 2–3 km wide and up to 160 m deep, thus confirming it as a deep-water subglacial lake and an ideal candidate for direct measurement sampling (Woodward *et al.* 2010). The data revealed the likely presence of sediments on the lake floor, and that the lake was contained within a subglacial topographic valley, formed by the action of dynamic glacial erosion when the West Antarctic Ice Sheet was restricted to regional highlands (Ross *et al.* 2014). The data also identified the best location to attempt direct access, based on maximizing scientific value whilst minimizing experimental cost. As a consequence of the first field-season's results, and through an extensive proposal to design, build and deploy bespoke equipment to cleanly drill through 3.3 km of ice, and to measure and sample the lake water and sediment, funding was awarded in late 2008 to undertake the exploration mission.

Lake Whillans was first identified through analysis of time-series satellite altimetry; the ice surface was observed to rise and lower twice as a consequence of two cycles of water input and discharge, respectively (Fricker *et al.* 2011). The boundaries of the surface change were well defined, implying that a single lake had received and issued the water, and that the lake's boundaries were robust to the inferred hydrological changes. Radar confirmed the outline of the lake, and measured the ice thickness over it to be *c.* 800 m. Seismic studies over the lake revealed no evidence for its depth, however, implying that it was either probably shallow (of the order of the wavelength of the sound wave in ice, *c.* 4 m) or was completely drained during data acquisition. Indeed there was an understanding that the depth of water would be likely to change in time owing to inputs of water from upstream and discharges. As a consequence of the US Obama Stimulus Package of funding for science, following the 2008 financial crash, the trilogy of projects aimed at investigating the Whillans ice stream system were funded, but in a way that merged the projects to form the WISSARD programme, with Lake Whillans being a priority.

Hence, by 2008, funding was in place to support the exploration of Lake Ellsworth and Lake Whillans, as well as continued Russian work at Lake Vostok. As a consequence, the SCAR SALE programme concluded that it had met its original terms of reference and, therefore, the final meeting was held in 2009 to formally close the programme.

To continue international dialogue between the three most prominent nations, and others, an AGU Chapman Conference was convened in Baltimore in March 2010 (Siegert *et al.* 2011*b*) – the sixth international meeting on subglacial lake exploration. Uniquely, the conference gave an opportunity for engineers to discuss the design of hot-water drills, equipment for water measurement and sampling and sediment recovery, and protocols for experimental cleanliness and environmental stewardship.

Following this meeting, SCAR drafted a 'code of conduct' on Antarctic subglacial lakes exploration, ratified at the 2011 ATCM (held in Buenos Aires, Argentina), which explained the scientific basis for cleanliness and the requirement for this to be achieved under *in situ* measurement and sampling. For the Lake Ellsworth programme, a prerequisite for exploration was a comprehensive environmental evaluation (CEE; as recommended by the 2007 NAS report) agreed by the ATCM CEP. The CEE was submitted to the Buenos Aires Meeting, and was ratified the following year, paving the way for the exploration of Lake Ellsworth to take place. The WISSARD programme did not complete a CEE because, in the opinion of US authorities, its exploration could be covered by existing permits, as it was located at the edge of the grounded ice sheet where direct access had occurred several times in the 1990s for glaciological purposes. Nonetheless, both the Lake Ellsworth and Whillans programmes were designed to be fully compliant with the SCAR code of conduct on subglacial lake access. By the end of 2011 subglacial access programmes were ready to commence at Lake Vostok, Lake Ellsworth and Lake Whillans.

Subglacial lake exploration

Lake Vostok

In February 2012, the Vostok ice core was continued to base of the ice sheet and into the surface water of Lake Vostok. In so doing the Russian programme became the first to access a subglacial lake. If there was ever a 'race', the Russian scientists had certainly won.

As the ice core's antifreeze drilling fluid, kerosene, is lighter than water, at the point of lake penetration lake water rushed into the borehole, leading to a hydrological shock in the lower borehole and the development of cracks within the ice core walls and damage to the drill bit, which caused *c.* 1.5 m^3 of drill fluid to overspill at the surface. On return to the surface, the drill bit was shown to have ice around it, which would have been from the lake water coating the metal and freezing to it (the drill bit retaining its cold temperature as it entered the lake). The lake water within the borehole froze, and was subsequently re-cored the following season to recover a lake sample.

The use of a kerosene-filled ice core to access Lake Vostok was controversial, with several negative comments made about the experiment at the ATCMs in 2010 and 2011, the issue of environmental protection and sample cleanliness being difficult to guarantee with the experiment. Nonetheless, samples of frozen lake water were acquired on which laboratory investigations could be made.

