Antarctic subglacial groundwater: a concept paper on its measurement and potential influence on ice flow

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Abstract: Is groundwater abundant in Antarctica and does it modulate ice flow? Answering this question matters because ice streams flow by gliding over a wet substrate of till. Water fed to ice-stream beds thus influences ice-sheet dynamics and, potentially, sea-level rise. It is recognized that both till and the sedimentary basins from which it originates are porous and could host a reservoir of mobile groundwater that interacts with the subglacial interfacial system. According to recent numerical modelling, up to half of all water available for basal lubrication, and time lags between hydrological forcing and ice-sheet response as long as millennia, may have been overlooked in models of ice flow. Here, we review evidence in support of Antarctic groundwater and propose how it can be measured to ascertain the extent to which it modulates ice flow. We present new seismoelectric soundings of subglacial till, and magnetotelluric and transient electromagnetic forward models of subglacial groundwater reservoirs. We demonstrate that multifaceted and integrated geophysical datasets can detect, delineate and quantify the groundwater contents of subglacial sedimentary basins and, potentially, monitor groundwater exchange rates between subglacial till layers. The paper thus describes a new area of glaciological investigation and how it should progress in future.

Water beneath the ice sheet

Antarctic ice-sheet flow is fundamentally affected by water at the bed, as it reduces basal friction to encourage sliding and weakens till to enable bed deformation. Subglacial hydrology – the flow of water beneath the ice – is therefore a key element of the ice-sheet system. Studies to date on subglacial hydrology, and its impact on ice flow, have concentrated on water at or very near to the bed of the ice sheet.

Basal water modulation of ice flow can be achieved in a number of ways. Over an impermeable bed, water can flow through channels cut either downwards into the substrate or upwards into the ice. Enhanced basal water pressures may occur where the channels and their linkages are distributed, increasing overriding ice flow through a reduction in the substrate's effective pressure. Conversely, where a well-organized channel system is formed, water pressures are lower and the hydrological effect on ice flow is reduced. If the ice stream rests on permeable subglacial till, its strength can affect ice flow as controlled by porewater pressures. High pressures lead to a reduction in material strength by pushing till grains apart, reducing bed friction and thus

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enhancing flow of the ice above. This so-called 'deformation of basal tills' is a significant process beneath large ice sheets, especially close to the margins of Antarctica where the ice sheet occupies deep marine sedimentary basins in a number of regions.

The presence of subglacial basins of sedimentary rock, hundreds of metres to several kilometres deep in the uppermost crust, is commonly a prerequisite for ice streaming (Anandakrishnan *et al.* 1998; Bell *et al.* 1998; Bamber *et al.* 2006; Smith *et al.* 2013; Muto *et al.* 2016; Siegert *et al.* 2016). The upper surfaces of sedimentary basins are relatively easily eroded by ice flow, producing a soft substrate of metres-thick till. Till layers can readily deform to facilitate fast basal slip when hydrological sources drive water into them, elevating porewater pressures while reducing shear strength (Bennett 2003). As the strength of basal material is related to porewater pressures, it is evident that groundwater could exert a major, and as yet understudied, influence on ice flow (e.g. Boulton *et al.* 2007*a*, *b*). It is therefore curious to note that investigations on Antarctic groundwater have yet to feature as a major activity in glaciology. In contrast to investigations of existing ice sheets, research on former ice sheets has revealed extensive evidence for major subglacial groundwater systems in exposed sedimentary sequences and seismic data (Boulton *et al.* 2009; Huuse *et al.* 2012).

Around 50% of the Antarctic ice-sheet bed is known to be wet, as is evident from hundreds of Antarctic subglacial lakes that have been detected using ice-penetrating radar (Siegert *et al.* 1996, 2005; Wright & Siegert 2011, 2012). Many of these lakes are connected hydrologically over large (hundreds of kilometres) distances (Wingham *et al.* 2006; Smith *et al.* 2009), some have been identified at the onset of fast flow (Siegert & Bamber 2000; Bell *et al.* 2007) and water issued from a few of them has been shown to influence ice-sheet flow (Stearns *et al.* 2008; Siegfried *et al.* 2016). The vast majority of subglacial lakes that experience major loss/gain in volume, and are hence integral components of the hydrological system, are located within large, deep (more than hundreds of metres) sedimentary basins around the onset of enhanced ice flow (Wright & Siegert 2011, 2012). Water deep within these basins, or subglacial groundwater, is therefore likely to be extensive across the continent in some of the regions that are most susceptible to change.

The 20 year horizon scan of the Scientific Committee on Antarctic Research (SCAR) uncovered, in 2014, the most pressing questions in Antarctic Science (Kennicutt *et al.* 2015, p9 and Table S2), including three that express these concerns: 'What are the processes and properties that control the form and flow of the Antarctic Ice Sheet?'; 'How does subglacial hydrology affect ice sheet dynamics, and how important is it?'; and 'How do the characteristics of the ice sheet bed, such as geothermal heat flux and sediment distribution, affect ice flow and ice sheet stability?'. It is clear that the hydrological processes by which subglacial water modulates ice-sheet flow, and the geological and thermal conditions that regulate them, are some of the largest unknowns in ice-sheet modelling.

Groundwater control of ice stream flow?

The West Antarctic Ice Sheet (WAIS) is a marine ice sheet largely grounded below sea level and fringed by floating ice shelves fed by fast-flowing ice streams. Because the dynamic flow regime of ice streams is maintained principally by slip over the base (Bennett 2003), basal lubrication by water controls the loss of grounded ice from the WAIS and, thus, its potential contribution to sea-level rise. There is now concern that climate warming could change the delicate dynamic balance of the WAIS, leading to ice-stream acceleration and marine ice-sheet instability (MISI) (Mercer 1978), as observed today in the Amundsen Sea sector (Park *et al.* 2013). Numerical ice-sheet models are the tool of choice to evaluate the stability of the WAIS and its future contribution to sea-level rise, but they are subject to major process uncertainties concerning the origin and flow of subglacial water.

The hydrological balance of ice streams has so far been considered to include, as water sources, melt from geothermal heating and basal friction, as well as inflow from upstream and, as water sinks, basal freezing and flow downstream (Christoffersen *et al.* 2014; Bougamont *et al.* 2015) (Figs 1 & 2). The flow of subglacial water from sources to sinks has traditionally been restricted to an interfacial hydrological system between ice above and a presumed impermeable sedimentary basin below (Fig. 1a), comprising interacting till layers, linked cavities, channels, lakes and areas of basal freezing (Fig. 2). Interactions between deep groundwater in subglacial sedimentary basins and ice sheets have been mooted through analysis of basal heat fluxes (Gooch *et al.* 2016 and references therein), but have commonly been neglected in models on the assumption of dominant subglacial hydrological processes in the interfacial system.

Numerical simulations of coupled ice flow and hydrology now suggest, however, that groundwater reservoirs in subglacial sedimentary basins may contribute up to half of all water affecting the basal lubrication of ice streams at the WAIS's Siple Coast (Christoffersen *et al.* 2014). This notable flow of water into and out of a porous groundwater system contradicts the common assumption of impermeable subglacial sedimentary basins in ice-flow models – bringing current models and forecasts of mass loss from the WAIS into question, as key hydrological

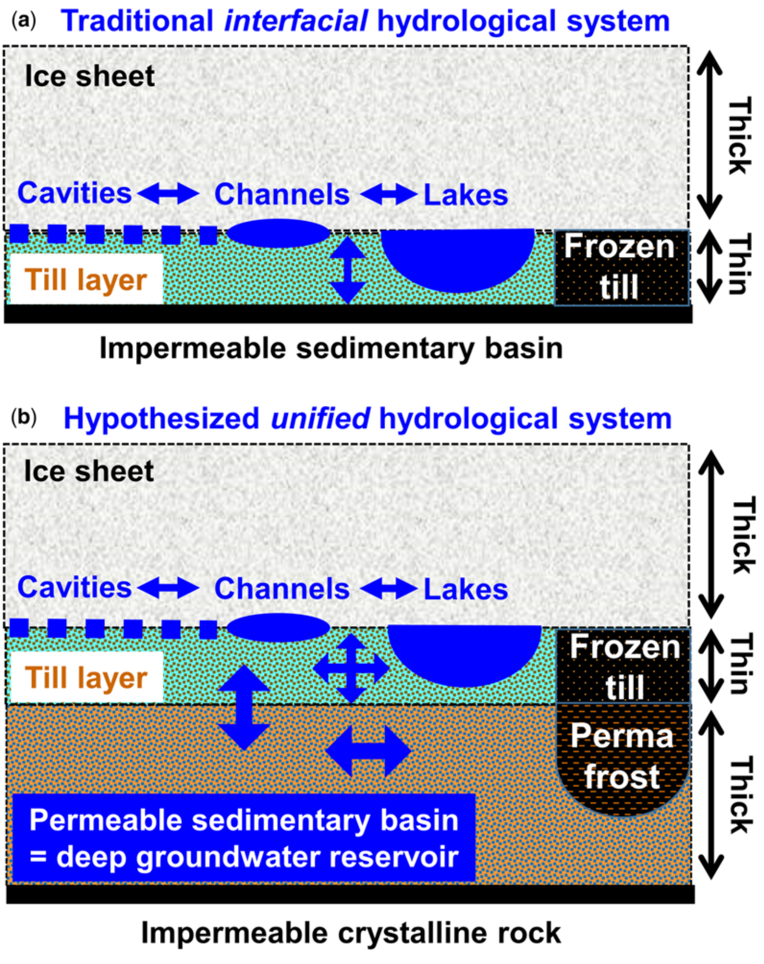

Fig. 1. (**a**) Interfacial subglacial water system of interconnected till, linked-cavities, channels, lakes and areas of basal freezing, considered in ice-sheet models so far (e.g. Fig. 3). (**b**) Unified subglacial water system, where the interfacial system exchanges water with a deep groundwater reservoir. The thick arrows are the main water-flow directions. An extra four hydrological processes arise in unified (b) compared to interfacial (a) systems, which must be evaluated by models (not to scale; ice and the sedimentary basin are often kilometres thick, the till layer is metres thick).

processes may be unaccounted for. Basal lubrication of ice streams may, in fact, be controlled by a unified hydrological system consisting of a deep groundwater reservoir as well as interfacial hydrology (Fig. 2b), and not just the latter as assumed so far (Fig. 1a).

