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Advancements in the Measurement of the Cryosphere Using Geophysics — Introduction

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Special Section

Advancements in the measurement of the cryosphere using geophysics — Introduction

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Frozen regions of the earth are known as the cryosphere. The arctic, Antarctica, permafrost, ice sheets, and glaciers are some of the most challenging places to measure subsurface parameters, but they can also be some of the most important places to science and engineering research due to their susceptibility to environmental change. Ground-based, airborne, and space-borne geophysical methods are deployed to observe targets below the ground or in ice that may be difficult or impossible to measure using conventional direct observations and measurements. The papers in this special section address recent advances in instrumentation development and deployment and computational capabilities that have advanced cryosphere geophysical sciences. As such, many of these papers discuss the science that the methodology has helped reveal.

A wide range of cryosphere science questions are being addressed using geophysical data, and most are highly relevant to climate change. For example: How does liquid water affect snow, glacier, and permafrost dynamics; what controls snowpack distribution and water content; what controls water movement in the active layer above permafrost; and how are sensitive special features like Antarctic lakes and ice shelves evolving? In all cases, geophysical measurements provide parameters vital to understanding the system function, often in 2D or 3D space or through time. We present 21 papers that include topics ranging from long-established direct-current electrical, seismic, and ground-penetrating radar (GPR) methods, to emerging measurements such as surface nuclear magnetic resonance (NMR), all with novel examples.

Holbrook et al. image snow stratigraphy and estimate snow water equivalent (SWE) from a GPR system mounted on a snowmobile. The authors measure snow thickness, snow density, and SWE over large areas from rapidly acquired common-offset GPR profiles, without the need for multioffset acquisition or snow cores.

Schroeder et al. improve empirical attenuation corrections for variable attenuation rates and ice-surface propagation losses for radar profiles from the interior of an ice sheet to its grounding zone. The authors apply their approach to airborne observations of the Thwaites Glacier catchment in West Antarctica, finding that its eastern shear margin transitions from a frozen to a thawed bed and that grounding-zone basal conditions vary across the Amundsen Sea Embayment.

Garambois et al. combine GPR and surface NMR to characterize and monitor a polythermal glacier containing a large water pocket capable of threatening the safety of residents in the valley below. The authors describe glacier geometry, water-filled fractures, and basal anomalies generated by diffuse water driven by a temperature increase at depth.

Schennen et al. present a GPR case study from northern East Siberia. The authors demonstrate that 3D survey geometry is able to image structures within complex, ice-rich permafrost deposits, and trace major lithological interfaces at depths larger than 20 m.

Hunkeler et al. demonstrate 1D inversion of multifrequency electromagnetic (EM) data with integration of a sensor-specific bucking-coil correction for resolving sea-ice thickness, conductivity, and the porosity. The observed resolution is sufficient to initiate field trials aimed at distinguishing between different sea-ice types, resolving flooded snow layers, or imaging the subice platelet layers near Antarctic ice shelves.

Axtell et al. show that, while basic crosshole radar data collection can interpret velocities to an accuracy of ± 0.005 m/ns, survey

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revisions can enhance data acquisition, improving the velocity uncertainty to ± 0.001 m/ns.

Arcone et al. use a robotic ground vehicle to acquire a 28 km^2 grid of multifrequency GPR profiles across the dangerously crevassed McMurdo Shear Zone, Antarctica. The profiles reveal the orientations, widths, and depths of crevasses in firn and orientations, widths, and forms of crevasses and fractures in basal marine ice.

Annan et al. apply GPR for winter road safety. The authors explain operational requirements and discuss the current state of practice, modern GPR instrumentation, ice-layer thickness variation, and variability of EM wave velocity in ice.

Rutishauser et al. acquire a large helicopter-borne GPR data set over temperate glaciers in the Western Swiss Alps. The authors record data with different acquisition systems and offer information on glacier bedrock topography and internal ice structures.