Lake Ellsworth

A purpose-built, clean hot-water drill, and sterile probes and sediment corers were deployed into Antarctica in November 2012 (Siegert *et al.* 2012). In December, the equipment was primed and drilling commenced. A number of issues prevented the drill from working properly, however. First, a component of the drill's electronic burner control unit failed, as did its replacement. The component was found subsequently to be faulty, but since the system was being run below its operating temperature (the unit was switched on at −17°C; ideally it should have been warmed to around 0°C), this could not be guaranteed as the reason for its failure. Nonetheless, this setback caused considerable delay as a new part (a reformed circuit board with a totally new component) had to be flown in. This delay led to the unplanned use of fuel, as the system had to be kept warm to avoid freezing. Although the new component worked well, pre-recorded data that helped optimize the boiler performance had been lost, meaning that the desired water temperature could not be achieved. This led to drilling at a much reduced speed and further unplanned loss of fuel. The drilling procedure required a subsurface reservoir, which had been developed successfully, to be linked by the main bore hole. Despite over 24 h of trying, this link was not made, owing to the boreholes not being drilled perfectly vertically (because of bending of the drill head as a consequence of low melting rates). Without this connection, drilling could not continue, and despite the boiler finally attaining the required temperatures, drilling was ceased on 24 December, owing to the lack of fuel to drill to the lake and to the loss of surface water needed to continue drilling.

Once back in the UK, the Natural Environment Research Council led a formal independent failure review board, in which the causes of the failure were confirmed and recommendations made for their remedy. Details of this review, the issues encountered during fieldwork and the modifications to the drill needed to achieve deep, clean measurement and sampling of subglacial environments, can be found in Siegert *et al.* (2014).

Lake Whillans

In January 2013, Lake Whillans became the first subglacial lake to be accessed using a clean hot water drill, and measured and sampled using clean instruments following agreed protocols (Fricker *et al.* 2011). As a consequence, samples retrieved became the first from a subglacial system in which contamination issues could be assured, adding confidence to the scientific results.

Drilling into the lake was successful, although several technical issues had to be overcome – demonstrating the difficulty inherent in this work. Upon access to the lake, instruments deployed measured the water column at *c.* 1.5 m. Samples of water and sediment were taken, and returned to the surface for both immediate inspection and transfer to laboratories in the USA. They showed that water within Lake Whillans contained 'metabolically active' micro-organisms, and that it was derived primarily from glacial ice melt with a minor component of seawater (Christner *et al.* 2014; Michaud *et al.* 2016), making it unique among known subglacial environments within Antarctica.

That the subglacial environment of Whillans ice stream contains a small level of seawater will not be a surprise to glaciologists as the region has been subject to seawater inundation and marine sedimentation during previous interglacials. The seawater influence is unlikely to be contemporary, as tidal pumping of modern ice-shelf-cavity seawater is limited to a distance of *c.* 10 km upstream of the grounding line, whereas Lake Whillans is *c.* 100 km upstream (Michaud *et al.* 2016). An observed increase in the proportion of seawater with sediment depth suggests that Antarctic groundwater flow may well be important to Whillans ice stream dynamics, as has been demonstrated by numerical ice flow and hydrology modelling (Christoffersen *et al.* 2014; Siegert *et al*. this volume, in press).

Seventh international meeting on subglacial lake exploration

Activity in the months following the fieldwork in 2012–13 varied considerably between respective

nations. While US colleagues were inspecting the samples obtained, UK engineers were involved in examining what had gone wrong with their drill and how best to put it right and Russian scientists were busy considering how to reactivate the ice core to repeat the lake access. At the same time, SCAR organized a global initiative to identify the most important scientific challenges that need to be addressed by 2035 – a 20 year horizon scan.

The scan, led by former SCAR President Chuck Kennicutt from Texas A & M University, with support from the Tinker Foundation, was a community-led activity. It worked by offering an open call for the most important questions to be faced in 20 years' time, with a second call to refine these questions and gather support for those deemed most important. These questions, numbering several hundred, were then attributed to scientific themes, to provide a loose organizational framework for discussion. A retreat was then held in New Zealand in March 2014, involving *c.* 75 scientists, nominated by the community, to consider the top 80 of these questions (details can be found in Kennicutt *et al.* 2015). Following this exercise the Council of Managers of National Antarctic Programmes began a matching exercise, to understand the logistics and engineering challenges that finding the answers to each question would require (Kennicutt *et al.* 2016).

