Exploration of subsurface Antarctica: uncovering past changes and modern processes

MARTIN J. SIEGERT[1]*, STEWART S. R. JAMIESON[2] & DUANNE WHITE[3]

[1]*Grantham Institute and Department of Earth Science and Engineering, Imperial College London, London, SW7 2AZ, UK*

[2]*Department of Geography, Durham University, South Road, Durham, DH1 3LE, UK*

[3]*Institute for Applied Ecology, University of Canberra, Canberra, ACT 2617, Australia*

Correspondence: m.siegert@imperial.ac.uk

Abstract: The Antarctic continent, which contains enough ice to raise sea level globally by around 60 m, is the last major scientific frontier on our planet. We know far more about the surfaces of the Moon, Mars and around half of Pluto than we do about the underside of the Antarctic ice sheet. Geophysical exploration is the key route to measuring the ice sheetâ s internal structure and the land on which the ice rests. From such measurements, we are able to reveal how the ice sheet flows, and how it responds to atmospheric and ocean warming. By examining landscapes that have been moulded by former ice flow, we are able to identify how the ice sheet behaved in the past. Geophysics is therefore critical to understanding change in Antarctica.

Numerical ice-sheet modelling reveals that, under atmospheric and ocean warming, the Antarctic ice sheet is likely to lose mass in the future and contribute to rising sea levels. Despite advances in modelling technology, our appreciation of ice-flow processes suffers from a lack of observations in critical regions (such as grounding lines and ice streams). The problem is these processes take place beneath the ice surface (englacially or subglacially), requiring the use of geophysics for their measurement. In this volume, we gather together a series of papers concerning the exploration of subsurface Antarctica, which collectively demonstrate how geophysics can be deployed to comprehend: (1) boundary conditions that influence ice flow such as subglacial topography, the distribution of basal water and ice-sheet rheology; (2) phenomena that might affect ice-flow processes, such as complex internal ice-sheet structures and the proposition of large stores of hitherto unappreciated groundwater; and (3) how glacigenic sediments and formerly glaciated terrain on, and surrounding, the continent can inform us about past ice-sheet dynamics. The volume takes a historical view on developments leading to current knowledge, examines active ice-sheet processes, and points the way forward on how geophysics can advance quantitative understanding of Antarctic ice-sheet behaviour.

Historical perspective

In 1950 little was known about the size and shape of the Antarctic continent, the volume of ice stored there, how this had changed in the past or what its impacts upon the rest of the globe could be. Expeditions to this point had been adventurous and, while some basic scientific data had been collected, widespread surveying of the ice sheet and the land beneath had not been contemplated in a systematic manner. With the advent of geophysical techniques such as seismic sounding, and the development of glaciology as a scientific discipline, the first serious attempts to measure the ice thickness began in 1952 (Naylor *et al.* 2008), when a young glaciologist named Gordon Robin, as part of the Norwegian–British–Swedish expedition to Dronning Maud Land in East Antarctica, revealed how active seismology could be deployed on ice sheets to get consistently reliable measurements of the thickness of ice and of the bed beneath (Robin 1953, 1958). This technical advance was influential in the pioneering exploratory overland traverses conducted as part of the International Geophysical Year (1957–58), in which Russian and US teams obtained seismic transects in East and West Antarctica, respectively. The findings showed that Antarctica was one continent (it seems incredible to understand now that in the 1950s this was not known), that the West

From: Siegert, M. J., Jamieson, S. S. R. & White, D. A. (eds) 2018. *Exploration of Subsurface Antarctica: Uncovering Past Changes and Modern Processes*. Geological Society, London, Special Publications, **461**, 1–6.
First published online September 25, 2017, https://doi.org/10.1144/SP461.15

Antarctic ice sheet contained ice up to 4 km thick, resting on a bed as much as 2 km below sea level, and that much of the East Antarctic ice sheet was on a bed largely above sea level. Despite these ground-breaking advances, basic questions remained on the size and shape of the continent, and the processes through which ice on it flowed.

One problem was the time-consuming process of acquiring seismic data, requiring holes to be drilled ~50 m into the ice for both the seismic charge and the geophones (according to Robin's methodological refinements). Robin himself made the breakthrough, in which his Cambridge team demonstrated the utility of radar mounted on an aircraft to obtain information on ice thickness at a rate that is more than 10 000 times faster than from seismics alone. Airborne radar, or radio-echo sounding (RES) as Robin and his colleagues referred to it, transformed our ability to map the ice sheet and the continent beneath (Dean *et al.* 2008).