Tomaškovičová et al. present a new protocol for estimating the grounding resistance of individual electrodes in multielectrode arrays used for electrical resistivity tomography (ERT). Through numerical modeling, the authors document the performance of the protocol and show that grounding resistances can typically be estimated to within $\pm 7\%$ for arrays of 30 electrodes or more when the ratio of instrument input impedance to half-space resistivity is 1000 ohm m^{-1} or more.

Ingeman-Nielsen et al. continue the work of Tomaškovičová et al. by providing quantitative information on the range of grounding resistances determined from laboratory and field experiments, and cryospheric ERT monitoring. The authors discuss improvements that can be achieved by using optimized electrode design.

Schmid et al. address the opportunities and limitations of full-waveform inversion techniques applied to data of an upward-looking GPR system. The authors show that it is generally possible to delineate a detailed stratigraphy of the snowpack, but additional issues need to be addressed.

Vélez et al. measure seismic anisotropy in the field to determine the distribution of preferred ice crystal orientation in ice sheets and glaciers. The authors present results from the North Greenland Eemian Ice Drilling site, a no-flow location, and from the fast-flowing Jakobhsavn Isbræ glacier.

Merz et al. present a joint interpretation of helicopter-borne GPR, seismic, geoelectric, and crosshole GPR data acquired over an alpine rock glacier. By combining these methods, inherent ambiguities of the individual data sets are reduced and a comprehensive subsurface model is presented.

Dugan et al. discuss high-resolution 850 MHz GPR profiles over deep perennial lake ice in the McMurdo Dry Valleys of Antarctica. The profiles reveal unconformably eroded and folded horizons, incised fluvial bottom deposits and up to 4.5 m of subbottom penetration, and the spatial heterogeneity of lake ice.

Bradford et al. use time-domain reflection waveform inversion of 500 MHz GPR data to estimate the thickness of oil spills trapped under sea-ice in a controlled experiment. The method accurately estimates the thickness of an oil layer that varied from 2–5 cm, which is just 5.9%–14% of the dominant wavelength.

Voytek et al. combine ERT and self-potential measurements (SP) to map shallow subsurface flowpaths in and around water-track drainage features common to arctic hillslopes. The authors identify complex 3D flowpaths within the thawed zone and suggest that traditional techniques may underestimate active layer thaw and the extent of the flowpath networks.

Dafflon et al. integrate ERT data, EM data, laboratory core analysis, high-resolution digital surface models, and color mosaics inferred from kite-based landscape imaging to understand the spatial distribution of shallow Arctic permafrost soil properties and its links with landscape microtopography. The authors find that salinity variations directly influence permafrost porosity and unfrozen water content and indirectly influence the soil organic matter content.

Dou et al. present a laboratory ultrasonic study to explore the seismic properties of unconsolidated saline permafrost, which is common in the subsea and coastal arctic and particularly susceptible to deformation. The authors present an experimental data set covering temperature-dependent P-wave velocities for saline permafrost at a range of salinities, and temperatures.

Foley et al. demonstrate the use of airborne transient EM to investigate subsurface brines beneath permafrost and glacier ice in the McMurdo Dry Valleys, Antarctica. The authors' results indicate widespread brines about 150–250 m below the surface, at temperatures between -10°C and -6°C.

Booth et al. simplify the complicated Knott-Zoeppritz equations and apply them to amplitude-variation-with-angle analysis of glaciological seismic data to find englacial anisotropy and subglacial material composition. The authors consider the circumstances under which such approximations are valid in typical glaciological cases of reflectivity and suggest alternate practice where required.

Douglas et al. link ERT, airborne LiDAR, and point scale and imagery surveying to identify relationships between permafrost geomorphology and time since fire at five scars on the Tanana Flats in central Alaska. The authors suggest that attempts to quantify permafrost distribution using aerial measurements alone could lead to incomplete results because of unpredictable morphologies within transition zone boundaries between permafrost soils and unfrozen soils in collapse scar bogs.