In March 2015, the seventh international meeting on subglacial lake exploration was held at the Royal Society's Chicheley Hall, to discuss the first results and lessons learned from the three exploratory missions (Siegert *et al.* 2016*b*). It also focused on the future development of research. To this end, attendees completed a questionnaire relating to their scientific ambitions and preferred programme arrangements to meet them. Attendees were first asked to list which of the horizon scan questions they planned to address. The top four answers were: (1) how does subglacial hydrology affect ice sheet dynamics, and how important is this linkage; (2) how do the characteristics of the ice sheet bed, such as geothermal heat flux and sediment distribution, affect ice flow and ice sheet stability; (3) how will the sedimentary record beneath the ice sheet inform our knowledge of the presence or absence of continental ice; and (4) 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, downborehole 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, not being restricted 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, testifying to a wide variety of unique subglacial lake environments (Siegert 2016). 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, the majority of responses focused on equipment not yet configured, such as downborehole 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.

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 of 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 of 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 (where possible) to ensure the 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.

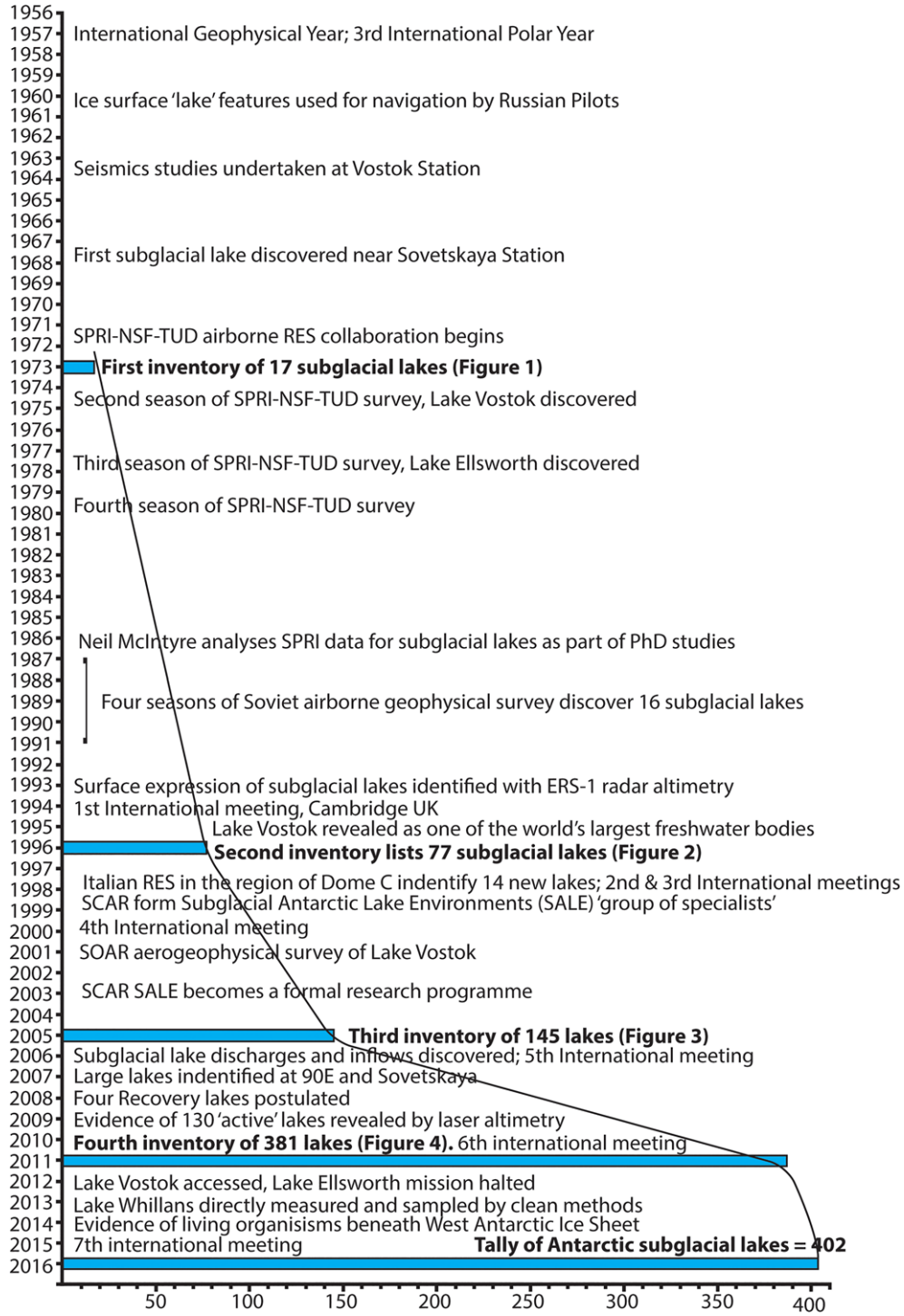

Fig. 5. A timeline of subglacial lake discoveries showing key events between 1956 and 2016. Horizontal bars show the total number of known subglacial lakes in published inventories. Adapted from Wright & Siegert (2012) and Siegert *et al.* (2016*b*).