What followed was one of the key scientific expeditions in the history of Antarctic exploration – a UK–US–Danish programme of long-range airborne surveying of Antarctica over several seasons during the 1970s. Around half of the continent was mapped in this decade, revealing the landscape beneath the ice (Drewry 1983), structures within the ice (Millar 1981), water (including lakes) at the bed (Oswald & Robin 1973), and evidence of dynamic ice-sheet change (Rose 1979). At around this time the first numerical ice-sheet models were being developed (Budd & Smith 1982), requiring as input a determination of the basal topography of Antarctica (Drewry 1983).

The 1980s was characterized by a cessation of long-range airborne surveying in Antarctica. In its place, site-specific hypothesis-driven research often used the RES data collected a decade earlier to form a scientific case that was then developed further using additional targeted geophysics (Turchetti *et al.* 2008). A step-change in knowledge generated from such geophysical fieldwork was the confirmation that many ice streams lay over weak sediments (Blankenship *et al.* 1986), and that subglacial hydrology was critical to the flow of ice above (Alley 1989).

Technology again moved Antarctic scientific progress forward in the late 1980s and early 1990s, with the advent of satellite remote sensing, and in particular the European Remote Sensing satellite (ERS-1), which allowed highly accurate measurements of the ice surface elevation, and Radarsat, which imaged the surface morphology of the ice. Such data were used to identify flat, featureless regions as the extent of lakes beneath the ice (see **Siegert 2017**). By this time it was possible for the outputs of ice-sheet models to be compared with the modern surface elevation of the ice sheet, the flow pattern of ice and the degree to which the bed was frozen or warm (Huybrechts 1990), from which a suitably 'tuned' model (adjusting flow parameters so that output matched the modern measurements) could then be used to ascertain how the future ice sheet would behave under global warming scenarios (Huybrechts & de Wolde 1999). By 2000, ice-sheet models were still being run on a depiction of bed topography established in 1983, and which was based on data collected a decade earlier. The Scientific Committee on Antarctic Research (SCAR) commissioned the collation of new geophysical data, to form an updated elevation model for Antarctica – Bedmap (Lythe *et al.* 2001). While Bedmap was certainly an improvement on the Drewry (1983) bed topography, the lack of data collected since the 1970s was apparent, with large data-free areas remaining, and thus adding significant uncertainty to model results.

The necessity for ice-sheet models to be fed by accurate topography, and for glacial processes to be identified and resolved at high resolution, was underlined by time-series satellite altimetric data, which showed major loss of ice across the northern seaward margin of the West Antarctic Ice Sheet due to ocean-driven melting (Pritchard *et al.* 2012). A complete understanding of the processes involved both here and elsewhere in Antarctic was significantly held up by a lack of geophysical data. To fill the obvious data void, numerous projects acquiring airborne geophysical data were established, including the US–UK–Australian ICECAP (International Collaborative Exploration of Central East Antarctica through Airborne geophysical Profiling), the US CReSIS (Center for the Remote Sensing of Ice Sheets) and NASA OIB (Operation Ice Bridge) programmes. The data collected by these and other programmes led to the formation of a much revised Antarctic bed product, named Bedmap2 (Fretwell *et al.* 2013). This quantitative knowledge of the modern ice-sheet bed has been combined with geophysical data from beyond the ice margin and with measurements from the currently ice-free regions of Antarctica to expand our understanding of how the modern ice sheet came to reach its current configuration.

Current status of Antarctic research

The utility of geophysics in Antarctica cannot be overstated in terms of the scientific advances that have resulted. Yet many basic questions about the form and flow of the ice remain. In 2014, SCAR led an initiative to identify the most pressing scientific questions that needed to be answered in the following 20 years; it formed an international horizon scan of 80 scientific questions (Kennicutt *et al.*

2015) and an accompanying assessment of the role of logistics and technology in being able to answer them (Kennicutt *et al.* 2016). The horizon scan results underline how little we know about the subsurface of Antarctica, how ill-equipped we are to accurately predict future sea-level change, and indeed how geophysics remains the only viable way of getting the necessary observations and measurements consistently, and over large and remote areas. Of the 80 questions in the scan at least 14 relate to subsurface Antarctica and focus on: (1) revealing the structural evolution and age of the subglacial landscape, (2) determining how basal morphology affects ice-sheet flow; (3) assessing how important subglacial hydrology is to ice flow; (4) quantifying geothermal heat flux; (5) understanding how tectonics influences sea-level change; (6) comprehending how volcanism may influence ice dynamics; and (7) recognizing subglacial environments as viable habitats for microbial life.