A unified concept of subglacial hydrology, including groundwater

Knowledge of the governing patterns and processes of water flow and storage in unified hydrological systems beneath ice streams in the WAIS does not yet exist. Existing simulations are restricted to vertical flows in till layers that interact with a regional hydrological model, where water is routed along the ice–bed interface (Figs 1a & 2). In unified systems, four additional hydrological processes arise that models must become capable of capturing (Fig. 1b):

(i) water exchange through the base of till layers from the deep groundwater reservoir below;
(ii) horizontal flows within the reservoir and the till layer (Christoffersen & Tulaczyk 2003);
(iii) subglacial permafrost at the reservoir's upper surface, in which groundwater is frozen;
(iv) time lags, potentially up to millennia, between hydrological forcing and ice-flow response.

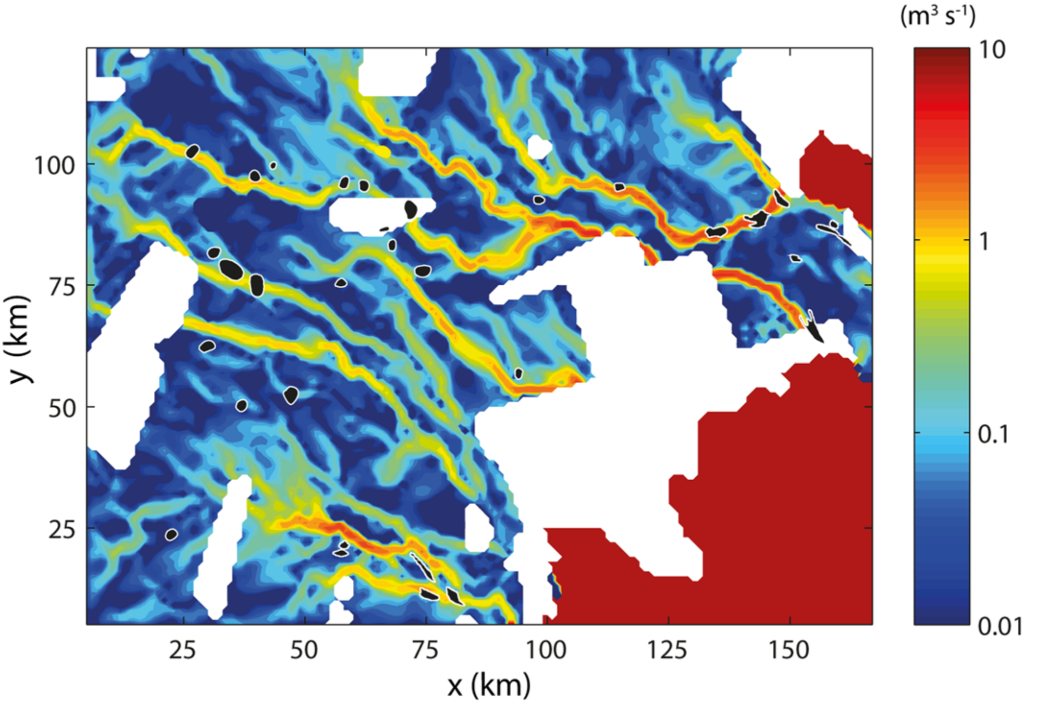

Fig. 2. 'Interfacial' water system (Fig. 1a) of the Siple Coast in West Antarctica, constructed by Christoffersen *et al.* (2014) with the CISM-2 model. Major water-flow pathways connect subglacial lakes (in black) within a large-scale distributed system of subglacial till layers and linked cavities. Sources are regions where basal water production is greater than the flow of water into till or where basal freezing is less than flow of water out of till. Sinks are regions where basal water production is less than the flow of water into till or where basal freezing is greater than the flow of water out of till. Areas not covered by surface velocity data from 1997 are shown in white. The floating Ross Ice Shelf is masked in the lower right of the diagram. Axes (*x*, *y*) show distance (km) in a polar stereographic grid with reference to 76.727°S and 141.53°W.

The permeabilities of the till and sedimentary rock control the rates of water flow and exchange – processes (i) and (ii) – and are therefore governing quantities in model simulations (Christoffersen & Tulaczyk 2003). Time lags – process (iv) – are evidenced, for example, by contemporary sedimentary basins in the northern USA (Bense & Person 2008). There, groundwater reservoirs were re-charged and overpressured during growth of the Laurentide Ice Sheet, up to the last glacial maximum approximately 20 kyr ago. Ice-sheet retreat over following millennia then enabled the slow release of pressure and, therefore, the upwards flow of groundwater into the interfacial hydrological system (Fig. 1b). Although glaciation ended more than 10 kyr ago, overpressure in ground reservoirs still remains to the present day, indicating long time lags in hydrological responses to ice-sheet loading. We are unaware of whether permafrost in sedimentary basins in the Antarctic – process (iii) – has been examined before.

By analogy, because the WAIS has reduced in size and extent since its last maximum configuration, groundwater release from subglacial sedimentary reservoirs is expected – and, indeed, agrees with modelled groundwater flows into the modern-day interfacial water system beneath Siple Coast ice streams (Christoffersen *et al.* 2014). The spatial and temporal distributions of subglacial water volumes, till deformation, and thus the magnitudes and timings of basal lubrication of ice flow will therefore be likely to differ significantly between models of interfacial (Fig. 1a) and unified (Fig. 1b) hydrological systems; inspiring a hypothesis that 'deep subglacial groundwater impacts the flow of ice streams in West Antarctica'. In line with the SCAR horizon scan (Kennicutt *et al.* 2015), it is both timely and urgent that this hypothesis is rigorously tested. Doing this will require an integrated programme of numerical modelling and field measurements to initiate and calibrate the simulations.

In the next section we discuss how such a field programme could be configured, and what it might aim to achieve. While we do not discuss details of how modelling can be integrated with field data, we acknowledge the need for modelling to ultimately address the hypothesis (see Flowers 2015 and references therein). In the first instance, however, field data are needed to observe and measure the phenomenon.

Potential groundwater location

Identifying a suitable location to search initially for Antarctic groundwater must consider a number of aspects, including the likely presence of deep basal sediments and water. While there are likely to be several suitable locations across the Antarctic continent, one is in the Weddell Sea sector of the West Antarctic Ice Sheet (Fig. 3). The Institute Ice Stream (IIS) is at the centre of the 1.8 km-deep Robin Subglacial Basin in West Antarctica, where thick sequences of porous sediments are likely. The ice sheet, and topographical and geological settings of the region are known well through an extensive airborne geophysical survey of the IIS, undertaken in 2010–11. The grounding line of the IIS is located on the edge of a steep reverse-sloping bed, meaning it is at a physical threshold of potential marine ice-sheet instability (Ross *et al.* 2012).

Similar to the flow of Siple Coast ice streams, the IIS is influenced by water emanating from an 'active subglacial lake' named Institute E1, which was detected by ICESat measurements of surface-elevation changes, and is located in the onset region of enhanced flow. Analysis from five pairs of repeat ICESat track data showed the lake 'filled' by approximately 0.5 km^3 between October 2003 and March 2008 (Smith *et al.* 2009; Siegert *et al.* 2016). Although the true nature of 'active subglacial lakes' is disputed (e.g. Siegert *et al.* 2014), owing to the lack of radio-echo sounding (RES) evidence for the sharp ice–water interface that occurs at Lake Ellsworth, for example (Woodward *et al.* 2010), the surface changes detected are highly likely to be due to subglacial water flow, making them important conduits of the subglacial hydrological system. Institute E1 is located immediately downstream of a fault marking the edge of the Pagano Shear Zone, separating Jurassic intrusions from Cambrian–Permian meta-sediments (Jordan *et al.* 2013), suggesting that the flow of water to the IIS is tectonically controlled. Water from the lake flows to the trunk of the ice stream and eventually exits the ice sheet as a plume that etches a major channel upwards into the adjacent floating ice shelf (Le Brocq *et al.* 2013).

RES data reveal that the Robin Subglacial Basin, in which the trunk of the IIS is located, is highly likely to contain weak porous tills, based on the smooth highly reflective bed (Figs 3 & 4) that is similar to those from the Siple Coast where basal tills have been collected and studied in detail (Tulaczyk *et al.* 2000*a*,*b*). The greatest ice-flow velocity of the IIS occurs where RES data show that soft tills are most likely (Siegert *et al.* 2016). This is consistent with high porewater pressures within these tills, which means that groundwater may be affecting ice flow here. Hence, the fast-flowing IIS downstream of Institute E1 is a location well suited to the search for groundwater and an assessment of its control on ice-sheet dynamics.

Numerical modelling revealed three traits typical of deep groundwater control of ice-stream flow (Christoffersen *et al.* 2014). The IIS system typifies all of these. The first trait is the presence of a deep basin of porous sedimentary rock below the ice stream. Extending more than 150 km upstream into the Robin Subglacial Basin (Fig. 3b), the onset of the fast flow (Fig. 3c) of the IIS's approximately 2000 m-thick trunk coincides with the transition from a major tectonic rift, the Pagano Shear Zone, into a deep sedimentary basin (Figs 3 & 5) (Jordan *et al.* 2013). The second trait is the presence of deformable subglacial till (Fig. 4). The bed of the Institute Ice Stream–Bungenstock Ice Rise (IIS–BIR) system is remarkably smooth in radargrams, an exposition common for continuous till layers (Fig. 4) (Siegert *et al.* 2016). Exceptionally bright basal reflectors beneath the IIS and much reduced radar reflectivities beneath the BIR are consistent with wet and deformable tills beneath the former, and a frozen till base at the latter (Fig. 4). The third trait is the likely hydrological control of ice flow. Akin to the Siple Coast, the IIS–BIR system is characterized by major subglacial flow pathways that connect with each other and with the 'active' subglacial lake Institute E1 (Fig. 3); a temporary storage site of interfacial water (Siegert *et al.* 2016).

