Exploration of subsurface Antarctica: uncovering past changes and modern processes

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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 that ice-sheet processes take place beneath the ice surface (englacially or subglacially), requiring the use of geophysics to measure. In this volume, we gather 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 may influence 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 might impact the rest of the globe. Expeditions to this point had been adventurous and, while some basic scientific data had been collected, widespread survey 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, 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 both 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 Antarctic ice sheet contained ice up to 4 km thick, resting on a bed as much as 2km below sea level, and that 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 a half of the continent was mapped in this decade, revealing the landscape beneath the ice (Drewry, 1983), structures within the ice (Millar et al., 1982), water (including lakes) at the bed (Oswald and Robin, 1973), and evidence of dynamic ice-sheet change (Rose, 1978). At around this time the first numerical ice sheet models were being developed (Budd and Smith, 1982); requiring as input a determination of the basal topography of Antarctica (Drewry, 1983).

The 1980s was characterised by a cessation of long-range surveying. 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 geophysical research (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 et al., this volume a). By this time ice-sheet models were able to compare their output 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 ascertain how the future ice sheet would behave under global warming scenarios (Huybrechts and 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 and Vaughan, 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 West Antarctica due to ocean-driven melting (Pritchard et al. 2012). The lack of geophysical data available to fully comprehend the processes involved both here and elsewhere in Antarctica was striking. 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), and 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 must be answered in the next 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 both 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) recognising 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 works from across the Antarctic continent, revealing the geographical spread of subsurface exploration and investigation (Figure 1). New airborne geophysical studies of the ice sheet bed, geology and hydrology are described by Forsberg et al. (this volume), 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 characterises the bed in new detail where it lies below sea level. Further airborne geophysical data are discussed in Beem et al. (this volume), where the seemingly contradictory evidence of basal freezing at 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. (this volume), 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. (this volume), whose assessment of mass transport processes in sedimentary fans, has implications for characterising 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. (this volume) 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 behaviour.

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

Toward the ice sheet margin, Jeofry et al. (this volume) use airborne geophysics to discover a subglacial embayment near the Institute Ice Stream in West Antarctica that is likely connected to the ice shelf cavity, and which may influence how the ice stream responds to the ocean-driven warming predicted toward the end of this century. Meanwhile, across the other side of the continent in East Antarctica, Roberts et al. (this volume) 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. (this volume) describe 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. (this volume) describe an experiment that may identify and measure stores of groundwater beneath the ice sheet bed, and how the influence of such water, although poorly quantified, may be integral to the macro flow of ice in Antarctica. Goodwin et al. (this volume) 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 (this volume) assess the geophysical evidence for volcanic activity in West Antarctica, providing an inventory of proposed volcanos 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.