Introduction to the volume

This volume is the first book on Antarctic subglacial exploration since the horizon scan, and allows an initial assessment of the immediate international response to it in some areas. It includes studies from across the Antarctic continent, revealing the geographical spread of subsurface exploration and investigation (Fig. 1). New airborne geophysical studies of the ice-sheet bed, geology and hydrology are described by **Forsberg *et al.* (2017)** through an assessment of the large subglacial lakes that exist at the heads of the Recovery ice stream system, and the deeply eroded topography that lies between them and the coast. The work provides essential boundary conditions that will both add to Bedmap2, and lead to better models of ice-sheet change because it characterizes the bed in new detail where it lies below sea level. Further airborne geophysical data are discussed in **Beem *et al.* (2017)**, where the seemingly contradictory evidence of basal freezing at the South Pole coincident with a subglacial lake is explained by significant change in the region, leading to the lake being a legacy of basal conditions from more than 10 000 years ago.

Past changes in Antarctica highlight the emerging trend of larger responses in the northern latitudes compared to those in the south. In the sub-Antarctic, **White *et al.* (2017)** consider glacial sediments on South Georgia to suggest a large ice mass existed at this location at the last glacial maximum 20 000 years ago. On the Antarctic Peninsula, marine sediments are also measured by **Casas *et al.* (2017)**, whose assessment of mass transport processes in sedimentary fans has implications for characterizing past ice-sheet dynamics and rapid and large-scale movements of the ice margin over numerous glacial cycles. At the Wilkes Land margin of East Antarctica, **Pandey *et al.* (2017)** describe how heavy minerals in marine sediments can be used to define provenance of the material and, from this, an assessment of past East Antarctic ice sheet behaviour. Across the Schirmacher Oasis, in Donning Maud Land, **Swain (2017)** describes the bathymetry of a number of surface lakes to ascertain the geomphological characteristics on which they lay and, from this, provides an evaluation of their evolution.

Radar is used by both **Wrona *et al.* (2017)** and **Wang *et al.* (2017)**, to investigate internal layers beneath Dome A in East Antarctica: the former reveal a variety of complex englacial structures indicative of unappreciated ice-flow processes and non-uniform ice rheology; the latter identify layers of distinct crystal fabrics that develop under enhanced englacial stress and modify the nature of ice flow. At Dome A, **Talalay *et al.* (2017)** describe how the ice sheet may be drilled to directly sample these compelling englacial structures and reveal their crystallographic and rheological nature.

Towards the ice-sheet margin, **Jeofry *et al.* (2017)** use airborne geophysics to discover a subglacial embayment near the Institute Ice Stream in West Antarctica that is probably connected to the ice-shelf cavity, and which may influence how the ice stream responds to the ocean-driven warming predicted towards the end of this century. Meanwhile, across the other side of the continent in East Antarctica, **Roberts *et al.* (2017)** use airborne radar, satellite data and numerical modelling to explain how ice-flow changes observed on Totten Glacier relate to ocean-driven melting in a manner similar to that proposed across vulnerable margins in the Amundsen Sea.

Concerning water beneath the ice sheet, **Alekhina *et al.* (2017)** use early results from the exploration of Lake Vostok in 2012 to understand the chemical nature of water that was collected within the ice-core borehole, while **Siegert *et al.* (2017)** describe an experiment that may enable the identification and measurement of stores of groundwater beneath the ice-sheet bed, and that may demonstrate how the influence of such water, although poorly quantified, may be integral to the macro flow of ice in Antarctica. **Goodwin *et al.* (2017)** discuss the subglacial hydrology of Law Dome from geophysical surveying of the ice bed and, importantly, through chemical measurements of water flushed out from beneath the ice cap in 1985 and 2014. By examining ice-marginal sediments, including rare Polar ooids, they show such events have occurred regularly in the past and infer similar outbursts may occur in other regions of East Antarctica. Finally, **van Wyk de Vries *et al.* (2017)** assess the geophysical evidence for volcanic activity in West Antarctica,