Geophysical measurements required

Scientific approach

The identification, measurement and analysis of Antarctic groundwater would represent a major advance in our understanding of subglacial water and its interrelation with the ice above. While geophysics is commonly used to delineate and characterize groundwater systems in many regions of the world, a major issue with the use of standard methodologies is that simple fact that the land surface is covered by an ice sheet more than 4 km thick in places (Keller & Frischknecht 1960). As well as operational difficulties, this high seismic velocity and low conductivity surface layer can reduce the effectiveness of some of the geophysical methods, affecting the ability to determine subsurface properties unequivocally. To solve these issues, a number of ground-based geophysical techniques are likely to be needed in combination. To understand, as far

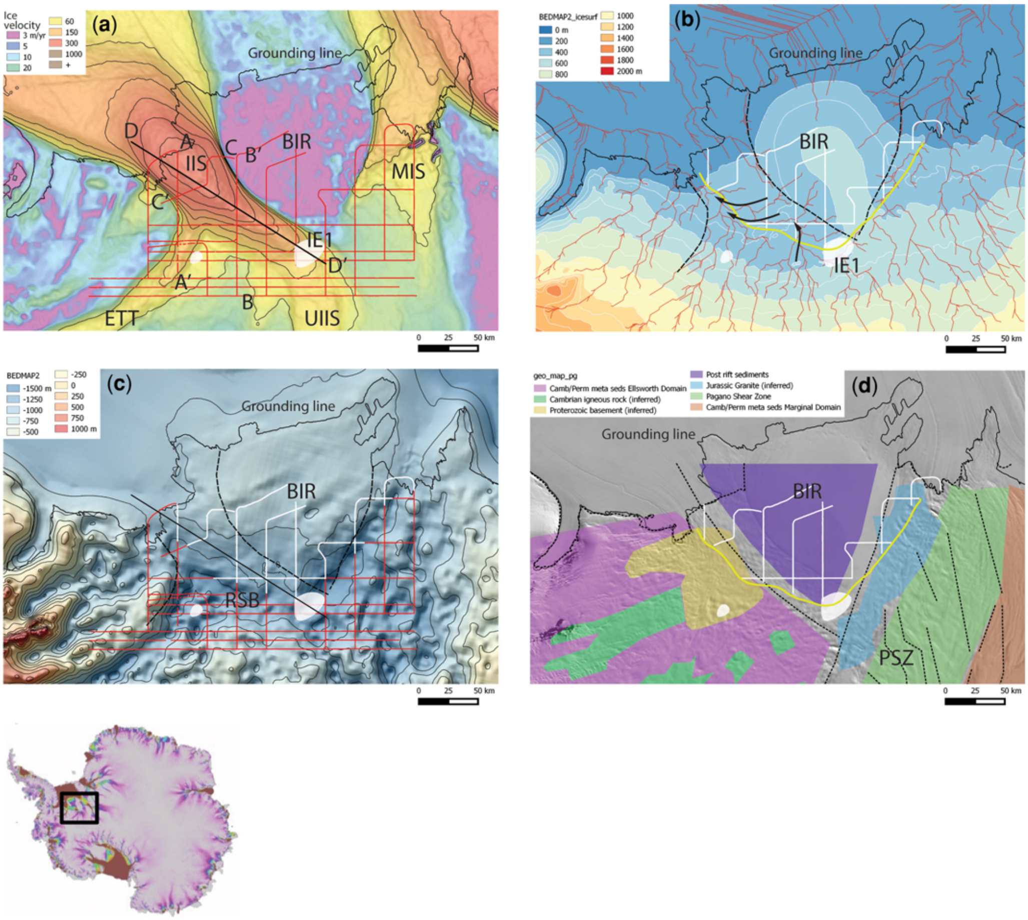

Fig. 3. Boundary conditions at the onset region, trunk and grounding line of the Institute Ice Stream (IIS). (**a**) Airborne radar profiles, annotated as in Figure 4, superimposed over InSAR-derived ice-surface velocities (Rignot *et al.* 2011). (**b**) Direction of interfacial basal water flow (after Shreve 1972) superimposed over ice-sheet surface elevation (Fretwell *et al.* 2013). (**c**) Subglacial bed topography (Fretwell *et al.* 2013). (**d**) Crustal lithological structures and units (adapted from Jordan *et al.* 2013), superimposed on MODIS imagery. In (b) & (d), the yellow line denotes the transition between the smooth, bright bed reflector from the water-saturated subglacial sediments, and the grey shade denoting the position and extend of 'active subglacial lake' Institute E1 (Smith & others 2009). IIS, Institute Ice Stream; MIS, Möller Ice Stream; BIR, Bungenstock Ice Rise; ETT, Ellsworth Trough Tributary; UIIS, Upstream Institute Ice Stream; RSB, Robin Subglacial Basin; IE1, Institute E1; PSZ Pagano Shear Zone. A location map is provided in the inset. Taken from Siegert *et al.* (2016).

as is practicable, the types of experiment needed and what observations they can offer, we consider each individually and understand how they might contribute knowledge on subglacial groundwater detection and measurement. The observations necessary are: (i) the ice-sheet geometry and ice velocities; (ii) the thicknesses, any internal structures and porosities of both the till layer and the sedimentary basin; and (iii) the spatial patterns of liquid groundwater v. permafrost in the sedimentary rocks, within the larger-scale hydrological and thermal setting of the upper and lower crust. Of these (i) can be obtained by standard airborne surveying (e.g. radar) and from satellite data, while (ii) and (iii) are as yet largely unavailable and must therefore be generated by bespoke surveying. Specifically, we need to: determine the thicknesses, internal structures and porosities of the subglacial till layer and sedimentary basin beneath using seismic sounding; and delineate subglacial groundwater and permafrost in the basin, and the hydrological and thermal setting of the surrounding crust, using electromagnetic (EM) geophysical techniques constrained by seismic and airborne geophysical data.

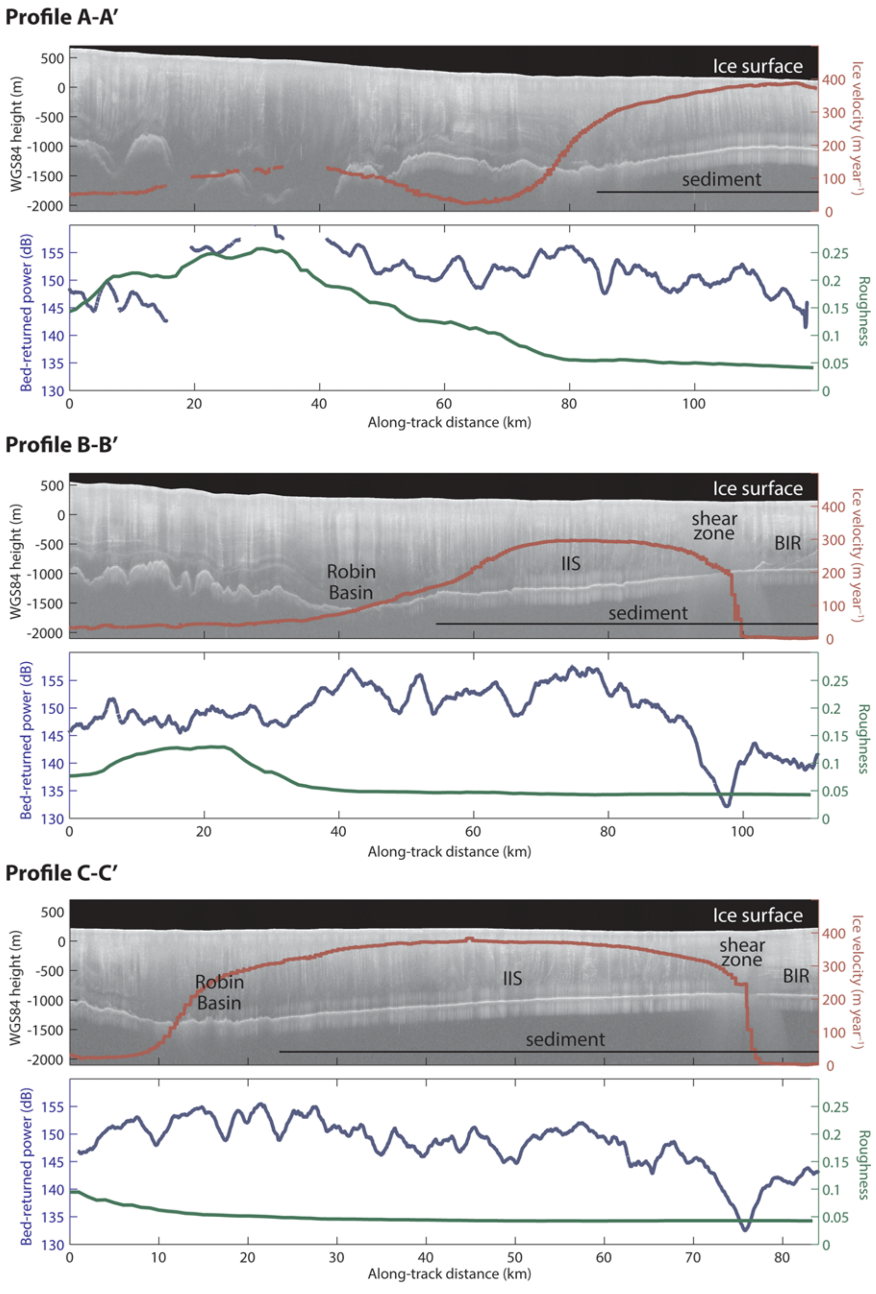

Fig. 4. Radar-sounding profiles, acquired by the British Antarctic Survey in 2010–11, revealing the flat interface indicative of water-saturated basal sediment. Locations for each profile are annotated in Figure 1. IIS, Institute Ice Stream; BIR, Bungenstock Ice Rise. (**a**) A–A′. (**b**) B–B′. (**c**) C–C′. Ice-surface velocities (after Rignot *et al.* 2011) are provided with bed reflectivities and basal roughness along each profile. Note that in all profiles the association between the greatest ice velocities within the IIS and the region of the bed interpreted as comprising water-saturated basal sediments. Note also in B–B′ and C–C′ the association between the marked change in ice-surface velocity across the IIS shear margin and the bed reflection strength due a sharp transition between wet (IIS) and frozen (BIR) basal sediments. Taken from Siegert *et al.* (2016).

