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

Martin J. Siegert1, Bernd Kulessa2, Marion Bougamont3, Poul Christoffersen3, Kerry Key4, Kristoffer R. Andersen5, Adam D. Booth6, Andrew M. Smith7

1. Grantham Institute, and Department of Earth Science and Engineering, Imperial College London, UK

2. Department of Geography, University of Swansea, UK

3. Scott Polar Research Institute, University of Cambridge, UK

4. Lamont-Doherty Earth Observatory, Columbia University, USA

5. Department of Geosciences, Aarhus University, Aarhus 8000, Denmark.

6. School of Earth and Environment, University of Leeds, UK

7. British Antarctic Survey, High Cross, Cambridge, UK.

**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 recognised 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 multi-facetted 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.**

**INTRODUCTION**

**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 reduction in the substrate’s effective pressure. Conversely, where a well-organised 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 pore-water pressures. High pressures lead to a reduction in material strength by pushing till grains apart, reducing bed friction and thus 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 pre-requisite for ice streaming (Anandakrishnan et al., 1998; Bell et al., 1998; 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 pore water pressures while reducing shear strength (Bennett, 2003). As the strength of basal material is related to pore-water pressures, it is evident that groundwater could exert a major, and as yet understudied, influence on ice flow (e.g., Boulton et al., 2007a; 2007b). 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; Musse 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; Siegert et al., 2005; Wright and Siegert, 2012). Many of these lakes are connected hydrologically over large (100s km) distances (Wingham et al., 2006; Smith et al., 2009), some have been identified at the onset of fast flow (Siegert and Bamber, 2000; Bell et al. 2007), and water issued from a few of them has been shown to influence ice-sheet flow (Siegfried et al., 2016; Stearns et al., 2008). 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 (>100s m) sedimentary basins around the onset of enhanced ice flow (Wright and Siegert, 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), 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?’ ‘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 sinkshas traditionally been restricted to an *interfacial* hydrological system between ice above and a presumed impermeable sedimentary basin below (Fig. 1a), comprised of 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 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 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):

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

The permeability of 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 and Tulaczyk, 2003). Time lags (process (iv)) are evidenced for example by contemporary sedimentary basins in the northern USA (Bense and Person, 2008). Their groundwater reservoirs were re-charged and over-pressured during growth of the Laurentide Ice Sheet, up to the last glacial maximum ~20ka ago. Ice sheet retreat over following millennia then enabled slow release of pressure and therefore upward flow of groundwater into the interfacial hydrological system (Fig. 1b). Although glaciation ended more than 10ka ago, over-pressure 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 likely 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 program 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, topographic 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 5 pairs of repeat ICESat track data showed the lake ‘filled’ by ~0.5 km3 between Oct. 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., 2014), suggesting 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 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., 1998; 2000). The greatest ice-flow velocity of the IIS onset occurs where RES data show soft tills are most likely (Siegert et al. 2016). This is consistent with high pore-water pressures within these tills, which means 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 fast flow (Fig. 3c) of IIS’s ~2000m 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 thepresence of deformable subglacial till (Fig. 4). The bed of the 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 IIS, and much reduced radar reflectivities beneath BIR are consistent with wet and deformable tills beneath the former, and a frozen till base at the latter (Fig. 4). The third trait isthe likely hydrological control of ice flow*.* Akin to the Siple Coast, the IIS/BIR system is characterised by major subglacial flow pathways that connect with each other and with the ‘active’ subglacial lake Institute E1 (Fig. 3); a temporary storage reservoir of interfacial waters (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 characterise 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 and 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, affect resolution and 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 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 vs. 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.

Geophysical techniques offer the only feasible means 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 characterising 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, topographic and geologic 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 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 and 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 contents 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 subglacial lakes (Siegert et al., 1996; Siegert et al., 2005; Wright and Siegert, 2012), though 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, 1967; Smith et al., 1997, 2007; Peters et al., 2007; Woodward et al., 2010). A growing number of glaciological applications have been using Amplitude Versus 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 and 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 and Geldart, 1995; Simm et al., 2000; Booth et al., 2016).