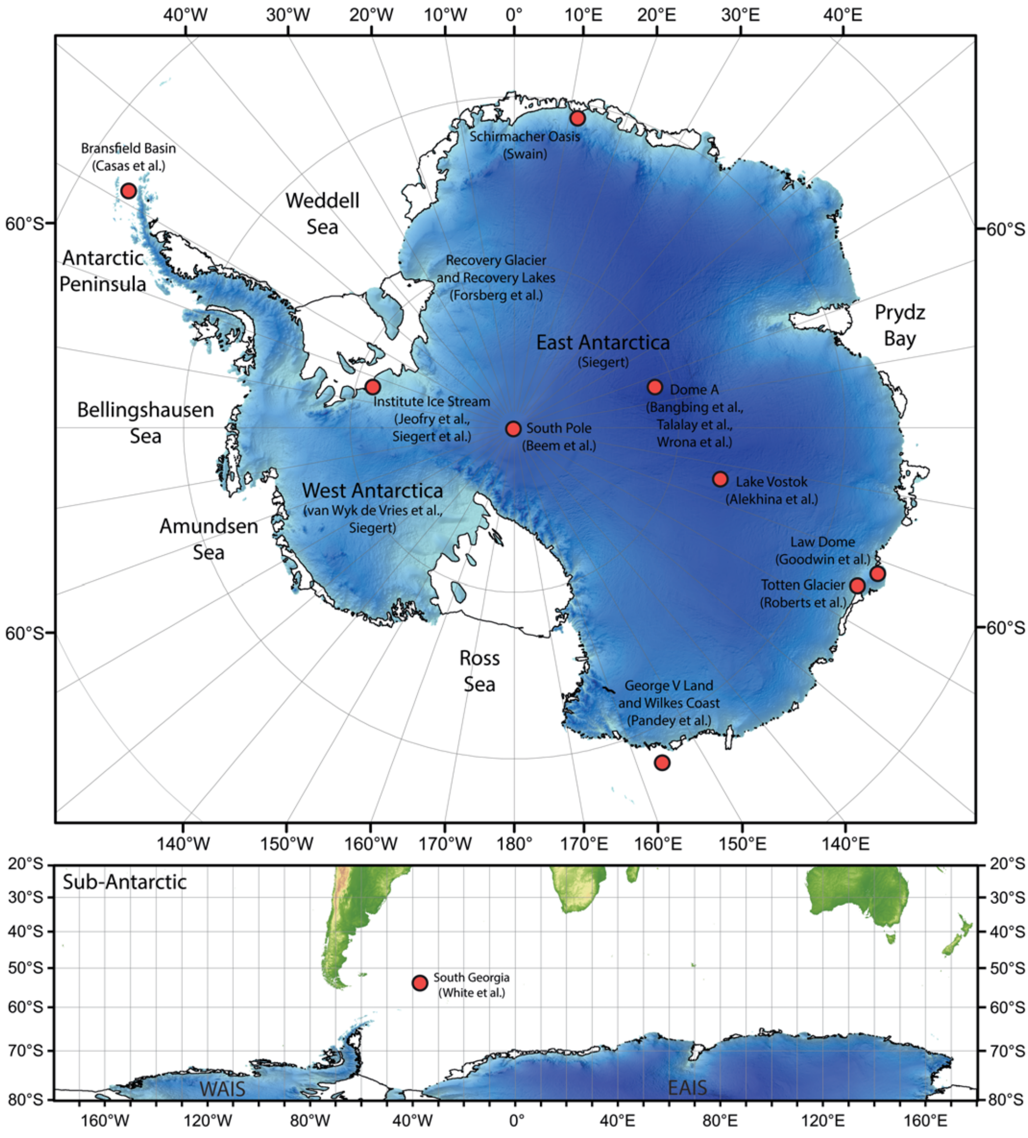

Fig. 1. Surface image of Antarctica with locations of field sites (red dots) referred to in the papers of this volume as follows: Dome A region (Wrona *et al.* 2017; Talalay *et al.* 2017; Wang *et al.* 2017); Offshore George IV Land Wilkes Coast (IODP 318) (Pandey *et al.* 2017); South Georgia (White *et al.* 2017); Bransfield Basin (Antarctic Peninsula) (Casas *et al.* 2017); Schirmacher Oasis (central Dronning Maud Land) (Swain 2017); Institute Ice Stream grounding line (Jeofry *et al.* 2017) and trunk (Siegert *et al.* 2017); Lake Vostok (Alekhina *et al.* 2017); South Pole (Beem *et al.* 2017); Totten Glacier (Roberts *et al.* 2017); Recovery Glacier and Recover Lakes (Forsberg *et al.* 2017); West Antarctic volcanics (van Wyk de Vries *et al.* 2017).

providing an inventory of proposed volcanoes beneath the ice sheet, which are testament to high levels of geothermal heat flux, which acts as an important parameter for the production of basal water and, thus, ice sheet processes.