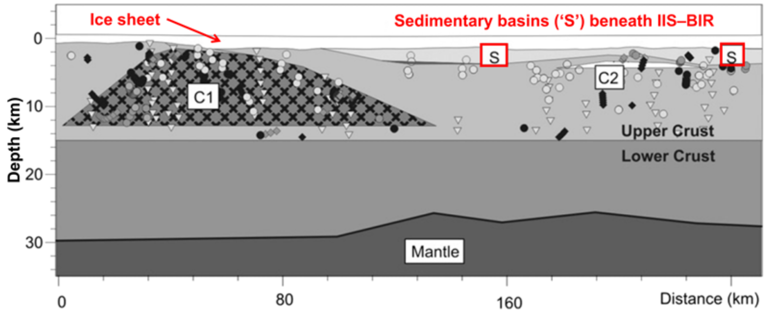

Fig. 5. Previous tectonic interpretation of airborne gravity and magnetic data. The sedimentary basin (light grey shaded, labelled 'S', profile line B–B′ in Fig. 4) beneath IIS–BIR is up to about 2.5 km thick beneath ice up to about 2 km thick. The black and grey symbols represent specific gravity solutions, as explained in Jordan *et al.* (2013), and labels 'C1' and 'C2', respectively, mark the inferred Proterozoic basement and an intrusion of Jurassic age.

Geophysical techniques offer the only feasible means (compared with drilling, for example) of delineating structures and physical properties of till and groundwater reservoirs in subglacial basins of sedimentary rock beneath kilometre-thick ice. To do this, commonly used multi-technique approaches in characterizing the Earth's crust need to be modified for glaciological investigation. As individual techniques will likely have restricted use in detecting and measuring subglacial groundwater, an integrative approach to field measurements is essential. Such an approach will allow (1) discrete physical properties of groundwater to be recorded independently, resulting in (2) its unambiguous detection within fully quantified glaciological, topographical and geological settings. We envisage that an ideal experiment would achieve this using a four-step approach, as described in the following subsections.

Ice-sheet surface and thickness

The first step would constrain the most recent topography of the ice-sheet surface using satellite measurements constrained by GPS tie-in points on the ground, updating existing digital elevation models (DEMs) of the region and accounting for its isostatic adjustment (Martín-Español *et al.* 2016). Airborne RES is undisputedly the tool of choice in measuring ice thicknesses on regional scales, exploiting the low attenuation of radar energy in glacial ice and with an extensive history of successful thickness mapping in much of Antarctica (Bingham & Siegert 2007; Fretwell *et al.* 2013).

Hydrological and mechanical conditions at the ice-sheet bed

The second step of an ideal experiment would elucidate the conditions at the base of the ice sheet, distinguishing wet from frozen areas, reconstructing the geometry of basal hydrological systems, and ascertaining the presence and mechanical state of subglacial till. Once corrected for variable englacial attenuation rates, RES data are well suited for regional-scale mapping of wet and frozen basal areas (Fig. 3), and of basal topography which can then be used in hydraulic reconstructions of catchment-scale subglacial hydrological systems (Jordan *et al.* 2016 and references therein). Indeed, where RES data are suitable for synthetic aperture radar (SAR) processing, the specularity content of the bed echoes has been used to directly measure discrete subglacial channels and distinguish them from distributed canals (Schroeder *et al.* 2013). RES is also able to detect deep-water (>10 m) subglacial lakes (Siegert *et al.* 1996, 2005; Wright & Siegert 2012), although not normally 'active subglacial lakes' (Siegert *et al.* 2014).

Having been applied in glaciology for several decades, the seismic reflection method is a powerful means of identifying the nature of ice-sheet substrates, of measuring the water depths of subglacial lakes and, where subglacial till is present, of inferring its mechanical state (Doell 1963; Smith 1997, 2007; Peters *et al.* 2007; Woodward *et al.* 2010; Siegert *et al.* 2011). A growing number of glaciological applications have been using amplitude v. offset (AVO) data as powerful diagnostics of acoustic impedance – the product of seismic velocity and density – and Poisson's ratio – a measure of material stiffness calculated from compressional and shear wave velocities – as proxies for subglacial till deformation (Nolan & Echelmeyer 1999; Anandakrishnan 2003; Peters *et al.* 2007, 2008; Booth *et al.* 2012; Dow *et al.* 2013; Christianson *et al.* 2014; Kulessa *et al.* In review). For example, lower acoustic impedances and higher Poisson's ratios diagnose weaker higher-porosity tills that dilate to accommodate basal slip, while the opposite applies to stiff non-deforming tills. Glaciological AVO analysis is analogous to similar applications in the hydrocarbon sector that routinely uses AVO attributes as indicators of changes in reservoir lithology, and especially of porosity, fluid type and saturation (Sheriff & Geldart 1995; Simm *et al.* 2000; Booth *et al.* 2016).

The seismoelectric method promises to become a powerful means of detecting, delineating and physically characterizing subglacial till layers (Kulessa *et al.* 2006*a*, *b*). In wet subglacial till, an electrically-charged layer exists at the interface between the constituent mineral grains and the water in the pore space, where the latter will be forced to flow when a propagating seismic wave causes transient till deformation. Two modes of energy occur and are relevant to determining subglacial conditions: seismoelectric conversions and coseismic energy. As a seismic wave propagates, the resulting disturbance to the electrically-charged interface generates an EM pulse that travels at the speed of light to the ice-sheet surface, where electrode antennas can measure it with one-way seismic travel time (Fig. 6). There are two main reasons why this so-called seismoelectric conversion is of particular interest (Kulessa *et al.* 2006*a*, *b*), namely exceptional sensitivity to: (i) till permeability (Thompson & Gist 1993; Garambois & Dietrich 2002), a fundamental parameter in ice-sheet modelling (Christoffersen *et al.* 2014; Bougamont *et al.* 2011, 2015) that cannot be measured with existing methods; and (ii) thin deformable till horizons (Haines & Pride 2006), which are the primary control of an Antarctic ice-stream's basal slip but are difficult to resolve in seismic data (Booth *et al.* 2012). In contrast to seismoelectric conversions, coseismic energy is generated by small charge displacements inside seismic waves when they propagate by elastic deformation. Coseismic energy is therefore intrinsically tied to such waves and thus arrives at the two-way travel time characteristic of the corresponding seismic reflections (Kulessa *et al.* 2006*a*, *b*).

Figure 6 shows a seismoelectric sounding acquired during the summer melt season in the ablation area of the Russell Glacier Catchment of the West Greenland Ice Sheet, at a time when no snow or firn was present. Two electrode antennas centred on a common hammer-and-plate source location were used (Kulessa *et al.* 2006*a*, *b*, their fig. 2), and instrumentation was custom-designed for use in low-noise survey (Butler *et al.* 2007). Key processing steps involved median filtering and spectral whitening of five repeat soundings. Seismic AVO surveys had revealed the presence of a subglacial till layer at a depth of approximately 1145 ± 15 m, whose upper horizon is thin and deforming (Booth *et al.* 2012; Kulessa *et al.* In review). Two clear

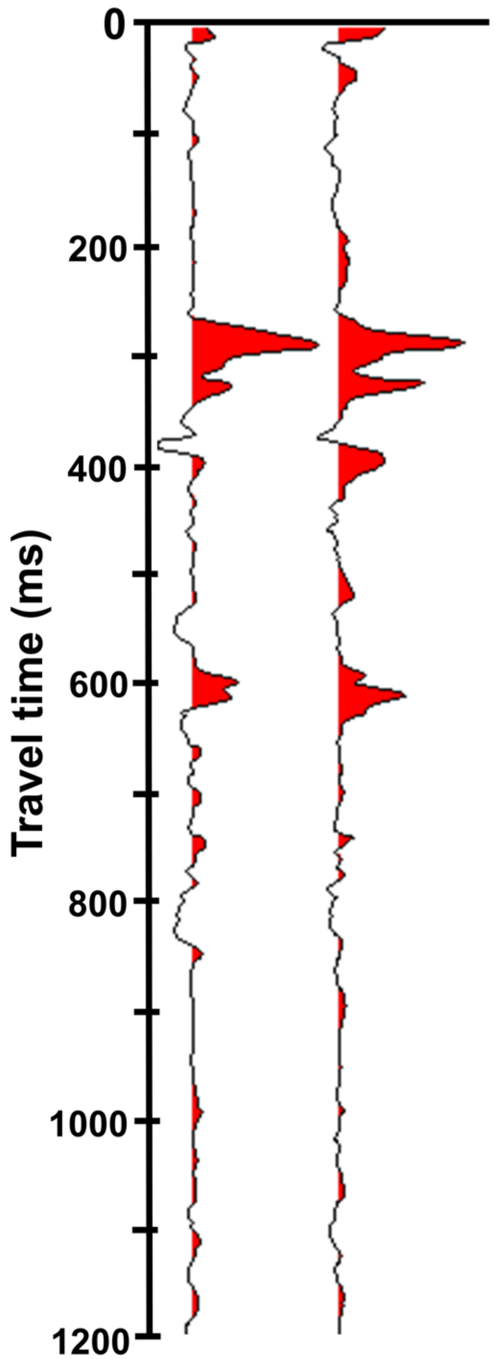

Fig. 6. Representative seismoelectric soundings on the West Greenland Ice Sheet. The two dominant seismoelectric arrivals at *c.* 305 ms and *c.* 610 ms were both generated at the ice–bed interface (*c.* 1145 ± 15 m: Booth *et al.* 2012; Kulessa *et al.* In review), and are consistent with a seismoelectric conversion and the arrival of co-seismic energy, respectively.

seismoelectric returns are observed, the first centred at *c.* 305 ms and the second at twice that time, at *c.* 610 ms (Fig. 6). The first return at *c.* 305 ms is therefore fully consistent with a seismoelectric conversion in the till layer beneath the ice-sheet base, while the second at *c.* 610 ms is fully consistent with a coseismic arrival from the base. The processed seismoelectric conversion at *c.* 305 ms has a peak-to-peak amplitude of *c.* 10 µV, which is consistent with conversions observed previously in groundwater settings (Dupuis *et al.* 2007). The inherent consistency of seismoelectric arrival times with origins in the subglacial till layer is striking, and thus encourages future developments of the seismoelectric method for the hydrological and mechanical characterization of ice-sheet substrates.