Future research

Testing the hypotheses of life in the extreme environments of subglacial lakes, and the climate records held in sediments across their floors, continues to drive future research planning. If we speculate that, within 50 years' time, subglacial lake exploration will be common, then between now and then reliable, clean access to deep subglacial environments needs to be established. In doing so, scientific targets in addition to subglacial lakes become possible. For example, we know that there are several deep sedimentary basins in Antarctica, which heavily influence the flow of ice above. Such sediments are likely to be permeable, offering opportunity for water storage (groundwater; Siegert *et al.* 2016*a*; Siegert *et al*. this volume, in press), geological records and, potentially, the build-up of methane owing to biogeochemical processes (Wadham *et al.* 2014).

Medium-sized deep-water lakes at the ice-sheet centre, such as Lake Ellsworth, remain well suited to exploration. However, of the more than 400 known lakes, others are emerging as equally appealing candidates. For example, a large (>100 km long) subglacial lake has been proposed in Princess Elizabeth Land in East Antarctica (Jamieson *et al.* 2016), which is around 100 km from a logistics hub of the Chinese Antarctic programme. If confirmed, it will be one of four subglacial lakes that are controlled by the tectonic setting of the region, the others being Lakes Vostok, Sovetskya (the very first lake to be discovered) and 90E (Bell *et al.* 2006), which all occupy topographic troughs with long axes parallel to one another and roughly orthogonal to ice flow. Exploration of any of these deep, probably ancient, systems may yield substantial scientific advances. Exploring the easiest first is sensible, which places the new discovery as a feasible and realistic target for exploration in the coming years.

Summary and discussion

A time-line of selected key events within the history of subglacial lake exploration is provided in Figure 5. Sixty years ago, glaciologists were perfecting the field measurement of deep subglacial environments through pioneering developments in seismic and radar sounding. This early work led directly (i.e. provided data as well as methods) to the discovery of Lake Vostok as a huge deep-water body, buried beneath 4 km of ice for potentially millions of years. As a consequence, it was hypothesized to represent a unique and ancient environment for microbial life and a recorder of climate change. As these hypotheses are testable with direct measurement and sampling, the exploration of subglacial lakes became a serious proposition from the mid-1990s.

International discussion on how and where to explore in Antarctica was supported by SCAR, which convened a group of specialists, a scientific research programme and several international meetings. It also oversaw the development of protocols to protect these pristine sites from unnecessary contamination and disturbance. Slowly, three programmes began to take shape: a Russian plan to use the ice core facility at Vostok Station to break through the ice; a US programme to sample the hydrologically active bed of Whillans ice stream, including Lake Whillans; and a UK-led project to investigate Lake Ellsworth.

As it is easy to see the similarities between the projects – they are subglacial lakes – the notion of a 'race' between nations to explore these environments was reported regularly in the international media. However, while research is an inherently competitive business, participants of the three programmes did not view the competition as a race, in large part because of the distinctions between the three environments, Lake Vostok being huge and in East Antarctica, Lake Ellsworth being medium-sized and in West Antarctica, and Lake Whillans being shallow and potentially ephemeral. The fact that there was regular correspondence between the programmes, via SCAR and through seven international symposia, testifies to the openness of the programmes, in line with the long-held spirit of Antarctic research.

In February 2012, Lake Vostok was penetrated by the Russian Ice Core, allowing frozen lake water to be recovered by subsequent re-coring. In December 2012, the UK-led mission to Lake Ellsworth was halted owing to technical issues with the deep-ice drill. In January 2013, the US programme to Lake Whillans successfully recovered samples, demonstrating the ice base here to contain viable microorganisms. While these 12 months saw considerable advances in our knowledge of subglacial lake environments, and our ability to explore them, the main drivers for the exploration, namely the two hypotheses on life in ancient deep-water subglacial environments and on climate records, remain strictly untested. When one considers this, and the fact that there are over 400 known subglacial lakes, one can see why subglacial lakes research remains in its infancy as a topic.

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