The collection of papers in this volume cannot claim to cover all research on subglacial Antarctica. They do, however, align closely with many of the SCAR horizon scan questions relevant to Antarctic glaciology, hydrology and geology. Together, they constitute evidence that the most important scientific questions that we can ask in Antarctic exploration are being taken seriously by the community and are a demonstration that the active application of geophysics still has much to contribute to our understanding of the white continent.

Several of the papers listed in this volume were presented at meetings supported by the Scientific Committee on Antarctic Research (SCAR), including the 12th International Symposium on Antarctic Earth Sciences (Goa, India, August 2015) and the 2016 SCAR Open Science Meeting (Kuala Lumpur, Malaysia, August 2016). We are very grateful to the convenors of these meetings, and to SCAR for assistance in production costs. Finally, we thank the numerous referees for their important comments and recommendations on the papers submitted to this volume.

References

ALEKHINA, I., EKAYKIN, A., MOSKVIN, A. & LIPENKOV, V. 2017. Chemical characteristics of the ice cores obtained after the first unsealing of subglacial Lake Vostok. *In*: SIEGERT, M.J., JAMIESON, S.S.R. & WHITE, D.A. (eds) *Exploration of Subsurface Antarctica: Uncovering Past Changes and Modern Processes*. Geological Society, London, Special Publications, **461**. First published online May 24, 2017, https://doi.org/10.1144/SP461.3

ALLEY, R.B. 1989. Water-pressure coupling of sliding and bed deformation: I. Water System. *Journal of Glaciology*, **35**, 108–118.

BEEM, L.H., CAVITTE, M.G.P. *ET AL.* 2017. Ice-flow reorganization within the East Antarctic Ice Sheet deep interior. *In*: SIEGERT, M.J., JAMIESON, S.S.R. & WHITE, D. A. (eds) *Exploration of Subsurface Antarctica: Uncovering Past Changes and Modern Processes*. Geological Society, London, Special Publications, **461**. First published online August 11, 2017, https://doi.org/SP463.14

BLANKENSHIP, D.D., BENTLEY, C., ROONEY, S.T. & ALLEY, R.B. 1986. Seismic measurements reveal a saturated porous layer beneath an active Antarctic ice stream. *Nature*, **332**, 54–57.

BUDD, W.F. & SMITH, I.N. 1982. Large-scale numerical modelling of the Antarctic ice sheet. *Annals of Glaciology*, **3**, 42–49.

CASAS, D., GARCIA, M., BOHOYO, F., MALDONADO, A. & ERCILLA, G. 2017. The Gebra-Magia Complex: mass-transport processes reworking trough-mouth fans in the Central Bransfield Basin (Antarctica). *In*: SIEGERT, M.J., JAMIESON, S.S.R. & WHITE, D.A. (eds) *Exploration of Subsurface Antarctica: Uncovering Past Changes and Modern Processes*. Geological Society, London, Special Publications, **461**. First published online June 16, 2017, https://doi.org/10.1144/SP461.10

DEAN, K., NAYLOR, S. & SIEGERT, M. 2008. Data in Antarctic science and politics. *Social Studies of Science*, **38/4**, 571–604.

DREWRY, D.J. 1983. *Antarctica: Glaciological and Geophysical Folio*. Scott Polar Research Institute, University of Cambridge, UK.

FORSBERG, R., OLESEN, A.V., FERRACCIOLI, F., JORDAN, T.A., MATSUOKA, K., ZAKRAJSEK, A., GHIDELLA, M. & GREENBAUM, J.S. 2017. Exploring the Recovery Lakes region and interior Dronning Maud Land, East Antarctica, with airborne gravity, magnetic and radar measurements. *In*: SIEGERT, M.J., JAMIESON, S.S.R. & WHITE, D.A. (eds) *Exploration of Subsurface Antarctica: Uncovering Past Changes and Modern Processes*. Geological Society of London, Special Publications, **461**. First published online September 20, 2017, https://doi.org/10.1144/SP461.17

FRETWELL, P., PRITCHARD, H.D. *ET AL.* 2013. Bedmap2: improved ice bed, surface and thickness datasets for Antarctica. *The Cryosphere*, **7**, 375–393.