Geometry and structure of subglacial sedimentary basins within the uppermost crust

Subglacial basins of sedimentary rock are relatively poorly explored compared to the hydrological and mechanical characterization of the ice-sheet bed. An ideal approach would initially combine reconnaissance mapping of the regional crustal and upper mantle structure using airborne gravity and magnetic techniques, akin to that shown in Figure 5 for the IIS–BIR region. Ambiguity in the inversion of airborne gravity and magnetics data can be reduced through mutual constraints, and specification of ice thicknesses from RES data helps to refine interpretations. Because such inversions can reveal the presence, and hypothesize the approximate spatial extents, of subglacial sedimentary basins within larger-scale crustal and mantle-scale settings, they provide the information required for more targeted passive- and active-source seismic surveys of basin structures, respectively, at intermediate and best-resolution scales.

Modern passive seismic methods promise to investigate basin structures at intermediate spatial scales between airborne surveys and active-source seismic surveys (below). Most relevant are very recent developments in seismic ambient noise (SAN) techniques, which are able to extract high-quality information from what was previously seen as nuisance in seismic surveys. This is because it emerged that noise in global seismometer data is deterministic rather than random, being mostly generated by interactions between ocean waves during storms (Kedar *et al.* 2008). The fundamental mode of surface Rayleigh waves accounts for the majority of measured SAN amplitudes, and advanced processing techniques can extract two main types of information from it that are highly relevant here. This information includes the ellipticity of Rayleigh waves – the H/V ratio between its horizontal and vertical amplitude components (Ferreira *et al.* 2010) – and the dispersion or group velocity of Rayleigh waves that shows a diagnostic minimum known as the Airy phase (Gualtieri *et al.* 2015). Both of these measures are particularly sensitive to upper-crustal structures beneath individual (ellipticity) and in-between (dispersion) seismometer stations, so that their quantification promises to generate high-quality tomographical images of subglacial sedimentary basins and their broader crustal settings (Berbellini *et al.* 2016). SAN techniques can either be applied to archived data from existing permanent or temporary seismometer stations, or to bespoke stations deployed in the study area.

Vibroseis techniques have been used for several decades in hydrocarbon exploration, and the first bespoke vibroseis technology in the exploration of ice sheets (Eisen *et al.* 2010, 2015) promises to be powerful in mapping both depths and internal structures of subglacial sedimentary basins at the best possible spatial resolution. The technology is mobile and capable of recording some 20–30 line kilometres of multi-fold vibroseis data per day. Able to explore depths of >5000 m below the ice-sheet surface, the heavyweight Failing Y-1100 vibrator has a known, strong and repeatable source signal and would, therefore, be the ideal tool to map the up to about 2.5 km-deep sedimentary basins beneath the up to approximately 2 km-deep ice of the IIS–BIR region (Figs 3–5). Where contrasts in acoustic impedance exist between stratified layers beneath the ice-sheet bed, such as, for example, those expected at the subglacial till–sedimentary rock interface or interfaces between stratified units within groundwater aquifers in subglacial sedimentary basins (e.g. Boulton *et al.* 1995; Person *et al.* 2007, 2012; Bense & Person 2008; Piotrowski *et al.* 2009), then seismic techniques are readily able to resolve layers thicker than about one-quarter of the seismic wavelength – typically a few metres – and even thinner layers can be interpreted using diagnostic AVO techniques (Booth *et al.* 2012). Additional deep explosive shots into the snow-streamer would facilitate the generation of high-quality seismic velocity models and possibly AVO analysis of basin structures. Both types of information would aid in quantifying the permeability, porosity and groundwater contents of the rock layers within the sedimentary basin.

Groundwater detection, delineation and quantification in subglacial sedimentary basins

Both active- and passive-source seismic surveys proposed in the previous subsection can conceptually contribute to the identification of the groundwater contents of subglacial basins of sedimentary rocks. They suffer, however, from limitations related to spatial resolution as deployments of large explosive shots are logistically demanding and passive seismic stations will likely have considerable inter-station spacing. In addition, the link between seismic information and groundwater contents is not unambiguous, so that considerable data gaps and uncertainty bounds would prevail in practice. In other geoscientific areas, it is therefore common to complement passive- or active-source seismic surveys with deep EM surveys.

In glaciological practice, passive-source magnetotelluric (MT) surveys appear to be most promising in detecting, delineating and quantifying groundwater in kilometre-deep sedimentary basins beneath kilometre-thick ice, such as, for example, in the IIS–BIR region (Fig. 3). Geomagnetic field fluctuations induce electrical current flows (telluric currents) in ice sheets and the underlying crust, and MT techniques measure the accompanying electric and magnetic fields at the ice-sheet surface. MT surveying is able to sample the subsurface through a large depth range because the causative mechanisms can induce telluric currents with frequencies ranging from approximately 10^{-5} to 10^{4} Hz, where depth penetration and spatial resolution, respectively, scale inversely and directly with the frequency. Higher-frequency MT data can thus be inverted to produce images of bulk electrical resistivity within the ice sheet and underlying uppermost crust, including subglacial sedimentary rock. The inversion of lower-frequency data is then appropriate for the characterization of the surrounding setting of deeper crust and upper mantle. Low-resistivity anomalies are diagnostic of porous subglacial sedimentary basins saturated with groundwater, which contains an abundance of mobile ions to boost current flow. In contrast, crustal rocks of the Antarctic craton or permafrost are usually colder and of lower porosity, and hence have higher resistivities (Wannamaker *et al.* 2004; Mikucki *et al.* 2015). For example, EM surveys in the Dry Valleys of Victoria Land, Antarctica, clearly distinguished lower-resistivity groundwater-bearing sediments (*c.* 10^{1}–10^{2} Ωm) from higher-resistivity glacier ice, permafrost and crustal bedrock (typically *c.* 10^{3}–10^{4} Ωm) (Mikucki *et al.* 2015). A similarly low-resistivity range indicated kilometre-thick unfrozen sedimentary rock beneath nearly 3 km of ice at the South Pole (Wannamaker *et al.* 2004). Most recently, Key & Siegfried (In press) showed that the MT method may be capable of resolving conductive layers as thin as a few metres, such as, for example, a subglacial lake, especially when the thickness of the ice and the lake are constrained by complementary methods, such as seismic reflection and radar.

To demonstrate the utility of MT imaging of groundwater and permafrost in subglacial sedimentary basins, we conceptualized a physical model (Fig. 7) from the previous tectonic interpretation (Fig. 5) for the IIS–BIR system. At the heart of this model is a subglacial basin of homogeneous and isotropic sedimentary rock, which has high porosity and acts as a groundwater reservoir (Fig. 7a). Beneath the BIR, we introduced a hypothetical layer of permafrost, some 500 m thick with a resistivity intermediate between that of the ice sheet and the unfrozen groundwater-bearing sedimentary rock (French *et al.* 2006; Kulessa 2007; Mikucki *et al.* 2015; Foley *et al.* 2016), under the assumption that basal freezing caused the major reorganization of the region's ice flow possibly as recently as 400 years ago (Siegert *et al.* 2013). We then inverted synthetic MT data acquired at 40 simulated measurement stations along the profile line (Fig. 7b). It is clear that the inverted data (Fig. 7b) reproduce the physical model (Fig. 7a) very well, including even the permafrost layer, although the spatial sensitivity of inverted data is beginning to be lost at greater depths (Fig. 7b). In practice, glaciological MT data can be acquired with commercial off-the-shelf systems, although capacitive coupling of electrodes with highly resistive firn (Kulessa 2007 and references therein) must be boosted by high-input impedance buffer amplifiers that would normally be custom designed (Wannamaker *et al.* 2004).

Active-source transient EM (TEM) surveys come into their own where ice and sedimentary rock basins are thinner, where only the upper portion of deep sedimentary basins is of interest, or in providing additional constraints on the inversion of MT data. For example, the commercial airborne SkyTEM system was able to map brine-saturated sediments a few hundred metres thick in the Dry Valleys, including those below a range of glaciers flowing into Taylor Valley (Dugan *et al.* 2015; Mikucki *et al.* 2015; Foley *et al.* 2016). However, these glaciers are less than 400 m thick, whereas in most areas of Antarctica the ice is much thicker and sedimentary basins much deeper. In this case, a SkyTEM-type system can be modified for ground-based use, where larger loops and stronger currents can then sound through more than 1000 m of ice thickness and up to about 500 m depth into subglacial sedimentary basins. To ascertain the sensitivity of a large active-source TEM system to the sedimentary basin in the IIS–BIR region (Fig. 5), we conducted a synthetic modelling experiment that simulated the response to currents up to 100 A transmitted through a large loop of 200×200 m^2 with moments up to 4 MA m^2. We found that the resistivity (ρ) of groundwater-saturated sedimentary rock beneath the approximately 2000 m-thick ice sheet can readily be resolved within a range narrower than 1.6ρ to $\rho/1.6$ for subglacial permafrost thicknesses of less than about 500 m (Fig. 8). It appears, therefore, that active-source TEM sounding with a powerful ground-based system can image at least the top few hundreds of metres in subglacial sedimentary