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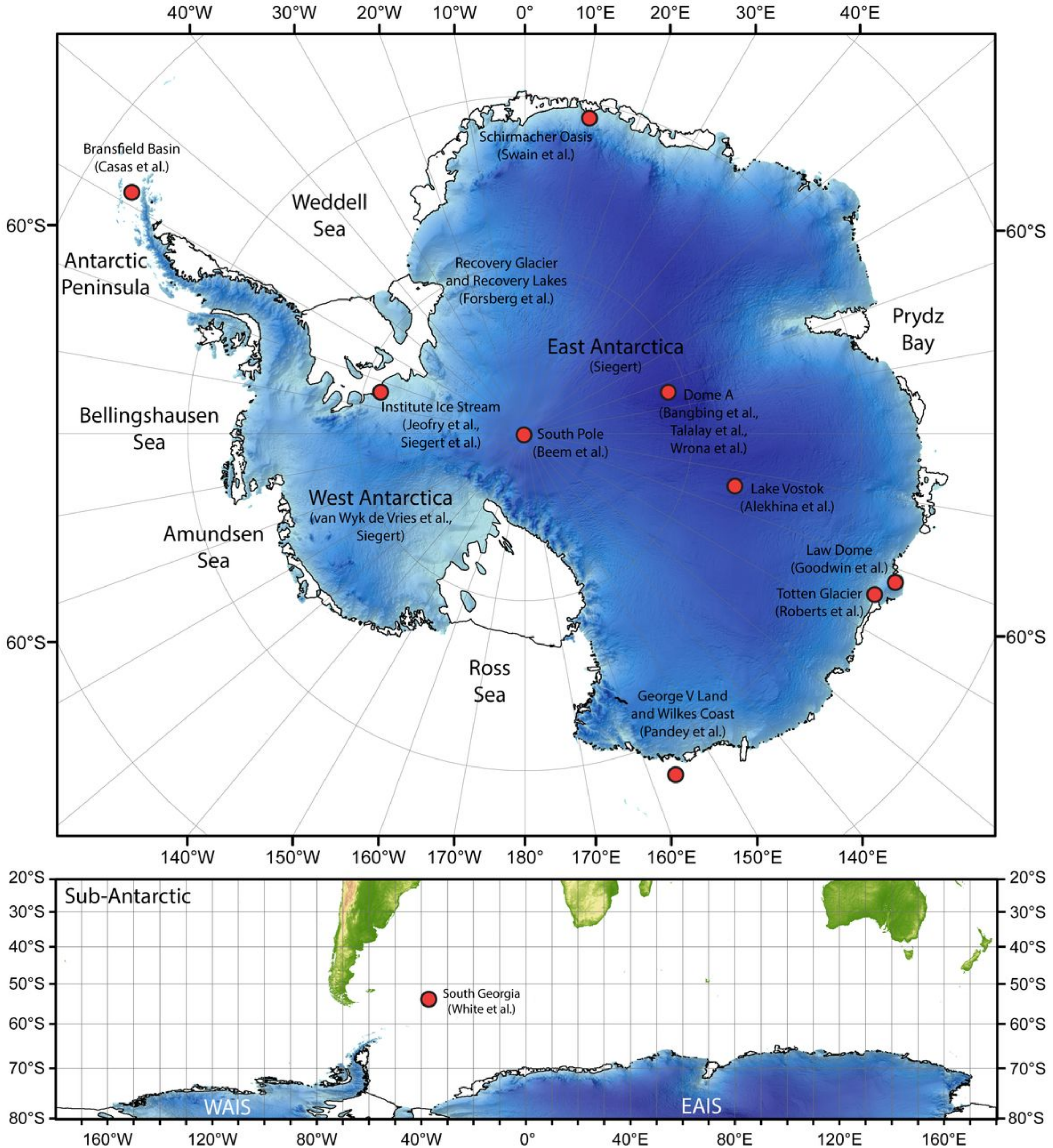
Figure Caption

Figure 1. Bedmap topography of subglacial Antarctica (Fretwell et al., 2013) with locations of fieldsites (red dots) referred to in the papers of this volume as follows: Dome A region (Wrona et al.; Talalay et al.; Bangbing et al.); Offshore Wilkes Land (IODP 318) (Pandey et al.); South Georgia (White et al.); Bransfield Basin (Antarctic Peninsula) (Casas et al.); Schirmacher Oasis (central Dronning Maud Land) (Swain); Institute Ice Stream grounding line (Jeofry et al.) and trunk (Siegert et al.); Lake Vostok (Alekhina et al.); South Pole (Beem et al.); Totten Glacier (Roberts et al.); Recovery ice stream onset (Forsberg et al.); West Antarctic volcanics (van Wyk de Vries et al.).


40°W
30°W
20°W
10°W
0°
10°E
20°E
30°E
40°E
60°S
Schirmacher Oasis
(Swain et al.)
Bransfield Basin
(Casas et al.)
Weddell
Sea
Antarctic
Peninsula
Recovery Glacier
and Recovery Lakes
(Forsberg et al.)
Prydz
Bay
East Antarctica
(Siegert)
Dome A
(Bangbing et al.,
Talalay et al.,
Wrona et al.)
Institute Ice Stream
(Jeofry et al.,
Siegert et al.)
Bellingshausen
Sea
South Pole
(Beem et al.)
Lake Vostok
(Alekhina et al.)
West Antarctica
(van Wyk de Vries et al.,
Siegert)
Amundsen
Sea
Law Dome
(Goodwin et al.)
Totten Glacier
(Roberts et al.)
Ross
Sea
George V Land
and Wilkes Coast
(Pandey et al.)
140°W
150°W
160°W
170°W
180°
170°E
160°E
150°E
140°E
Sub-Antarctic
20°S
30°S
40°S
50°S
60°S
70°S
80°S
South Georgia
(White et al.)
WAIS
EAIS
160°W
120°W
80°W
40°W
0°
40°E
80°E
120°E
160°E