GOODWIN, I.D., ROBERTS, J.L., ETHERIDGE, D.M., HELLSTROM, J., MOY, A.D., RIBO, M. & SMITH, A.M. 2017. Modern to Glacial age subglacial meltwater drainage at Law Dome, coastal East Antarctica from topography, sediments and jökulhlaup observations. *In*: SIEGERT, M. J., JAMIESON, S.S.R. & WHITE, D.A. (eds) *Exploration of Subsurface Antarctica: Uncovering Past Changes and Modern Processes*. Geological Society, London, Special Publications, **461**. First published online July 12, 2017, https://doi.org/10.1144/SP461.16

HUYBRECHTS, P. 1990. A 3-D model for the Antarctic Ice Sheet: a sensitivity study on the glacial-interglacial contrast. *Climate Dynamics*, **5**, 79–92.

HUYBRECHTS, P. & DE WOLDE, J. 1999. The dynamic response of the Greenland and Antarctic ice sheets to multiple-century climate warming. *Journal of Climate*, **12**, 2169–2188.

JEOFRY, H., ROSS, N., CORR, H.F.J., LI, J., GOGINENI, P. & SIEGERT, M.J. 2017. A deep subglacial embayment adjacent to the grounding line of Institute Ice Stream, West Antarctica. *In*: SIEGERT, M.J., JAMIESON, S.S.R. & WHITE, D.A. (eds) *Exploration of Subsurface Antarctica: Uncovering Past Changes and Modern Processes*. Geological Society, London, Special Publications, **461**. First published online June 13, 2017, https://doi.org/10.1144/SP461.11

KENNICUTT, M., CHOWN, S.L. *ET AL.* 2015. A roadmap for Antarctic and Southern Ocean science for the next two decades and beyond. *Antarctic Science*, **27**, 3–18, https://doi.org/10.1017/S0954102014000674

KENNICUTT, M., KIM, Y. *ET AL.* 2016. Enabling 21st century Antarctic and Southern Ocean science. *Antarctic*

Science, **28**, 407–423, https://doi.org/10.1017/S09541020160 00481

Lythe, M.B., Vaughan, D.G. *et al.* 2001. BEDMAP: a new ice thickness and subglacial topographic model of Antarctica. *Journal of Geophysical Research*, **106**, 11335–11351.

Millar, D.H.M. 1981. Radio-echo layering in polar ice sheets and past volcanic activity. *Nature*, **292**, 441–443.

Naylor, S., Dean, K. & Siegert, M.J. 2008. The IGY and the ice sheet: surveying Antarctica. *Journal of Historical Geography*, **34**, 574–595.

Oswald, G.K.A. & Robin, G.de Q. 1973. Lakes beneath the Antarctic Ice Sheet. *Nature*, **245**, 251–254.

Pandey, M., Pant, N.C., Biswas, P., Shrivastava, P.K., Joshi, S. & Nagi, N. 2017. Heavy mineral assemblage of marine sediments as an indicator of provenance and east antarctic ice sheet fluctuations. *In*: Siegert, M.J., Jamieson, S.S.R. & White, D.A. (eds) *Exploration of Subsurface Antarctica: Uncovering Past Changes and Modern Processes*. Geological Society, London, Special Publications, **461**. First published online June 22, 2017, https://doi.org/10.1144/SP461.2

Pritchard, H.D., Ligtenberg, S.R.M., Fricker, H.A., Vaughan, D.G., van den Broeke, M.R. & Padman, L. 2012. Antarctic ice-sheet loss driven by basal melting of ice shelves. *Nature*, **484**, 502–505, https://doi.org/10.1038/nature10968

Roberts, J., Galton-Fenzi, B.K. *et al.* 2017. Ocean forced variability of Totten Glacier mass loss. *In*: Siegert, M. J., Jamieson, S.S.R. & White, D.A. (eds) *Exploration of Subsurface Antarctica: Uncovering Past Changes and Modern Processes*. Geological Society, London, Special Publications, **461**. First published online August 23, 2017, https://doi.org/10.1144/SP461.6

Robin, G.de Q. 1953. Norwegian-British-Swedish Antarctic Expedition, 1949–52, Polar Record 6, 608–616.