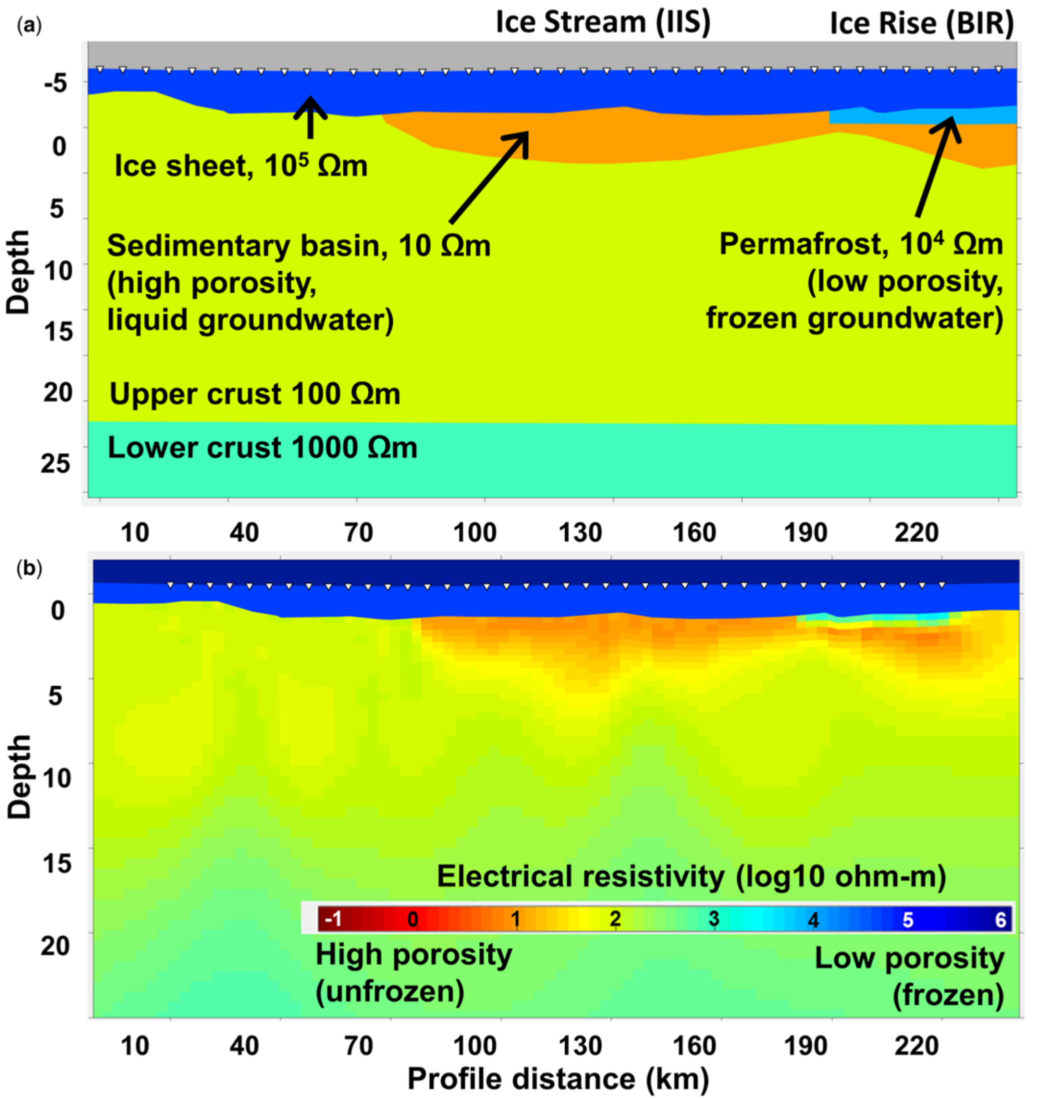

Fig. 7. Inverse modelling of synthetic MT data, acquired at 40 simulated stations on the Institute Ice Stream (IIS) and Bungenstock Ice Rise (BIR). (**a**) 'True' electrical resistivity model conceptualized from existing tectonic interpretation (Fig. 5), and also introducing a hypothetical layer of permafrost beneath the BIR not detectable using existing data. (**b**) Inverted model with 10% random noise added to the data. Both the sedimentary basin and the hypothetical permafrost layer are delineated well.

basins, although *in situ* testing and surveys are required to identify the scope and limitations of active-source TEM relative to passive MT sounding and imaging.

Integrated geophysical data interpretation and inversion

In practice, inversions of MT and TEM data are well known to be ambiguous and suffer from the principle of equivalence, which holds that resistivities and depths of a deep conductive layer cannot be determined independently from each other. If a programme of field investigation was conducted along the lines of what we proposed above, then high-quality topographical, ice thickness and crustal structural information would be available from seismic and radar data to constrain the MT and TEM inversions, and the latter would additionally be able to constrain each other. In favourable circumstances,

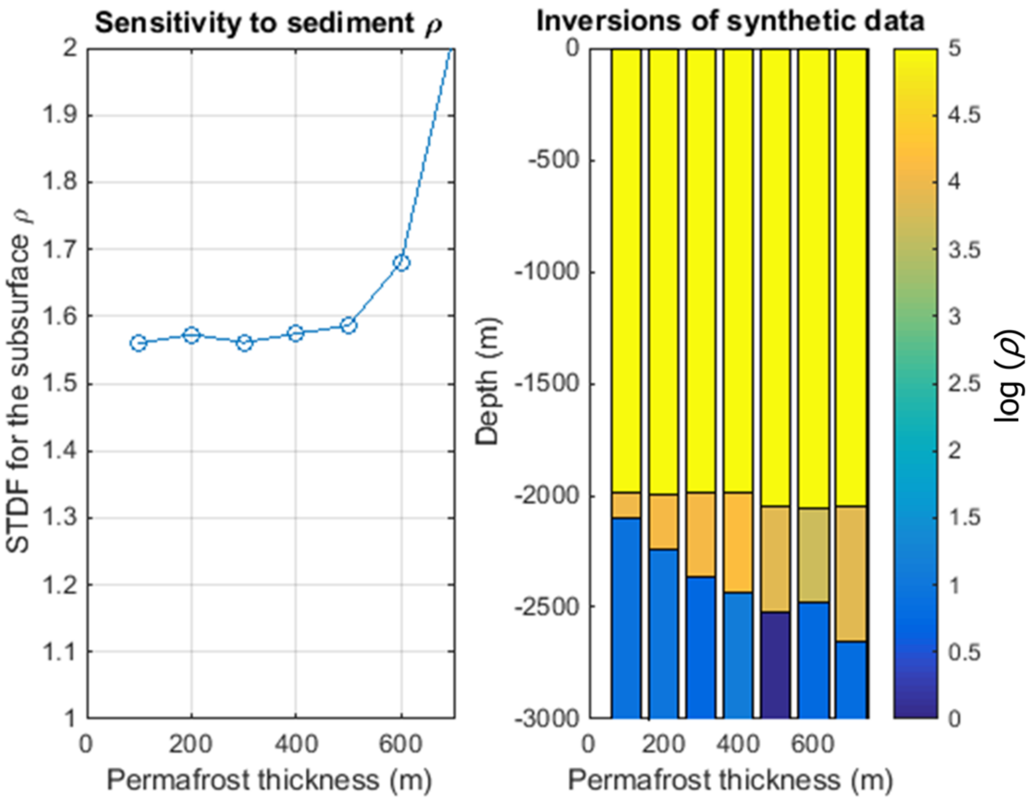

Fig. 8. One-dimensional TEM forward model of sensitivity to groundwater in the sedimentary basin, with ice (10^5 Ωm) over permafrost (10^4 Ωm: French *et al.* 2006), groundwater (10 Ωm) and upper crust (10^2 Ωm) (right-hand plot). For permafrost thicknesses <500 m, groundwater resistivity (ρ) is resolved within a range narrower than 1.6ρ to $\rho/1.6$ (left-hand plot).

we would thus expect not only to delineate subglacial till layers, stratified layers within and the base of the groundwater aquifer in the underlying sedimentary rock basin using seismic techniques, but also to obtain high-quality and relatively unambiguous images of the distribution of bulk resistivity within these till and sedimentary rock layers (Fig. 7) (Key & Siegfried In press). According to Archie's law (Archie 1942) bulk resistivity is a function of porosity, water saturation and water electrical conductivity; affirmed for subglacial till layers by Kulessa *et al.* (2006*a*, *b*). Although low resistivities are therefore consistent with unfrozen sedimentary rocks and liquid groundwater, and vice versa for subglacial permafrost (French *et al.* 2006; Mikucki *et al.* 2015; Foley *et al.* 2016), these three quantities cannot be determined independently from each other. An ideal interpretative framework would therefore combine the analysis of EM and seismic data to quantify the water contents of subglacial till layers and aquifers in the subglacial sedimentary basins, exploiting the fact that both types of data are sensitive to porosity, permeability and liquid water content.

Finally, where borehole access to the subglacial environment is available, the electrical self-potential (SP) geophysical method can quantify and monitor discharge rates of water along the ice–bed interface and through subglacial till layers (Kulessa *et al.* 2003*a*, *b*, French *et al.* 2006). The SP method is sensitive to water flow though geological media because such flows drive an electrical charge separation at the interface between the pore space and the mineral grains in porous media such as subglacial till layers or, indeed, sedimentary rocks, generating electrical fields that can be measured with suitable non-polarizing electrodes. Synthetic forward modelling (A. Binley Lancaster University unpublished data) revealed that the electrical fields drop off rather quickly, however, and are unlikely to be measureable at the surface of ice masses greater than about 30 m thick. The possibility that borehole SP surveys can measure groundwater seepage up to several tens of metres deep in subglacial sedimentary basins, and, indeed, water exchange between such basins and subglacial till layers, is highly intriguing, however, and must be ascertained by future work. We conclude, therefore, that multifaceted and intimately integrated geophysical surveys promise not only to be capable of detecting and delineating groundwater in subglacial sedimentary basins, but also of quantifying groundwater contents and possibly even of groundwater discharge rates.

Summary

Motivated by SCAR's topical 20-year horizon scan and new model simulations, we believe that it is timely and possible to deploy seismics and electrical methods in the search for subglacial groundwater beneath deep ice (greater than *c.* 2 km) in Antarctica. Numerical modelling studies of the Siple Coast ice streams show that groundwater may play an important role in modulating the flow of ice and mass loss from the WAIS. Such work needs to be corroborated by field measurements and expanded to include other regions if we are to understand the potential impact of groundwater on ice-sheet dynamics. It is possible and, perhaps, even likely that a critical source of subglacial water for basal ice-sheet lubrication has so far been overlooked. It is also possible that, due to the long timeframe involved in groundwater charging and discharging, lagged ice-flow responses to the overpressurization of subglacial groundwater reservoirs (e.g. during the last glacial maximum) may have been ignored. Based on significant contemporary changes likely to continue and possibly accelerate in the foreseeable future, groundwater below the WAIS may become increasingly important to ice-sheet stability as changes in ice-sheet geometry inevitably affect the relative distribution of water pressure, overburden, and, thus, the flow of water into and out of the groundwater reservoir.

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References

Anandakrishnan, S. 2003. Dilatant till layer near the onset of streaming flow of Ice Stream C, West Antarctica, determined by AVO (amplitude vs offset) analysis. *Annals of Glaciology*, **36**, 283–286.

Anandakrishnan, S., Blankenship, D.D., Alley, R.B. & Stoffa, P.L. 1998. Influence of subglacial geology on the position of a West Antarctic ice stream from seismic observations. *Nature*, **394**, 62–65.

Archie, G.E. 1942. The electrical log as an aid in determining some reservoir characteristics. *Transactions of the American Institute of Mining, Metallurgical, and Petroleum Engineers*, **146**, 54–64.

