Ice Core Detection with Spectral Induced Polarization: A Haines Junction Case Study

Hosein Fereydooni, Stephan Gruber, Derek Cronmiller & David Stillman

Carleton University

PermafrostNet NSERC | CRSNG

Introduction

Spectral Induced Polarization (SIP) reveals subsurface properties without drilling by analyzing impedance magnitude (|z(w)|) and phase shift angle ($\varphi(\omega)$) profiles at various frequencies (ω). The study in Haines Junction, Yukon, used SIP to identify a pingo's ice core, proving SIP's effectiveness with a FUCHS frequency domain instrument (1.46 Hz-40 kHz).

$$Impedance: Z(\omega) = R - iX = |Z(w)|e^{i\varphi(w)}\text{ , }R: Real\ Part, and\ X: Imaginary\ Part$$

$$Phase\ shift\ angle: \varphi(\omega) = arctan(\frac{-X}{R})$$

Measuring instrument and configuration

Data acquisition was conducted at this site using a survey line that spanned 30 meters and consisted of 30 electrodes. The electrodes were spaced at intervals ranging from one meter to five meters, following a dipole-dipole array configuration. To maximize the performance of the FUCHS system, precise placement of the 30 stainless steel ground stakes is crucial. They are positioned in alignment with the potential electrodes and positioned at the center of these electrodes. This setup ensures optimal functionality and accurate measurements.

Study Area

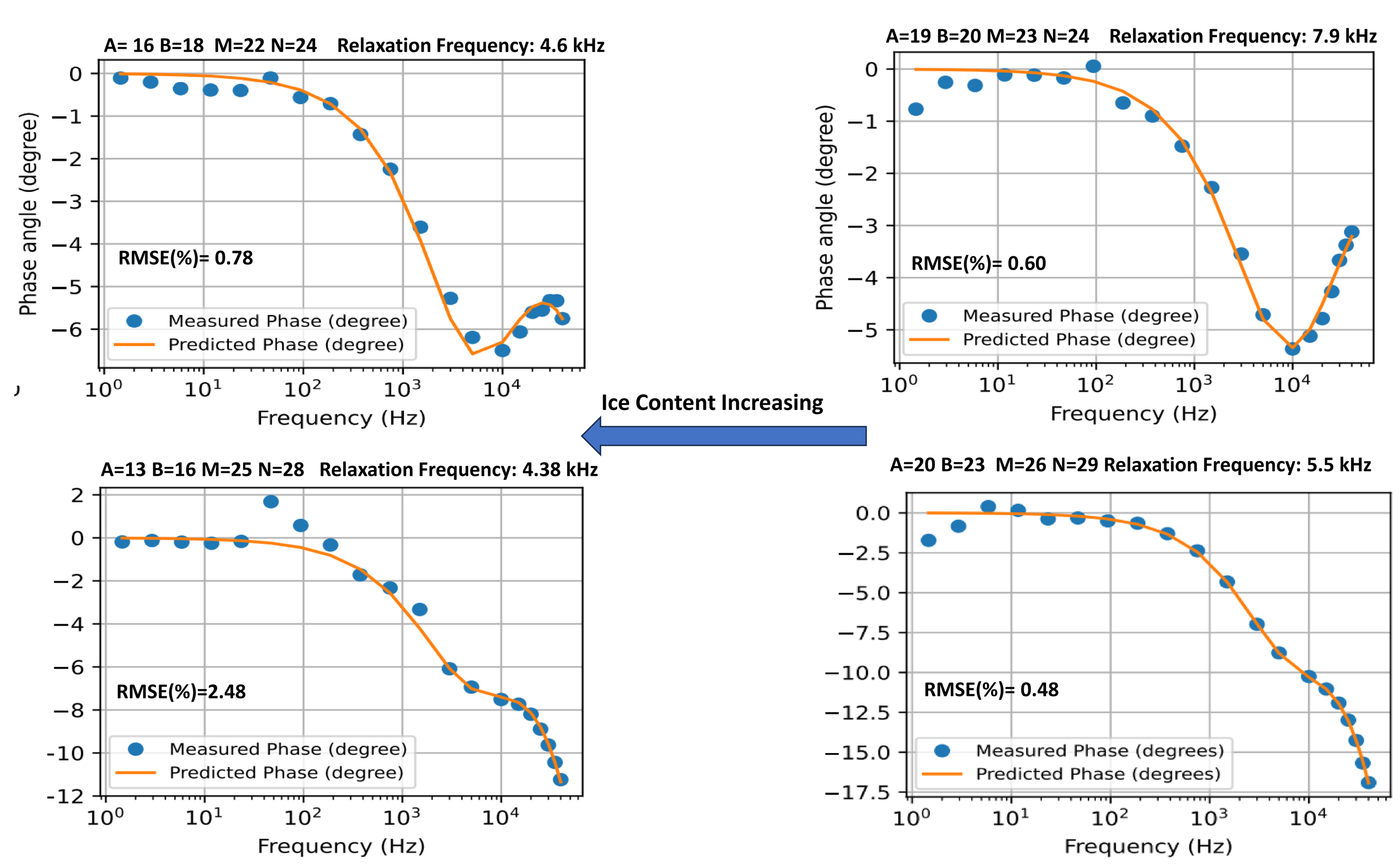
The research took place at a specific pingo site in Haines Junction, field measurements were carried out over a period of three days in March 2023. Throughout this time, the local average temperature exhibited variations, ranging from -2°C to +4° (60.7835º N 137.5321º W) .