Robin, G.de Q. 1958. *Norwegian-British-Swedish Antarctic Expedition 1949–52 Scientific Results, Vol. 5. Glaciology III: Seismic Shooting and Related Investigations*. Norsk Polarinstitutt, Oslo.

Rose, K.E. 1979. Characteristics of ice flow in Marie Byrd Land, Antarctica. *J. Glaciol.*, **24**, 63–75.

Siegert, M.J. 2017. A 60-year international history of Antarctic subglacial lake exploration. *In*: Siegert, M.J., Jamieson, S.S.R. & White, D.A. (eds) *Exploration of Subsurface Antarctica: Uncovering Past Changes and Modern Processes*. Geological Society, London, Special Publications, **461**. First published online May 25, 2017, https://doi.org/10.1144/SP461.5

Siegert, M.J., Kulessa, B. *et al.* 2017. Antarctic subglacial groundwater: a concept paper on its measurement and potential influence on ice flow. *In*: Siegert, M.J., Jamieson, S.S.R. & White, D.A. (eds) *Exploration of Subsurface Antarctica: Uncovering Past Changes and Modern Processes*. Geological Society, London, Special Publications, **461**. First published online May 25, 2017, https://doi.org/10.1144/SP461.8

Swain, A.K. 2017. Bathymetry of Schirmacher lakes as a tool for geomorphological evolution studies. *In*: Siegert, M.J., Jamieson, S.S.R. & White, D.A. (eds) *Exploration of Subsurface Antarctica: Uncovering Past Changes and Modern Processes*. Geological Society, London, Special Publications, **461**. First published online July 11, 2017, https://doi.org/10.1144/SP461.13

Talalay, P., Sun, Y. *et al.* 2017. Drilling project at Gamburtsev Subglacial Mountains, East Antarctica: recent progress and plans for the future. *In*: Siegert, M.J., Jamieson, S.S.R. & White, D.A. (eds) *Exploration of Subsurface Antarctica: Uncovering Past Changes and Modern Processes*. Geological Society, London, Special Publications, **461**. First published online May 24, 2017, https://doi.org/10.1144/SP461.9

Turchetti, S., Dean, K., Naylor, S. & Siegert, M. 2008. Accidents and opportunities: a history of the Radio Echo Sounding (RES) of Antarctica, 1958–79. *British Journal of the History of Science*, **41**, 417–444.

van Wyk de Vries, M., Bingham, R.G. & Hein, A.S. 2017. A new volcanic province: an inventory of subglacial volcanoes in West Antarctica. *In*: Siegert, M.J., Jamieson, S.S.R. & White, D.A. (eds) *Exploration of Subsurface Antarctica: Uncovering Past Changes and Modern Processes*. Geological Society, London, Special Publications, **461**. First published online May 29, 2017, https://doi.org/10.1144/SP461.7

Wang, B., Sun, B., Ferroccioli, F., Martin, C., Steinhage, D., Cui, X. & Siegert, M.J. 2017. Summit of the East Antarctic Ice Sheet underlain by thick ice-crystal fabric layers linked to glacialâ interglacial environmental change. *In*: Siegert, M.J., Jamieson, S.S.R. & White, D.A. (eds) *Exploration of Subsurface Antarctica: Uncovering Past Changes and Modern Processes*. Geological Society, London, Special Publications, **461**. First published online May 26, 2017, https://doi.org/10.1144/SP461.1

White, D., Bennike, O., Melles, M., Berg, S. & Binnie, S.A. 2017. Was South Georgia covered by an ice cap during the Last Glacial Maximum? *In*: Siegert, M.J., Jamieson, S.S.R. & White, D.A. (eds) *Exploration of Subsurface Antarctica: Uncovering Past Changes and Modern Processes*. Geological Society, London, Special Publications, **461**. First published online June 13, 2017, https://doi.org/10.1144/SP461.4

Wrona, T., Wolovick, M.J., Ferraccioli, F., Corr, H., Jordan, T. & Siegert, M.J. 2017. Position and variability of complex structures in the central East Antarctic Ice Sheet. *In*: Siegert, M.J., Jamieson, S.S.R. & White, D.A. (eds) *Exploration of Subsurface Antarctica: Uncovering Past Changes and Modern Processes*. Geological Society, London, Special Publications, **461**. First published online June 15, 2017, https://doi.org/10.1144/SP461.12