Bamber, J.L., Ferraccioli, F., Shepherd, T., Rippin, D.M., Siegert, M.J. & Vaughan, D.G. 2006. East Antarctic ice stream tributary underlain by major sedimentary basin. *Geology*, **34**, 33–36.

Bell, R.E., Blankenship, D.D., Finn, C.A., Morse, D.L., Scambos, T.A., Brozena, J.M. & Hodge, S.M. 1998. Influence of subglacial geology on the onset of a West Antarctic ice stream from aerogeophysical observations. *Nature*, **394**, 58–62.

Bell, R.E., Studinger, M., Shuman, C.A., Fahnestock, M. A. & Joughin, J. *et al.* 2007. Large subglacial lakes in East Antarctica at the onset of fast-flowing ice streams. *Nature*, **445**, 904–907.

Bennett, M.R. 2003. Ice streams as the arteries of an ice sheet: their mechanics, stability and significance. *Earth Science Reviews*, **61**, 309–339.

Bense, V.F. & Person, M.A. 2008. Transient hydrodynamics within intercratonic sedimentary basins during glacial cycles. *Journal of Geophysical Research*, **113**, F04005, https://doi.org/10.1029/2007JF000969

Berbellini, A., Morelli, A. & Ferreira, A.M.G. 2016. Ellipticity of Rayleigh waves in basin and hard-rock sites in Northern Italy. *Geophysical Journal International*, **206**, 395–407, https://doi.org/10.1093/gji/ggw159

Bingham, R.G. & Siegert, M.J. 2007. Radio-echo sounding over polar ice masses. *Journal of Environmental and Engineering Geophysics*, **12**, 47–62.

Booth, A.D., Clark, R.A., Kulessa, B., Murray, T., Carter, J., Doyle, S. & Hubbard, A. 2012. Thin-layer effects in glaciological seismic amplitude-v.-angle (AVA) analysis: implications for characterising a subglacial till unit, Russell Glacier, West Greenland. *The Cryosphere*, **6**, 909–922, https://doi.org/10.5194/tc-6-909-2012

Booth, A.D., Emir, E. & Diez, A. 2016. Approximations to seismic AVA responses: Validity and potential in glaciological applications. *Geophysics*, **81**, WA1–WA11, https://doi.org/10.1190/geo2015-0187.1

Bougamont, M., Price, S., Christoffersen, P. & Payne, A.J. 2011. Dynamic patterns of ice stream flow in a 3-D higher-order ice sheet model with plastic bed and simplified hydrology. *Journal of Geophysical Research*, **116**, F04018, https://doi.org/10.1029/2011JF002025

Bougamont, M., Christoffersen, P., Price, S.F., Fricker, H.A., Tulaczyk, S. & Carter, S.P. 2015. Reactivation of Kamb Ice Stream tributaries triggers century-scale reorganization of Siple Coast ice flow in West Antarctica. *Geophysical Research Letters*, **42**, 8471–8480, https://doi.org/10.1002/2015GL065782

Boulton, G.S., Caban, P.E. & Van Gijssel, K. 1995. Groundwater flow beneath ice sheets: Part I – Large scale patterns. *Quaternary Science Reviews*, **14**, 545–562.

Boulton, G.S., Lunn, R., Vidstrand, P. & Zatsepin, S. 2007*a*. Subglacial drainage by groundwater-channel coupling, and the origin of esker systems: Part I – Glaciologica observations. *Quaternary Science Reviews*, **26**, 1067–1090.

Boulton, G.S., Lunn, R., Vidstrand, P. & Zatsepin, S. 2007*b*. Subglacial drainage by groundwater-channel coupling, and the origin of esker systems:

Part II – Theory and simulation of a modern system. *Quaternary Science Reviews*, **26**, 1091–1105.

Boulton, G.S., Hagdorn, M., Maillot, P.B. & Zatsepin, S. 2009. Drainage beneath ice sheets: groundwater–channel coupling, and the origin of esker systems from former ice sheets. *Quaternary Science Reviews*, **28**, 621–638.

Butler, K.E., Dupuis, J.C. & Kepic, A.W. 2007. Improvements in signal-to-noise in seismoelectric acquisition. *In*: Milkerei, B. (ed.) *Proceedings of Exploration '07: Fifth Decennial International Conference on Mineral Exploration*. Prospectors and Developers Association of Canada, Toronto, Canada, 1137–1141.

Christianson, K., Peters, L.E. *et al.* 2014. Dilatant till facilitates ice-stream flow in northeast Greenland. *Earth and Planetary Science Letters*, **401**, 57–69.

Christoffersen, P. & Tulaczyk, S. 2003. Response of subglacial sediments to basal freeze-on – 1. Theory and comparison to observations from beneath the West Antarctic Ice Sheet. *Journal of Geophysical Research*, **108**, 2222, https://doi.org/10.1029/2002JB001935

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

Doell, R.R. 1963. Seismic depth study of the Salmon Glacier, British Colombia. *Journal of Glaciology*, **4**, 425–437.

Dow, C.F., Hubbard, A., Booth, A.D., Doyle, S.H., Gusmeroli, A. & Kulessa, Y.B. 2013. Seismic evidence of mechanically weak sediments underlying Russell Glacier, West Greenland. *Annals of Glaciology*, **54**, 135–141.

Dugan, H.A., Doran, P.T. *et al.* 2015. Subsurface imaging reveals a confined aquifer beneath an ice-sealed Antarctic lake. *Geophysical Research Letters*, **42**, 96–103, https://doi.org/10.1002/2014gl062431

Dupuis, J.C., Butler, K.E. & Kepic, A.W. 2007. Seismoelectric imaging of the vadose zone of a sand aquifer. *Geophysics*, **72**, A81–A85.

Eisen, O., Hofstede, C., Miller, H., Kristoffersen, Y., Blenkner, R., Lambrecht, A. & Mayer, C. 2010. A new approach for exploring ice sheets and sub-ice geology. *Eos, Transactions of the American Geophysical Union*, **91**, 429e430, http://www.agu.org/journals/eo/eo1046/2010EO460001.pdf

Eisen, O., Hofstede, C. *et al.* 2015. On-ice vibroseis and snowstreamer systems for geoscientific research. *Polar Science*, **9**, 51–65, https://doi.org/10.1016/j.polar.2014.10.003

Ferreira, A.M.G., Woodhouse, J.H., Visser, K. & Trampert, J. 2010. On the robustness of global radially anisotropic surface wave tomography. *Journal of Geophysical Research*, **115**, B04313, https://doi.org/10.1029/2009JB006716

Flowers, G.E. 2015. Modelling water flow under glaciers and ice sheets. *Proceedings of the Royal Society A*, **471**, 20140907, https://doi.org/10.1098/rspa.2014.0907

Foley, N., Tulaczyk, S. *et al.* 2016. Helicopter-borne transient electromagnetics in high-latitude environments: An application in the McMurdo Dry Valleys, Antarctica. *Geophysics*, **81**, WA87–WA99, https://doi.org/10.1190/geo2015-0186.1

French, H.K., Binley, A., Kharkhordin, I., Kulessa, B. & Krylov, S.S. 2006. Cold regions hydrogeophysics. *In*: Vereecken, H., Binley, A., Cassiani, C., Revil, A. & Titov, K. (eds) *Applied Hydrogeophysics*. Springer, New York.

Fretwell, P., Pritchard, H.D. *et al.* 2013. Bedmap2: improved ice bed, surface and thickness datasets for Antarctica. *The Cryosphere*, **7**, 375–393, http://www.the-cryosphere.net/7/375/2013/; https://doi.org/10.5194/tc-7-375-2013

Garambois, S. & Dietrich, M. 2002. Full waveform numerical simulations of seismoelectromagnetic wave conversions in fluid-saturated stratified porous media. *Journal of Geophysical Research*, **107**, ESE 5-1–ESE 5-18.

Gooch, B.T., Young, D.A. & Blankenship, D.D. 2016. Potential groundwater and heterogeneous heat source contributions to ice sheet dynamics in critical submarine basins of East Antarctica. *Geochemistry, Geophysics, Geosystems*, **17**, 395–409, https://doi.org/10.1002/2015GC006117

Gualtieri, L., Stutzmann, E., Capdeville, Y., Farra, V., Mangeney, A. & Morelli, A. 2015. On the shaping factors of the secondary microseismic wavefield. *Journal of Geophysical Research*, **120**, 6241–6262, https://doi.org/10.1002/2015JB012157

Haines, S.S. & Pride, S.R. 2006. Seismoelectric numerical modeling on a grid. *Geophysics*, **71**, N57–N65.

Huuse, M., Le Heron, D.P., Dixon, R., Redfern, J., Moscariello, A. & Craig, J. (eds) . 2012. *Glaciogenic Reservoirs and Hydrocarbon Systems*. Geological Society, London, Special Publications, **368**, http://sp.lyellcollection.org/content/368/1

Jordan, T.A., Ferraccioli, F. *et al.* 2013. Inland extent of the Weddell Sea Rift imaged by new aerogeophysical data. *Tectonophysics*, **585**, 137–160, https://doi.org/10.1016/j.tecto.2012.09.010

Jordan, T., Bamber, J. *et al.* 2016. An ice sheet wide framework for radar-inference of englacial attenuation and basal reflection with application to Greenland. *The Cryosphere*, **10**, 1547–1570, https://doi.org/10.5194/tc-10-1547-2016

Kedar, S., Longuet-Higgins, M., Webb, F., Graham, N., Clayton, R. & Jones, C. 2008. The origin of deep ocean microseisms in the North Atlantic Ocean. *Proceedings of the Royal Society A*, **464**, 777–793, https://doi.org/10.1098/rspa.2007.0277

Keller, G.V. & Frischknecht, F.C. 1960. Electrical resistivity studies on the Athabasca glacier, Alberta, Canada. *Journal of Research of the National Bureau of Standards*, **64D**, 439–448.

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

Key, K. & Siegfried, M.R. In press. The feasibility of imaging subglacial hydrology beneath ice streams with ground based electromagnetics. *Journal of Glaciology*.