Results – Phase Angle Spectra

A Python code was written to inverse the SIP data (11640 SIP data at 20 frequencies) and extract two relaxation frequencies based on Cole-Cole equation the decreases of relaxation frequency equivalent to ice content increasing.

Cole-Cole model: $\rho(\omega) = \rho_0\left\{1 - m_1\left[1 - \frac{1}{1+(i\omega\tau_1)^{c_1}}\right]\right\}\left\{1 - m_2\left[1 - \frac{1}{1+(i\omega\tau_2)^{c_2}}\right]\right\}$

ρ_0 Resistivity at the lowest frequency, m_1, m_2 Chargeability, τ_1, τ_2 Relaxation time, c_1, c_2 Frequency coefficients



Results – 2D inversion Image for the highest frequency

Figure 1 displays inverted impedance magnitude and phase shift angle at 40 kHz. The impedance magnitude plot uncovers a high resistivity layer about 2 meters below the surface, spanning 22 to 24 meters horizontally, with another distinct high resistive layer within 12 to 20 meters. The phase shift angle plot reveals higher negative phase values between 14 and 26 meters, indicating a positive correlation with the high resistivity area. Figure 2 shows real and imaginary parts of impedance at 40 kHz, with the higher values (in the red zone) indicating the pingo ice core.

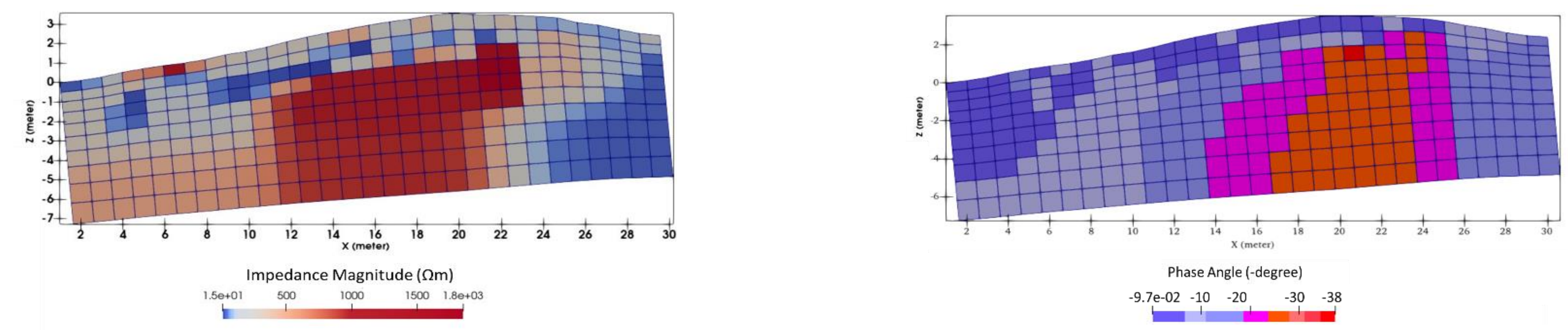


Figure 1. Impedance magnitude (Ωm) and phase angle (degree) at 40 kHz.