The seismoelectric method promises to become a powerful means of detecting, delineating and physically characterising subglacial till layers (Kulessa et al., 2006). 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 will therefore measure it at the 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), namely exceptional sensitivity to (i) till permeability (Thompson and Gist, 1993; Garambois and Dietrich, 2002), a fundamental parameter in ice sheet modelling (Christoffersen et al., 2014; Bougamont et al., 2014, 2015) that cannot be measured with existing methods; and (ii) thin deformable till horizons (Haines and 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).

Fig. 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; their Fig. 2), and instrumentation was custom-designed for use in low-noise survey (Butler et al., 2007; Butler et al., in review). 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 ~ 1145 ± 15 m, whose upper horizon is thin and deforming (Booth et al., 2012; Kulessa et al., in review). Two clear seismoelectric returns are observed, the first centred at ~ 305 ms and the second at twice that time of ~ 610 ms (Fig. 6). The first return at ~ 305 ms is therefore fully consistent with a seismoelectric conversion in the till layer beneath the ice sheet base, while the second at ~ 610 ms is fully consistent with a coseismic arrival from the base. The processed seismoelectric conversion at ~ 305 ms has a peak-to-peak amplitude of ~ 10 micro-V, 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 characterisation of ice sheet substrates.

**Geometry and structure of subglacial sedimentary basins within the uppermost crust**

Subglacial basins of sedimentary rock are relatively poorly exploredcompared to the hydrological and mechanical characterisation 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 Fig. 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 is 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* (Gualtier 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 tomographic 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 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 ~ 2.5 km deep sedimentary basins beneath the up to ~ 2 km deep ice of the IIS/BIR region (Figs. 3-5). Where contrasts in acoustic impedance exists between stratified layers beneath the ice sheet bed, such as e.g. 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 and Person, 2008; Piotrowski et al., 2009), then seismic techniques are readily able to resolve layers thicker than ~ ¼ of 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 above can conceptually contribute to the identification of 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 e.g. 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 ~ 10-5–104 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 characterisation 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 (Mikucki et al., 2015; Wannamaker et al., 2004). For example, EM surveys in the Dry Valleys of Victoria Land, Antarctica, clearly distinguished lower-resistivity groundwater-bearing sediments (~101–102 Ωm) from higher-resistivity glacier ice, permafrost and crustal bedrock (typically ~103–104 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 and Siegfried (in review) showed that the MT method may be capable of resolving conductive layers as thin as a few metres, such as e.g. 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 conceptualised 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 reorganisation 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 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 (Mikucki et al., 2015; Dugan 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 > 1000 m ice thickness and up to ~ 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 m2 with moments up to 4 MA m2. We found that the resistivity (ρ) of groundwater-saturated sedimentary rock beneath the ~ 2000 m thick ice sheet can readily be resolved within a range narrower than 1.6\*ρ to ρ/1.6 for subglacial permafrost thicknesses less than ~ 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 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 program of field investigation were conducted along the lines of what we proposed above, then high-quality topographic, ice thickness and crustal structural information would be available from seismic and radar data to constrain the MT and TEM inversions, and the latter are additionally able to constrain each other. In favourable circumstances 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 and Siegfried, in review). According to Archie’s law (Archie, 1942) bulk resistivity is a function of porosity, water saturation and water electrical conductivity, as indeed affirmed for subglacial till layers by Kulessa et al. (2006). 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 contents.

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., 2003a, 2003b, 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-polarising 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 ~ 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 multi-facetted 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 ~ 2km) 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 over-pressurisation of subglacial groundwater reservoirs (during, for example, 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.

**Acknowledgements**

We thank Huw Horgan and an anonymous referee for providing helpful and constructive reviews.

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