Kulessa, B. 2007. A critical review of the low-frequency electrical properties of ice sheets and glaciers. *Journal of Environmental and Engineering Geophysics*, **12**, 23–36, https://doi.org/10.2113/JEEG12.1.23

Kulessa, B., Hubbard, B. & Brown, G.H. 2003*a*. Cross-coupled flow modeling of coincident streaming and electrochemical potentials and application to subglacial self-potential data. *Journal of Geophysical Research*, **108**, 2381, https://doi.org/10.1029/ 2001JB001167

Kulessa, B., Hubbard, B., Brown, G.H. & Becker, J. 2003*b*. Earth tide forcing of glacier drainage. *Geophysical Research Letters*, **30**, 1011, https://doi.org/10.1029/2002GL015303

Kulessa, B., Hubbard, B. & Brown, G.H. 2006*a*. Time-lapse imaging of subglacial drainage conditions using three-dimensional inversion of borehole electrical resistivity data. *Journal of Glaciology*, **52**, 49–57, https://doi.org/10.3189/172756506781 828854

Kulessa, B., Murray, T. & Rippin, D. 2006*b*. Active seismoelectric exploration of glaciers. *Geophysical Research Letters*, **33**, L07503.

Kulessa, B., Hubbard, A.L. *et al*. In review. Seismic evidence for complex sedimentary control of Greenland Ice Sheet flow. *Science Advances*.

Le Brocq, A., Ross, N. *et al*. 2013. Evidence from ice shelves for channelized meltwater flow beneath the Antarctic Ice Sheet. *Nature Geoscience*, **6**, 945–948, https://doi.org/10.1038/ngeo1977

Martín-Español, A., Zammit-Mangion, A. *et al*. 2016. Spatial and temporal Antarctic Ice Sheet mass trends, glacio-isostatic adjustment, and surface processes from a joint inversion of satellite altimeter, gravity, and GPS data. *Journal of Geophysical Research*, **121**, 182–200.

Mercer, J.H. 1978. West Antarctic Ice Sheet and CO_2 greenhouse effect: a threat of disaster. *Nature*, **271**, 321–325.

Mikucki, J.A., Auken, E. *et al*. 2015. Deep groundwater and potential subsurface habitats beneath an Antarctic dry valley. *Nature Communications*, **6**, 6831, https://doi.org/10.1038/ncomms7831

Muto, A., Peters, L.E., Gohl, K., Saasgen, I., Alley, R.B., Anandakrishnan, S. & Riverman, K.L. 2016. Subglacial bathymetry and sediment distribution beneath Pine Island Glacier ice shelf modeled using aerogravity and in situ geophysical data: New results. *Earth and Planetary Science Letters*, **433**, 63–75, https://doi.org/10.1016/j.epsl.2015.10.037

Nolan, M. & Echelmeyer, K. 1999. Seismic detection of transient changes beneath Black Rapids glacier, Alaska, U.S.A.: I. Techniques and observations. *Journal of Glaciology*, **45**, 119–131.

Park, J.W., Gourmelen, N., Shepherd, A., Kim, S.W., Vaughan, D.G. & Wingham, D.J. 2013. Sustained retreat of the Pine Island Glacier. *Geophysical Research Letters*, **40**, 2137–2142, https://doi.org/10.1002/grl.50379

Person, M., McIntosh, J., Bense, V. & Remenda, V.H. 2007. Pleistocene hydrology of North America: The role of ice sheets in reorganizing groundwater flow systems. *Reviews of Geophysics*, **45**, RG3007, https://doi.org/10.1029/2006rg000206

Person, M., Bense, V., Cohen, D. & Banerjee, A. 2012. Models of ice-sheet hydrogeologic interactions: a review. *Geofluids*, **12**, 58–78, https://doi.org/10.1111/j.1468-8123.2011.00360.x

Peters, L.E., Anandakrishnan, S., Alley, R.B. & Smith, A.M. 2007. Extensive storage of basal meltwater in the onset region of a major West Antarctic ice stream. *Geology*, **35**, 251–254.

Peters, L.E., Anandakrishnan, S., Holland, C.W., Horgan, H.J., Blankenship, D.D. & Voigt, D.E. 2008. Seismic detection of a subglacial lake near the South Pole, Antarctica. *Geophysical Research Letters*, **35**, L23501, https://doi.org/10.1029/2008GL 035704

Piotrowski, J.A., Hermanowski, P. & Piechota, A.M. 2009. Meltwater discharge through the subglacial bed and its land-forming consequences from numerical experiments in the Polish lowland during the last glaciation. *Earth Surface Processes and Landforms*, **34**, 481–492, https://doi.org/10.1002/esp.1728

Rignot, E., Mouginot, J. & Scheuchl, B. 2011. Ice flow of the Antarctic ice sheet. *Science*, **333**, 1427–1430, https://doi.org/10.1126/science.1208336

Ross, N., Bingham, R.G. *et al*. 2012. Steep reverse bed slope at the grounding line of the Weddell Sea sector in West Antarctica. *Nature Geoscience*, **5**, 393–396, https://doi.org/10.1038/ngeo1468

Schroeder, D.M., Blankenship, D.D. & Young, D.A. 2013. Evidence for a water system transition beneath Thwaites Glacier, West Antarctica. *Proceedings of the National Academy of Sciences of the United States of America*, **110**, 12225–12228.

Sheriff, R.E. & Geldart, L.P. 1995. *Exploration Seismology*. Cambridge University Press, Cambridge, https://doi.org/10.1017/CBO9781139168359

Shreve, R.L. 1972. Movement of water in glaciers. *Journal of Glaciology*, **11**, 205–214.

Siegert, M.J. & Bamber, J.L. 2000. Subglacial water at the heads of Antarctic ice stream tributaries. *Journal of Glaciology*, **46**, 702–703.

Siegert, M.J., Dowdeswell, J.A., Gorman, M.R. & McIntyre, N.F. 1996. An inventory of Antarctic sub-glacial lakes. *Antarctic Science*, **8**, 281–286.

Siegert, M.J., Carter, S., Tabacco, I., Popov, S. & Blankenship, D. 2005. A revised inventory of Antarctic subglacial lakes. *Antarctic Science*, **17**, 453–460.

Siegert, M., Popov, S. & Studinger, M. 2011. Subglacial Lake Vostok: a review of geophysical data regarding its physiographical setting. *In*: Siegert, M., Kennicutt, C. & Bindschadler, B. (eds) *Subglacial Antarctic Aquatic Environments.* AGU Geophysical Monograph **192**, Washington DC, 45–60.

Siegert, M.J., Ross, N., Corr, H., Kingslake, J. & Hindmarsh, R. 2013. Late Holocene ice-flow reconfiguration in the Weddell Sea sector of West Antarctica. *Quaternary Science Reviews*, **78**, 98–107, https://doi.org/10.1016/j.quascirev.2013.08.003

Siegert, M.J., Ross, N. *et al*. 2014. Boundary conditions of an active West Antarctic subglacial lake: implications for storage of water beneath the ice sheet. *The Cryosphere*, **8**, 15–24, https://doi.org/10.5194/tc-8-15-2014

Siegert, M.J., Ross, N. *et al*. 2016. Controls on the onset and flow of Institute Ice Stream, West Antarctica. *Annals of Glaciology*, **57**, 19–24, https://doi.org/10.1017/aog.2016.17

Siegfried, M.R., Fricker, H.A., Carter, S.P. & Tulaczyk, S. 2016. Episodic ice velocity fluctuations triggered by a subglacial flood in West Antarctica. *Geophysical Research Letters*, **43**, 2640–2648, https://doi.org/10.1002/2016GL067758

Simm, R., White, R. & Uden, R. 2000. The anatomy of AVO crossplots. *The Leading Edge*, **19**, 150–155.

Smith, A.M. 1997. Basal conditions on Rutford Ice Stream, West Antarctic, from seismic observations. *Journal of Geophysical Research*, **102**, 543–552.

Smith, A.M. 2007. Subglacial bed properties from normal-incidence seismic reflection data. *Journal of Environmental & Engineering Geophysics*, **12**, 3–13.

Smith, B.E., Fricker, H.A., Joughin, I.R. & Tulaczyk, S. 2009. An inventory of active subglacial lakes in Antarctica detected by ICESat (2003–2008). *Journal of Glaciology*, **55**, 573–595.

Smith, A.M., Jordan, T.A., Ferraccioli, F. & Bingham, R.G. 2013. Influence of subglacial conditions on ice stream dynamics: seismic and potential field data from Pine Island Glacier, West Antarctica. *Journal of Geophysical Research*, https://doi.org/10.1029/2012JB009582

Stearns, L.A., Smith, B.E. & Hamilton, G.S. 2008. Increased flow speed on a large East Antarctic outlet glacier caused by subglacial floods. *Nature Geoscience*, **1**, 827–831.

Thompson, A.H. & Gist, G.A. 1993. Geophysical applications of electrokinetic conversion. *The Leading Edge*, **12**, 1169–1173.

Tulaczyk, S., Kamb, W.B. & Engelhardt, H.F. 2000*a*. Basal mechanics of Ice Stream B, West Antarctica 1. Till mechanics. *Journal of Geophysical Research*, **105**, 463–481.

Tulaczyk, S., Kamb, W.B. & Engelhardt, H.F. 2000*b*. Basal mechanics of Ice Stream B, West Antarctica 2. Undrained plastic bed model. *Journal of Geophysical Research*, **105**, 483–494.

Wannamaker, P.E., Stodt, J.A., Pellerin, L., Olsen, S.L. & Hall, D.B. 2004. Structure and thermal regime beneath the South Pole region, East Antarctica, from magnetotelluric measurements. *Geophysical Journal International*, **157**, 36–54, https://doi.org/10.1111/j.1365-246X.2004.02156.x

Wingham, D.J., Siegert, M.J., Shepherd, A.P. & Muir, A.S. 2006. Rapid discharge connects Antarctic subglacial lakes. *Nature*, **440**, 1033–1036.

Woodward, J., Smith, A. *et al*. 2010. Location for direct access to subglacial Lake Ellsworth: An assessment of geophysical data and modelling. *Geophysical Research Letters*, **37**, L11501, https://doi.org/10.1029/2010GL042884

Wright, A.P. & Siegert, M.J. 2011. The identification and physiographical setting of Antarctic subglacial lakes. *In*: Siegert, M.J. & Kennicutt, M.C. (eds) *Antarctic Subglacial Aquatic Environments*. American Geophysical Union, Geophysical Monograph Series, **192**, 9–26, https://doi.org/10.1029/2010GM000933

Wright, A.P. & Siegert, M.J. 2012. A fourth inventory of Antarctic subglacial lakes. *Antarctic Science*, **24**, 659–664.