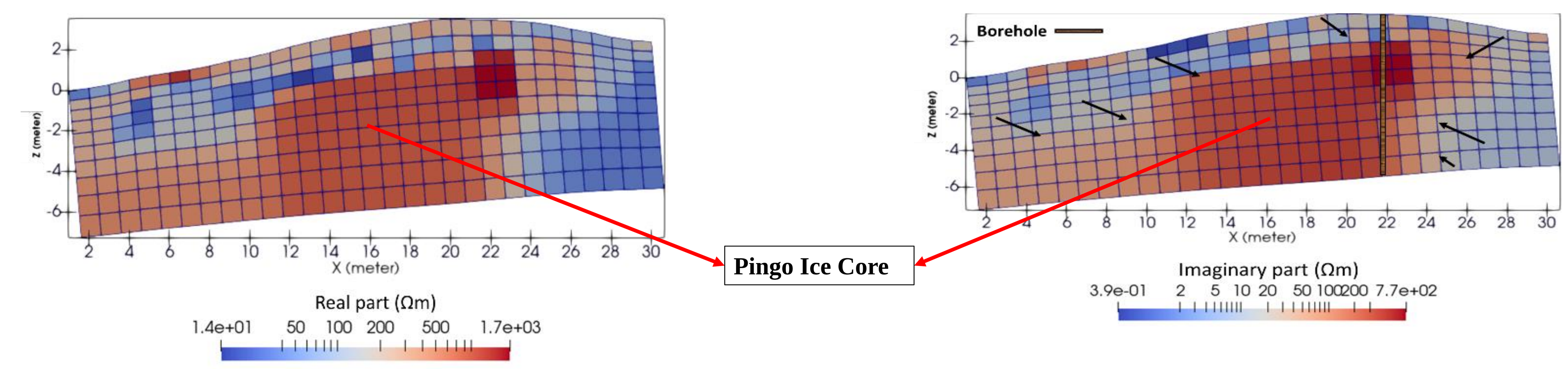


Figure 2. Real and Imaginary part (Capacitance Reactance) of impedance at 40 kHz.

Comparison with Drill Logs

Log details for borehole on pingo (Ice content is given in estimated volume percent of visible ice) shown in the below table:

Depth (m)	Material	Frozen	Ice (%)	Ice
0–0.1	Fibric organics	Y	Nil	Nf
0.1–0.3	Silt	Y	Nil	Nf
0.3–0.6	Air		Nil	-
0.6–2.4	Clayey silt	Y	5	Vx
2.4–2.9	Silty clay	Y	20	Vr
2.9–3.6	Silty clay	Y	30	Vr
3.6–8.3	Ice	Y	98	ICE+clay +diamict
8.3–10.8	Gravel	N	0	-

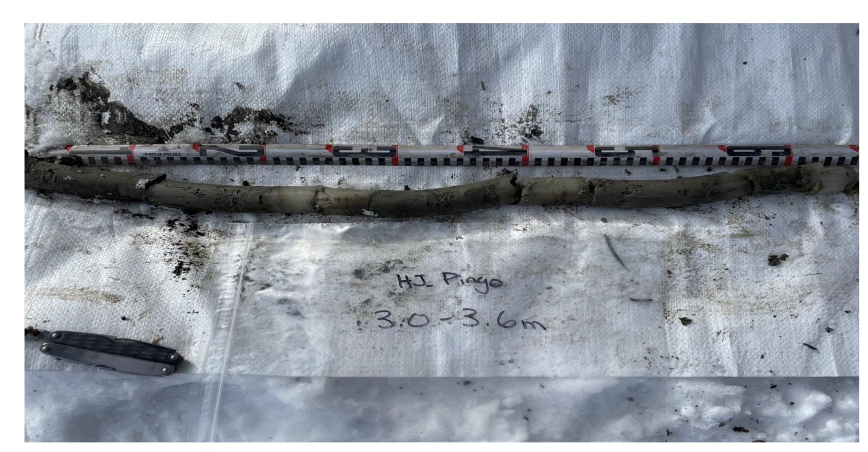


Figure 3. Core recovered from 3 0 to 3.6 meters depth.

Figure 4 illustrates phase shift angle variations at a borehole location. It shows a low phase shift of -2.83 degrees at 0-0.6 meters in the ice-free zone. With the presence of ice, it changes to -2.87 degrees at 0.6 meters, aligning with the clayey silt and air layer boundary. At 1.5 meters, a significant shift to -24.2 degrees likely due to ice polarization is observed. Another change occurs at 2.2 meters, marking the boundary between silty clay and clayey silt with more ice. From 3.6 to 8.3 meters, as ice volume increases, phase shift angles gradually become more negative, reaching -25.2 degrees at 8.3 meters. The last layer's initial phase shift change is at 4.7 meters one meter away from the boundary between the ice layer and silty clay , possibly due to lower resolution at greater depths.

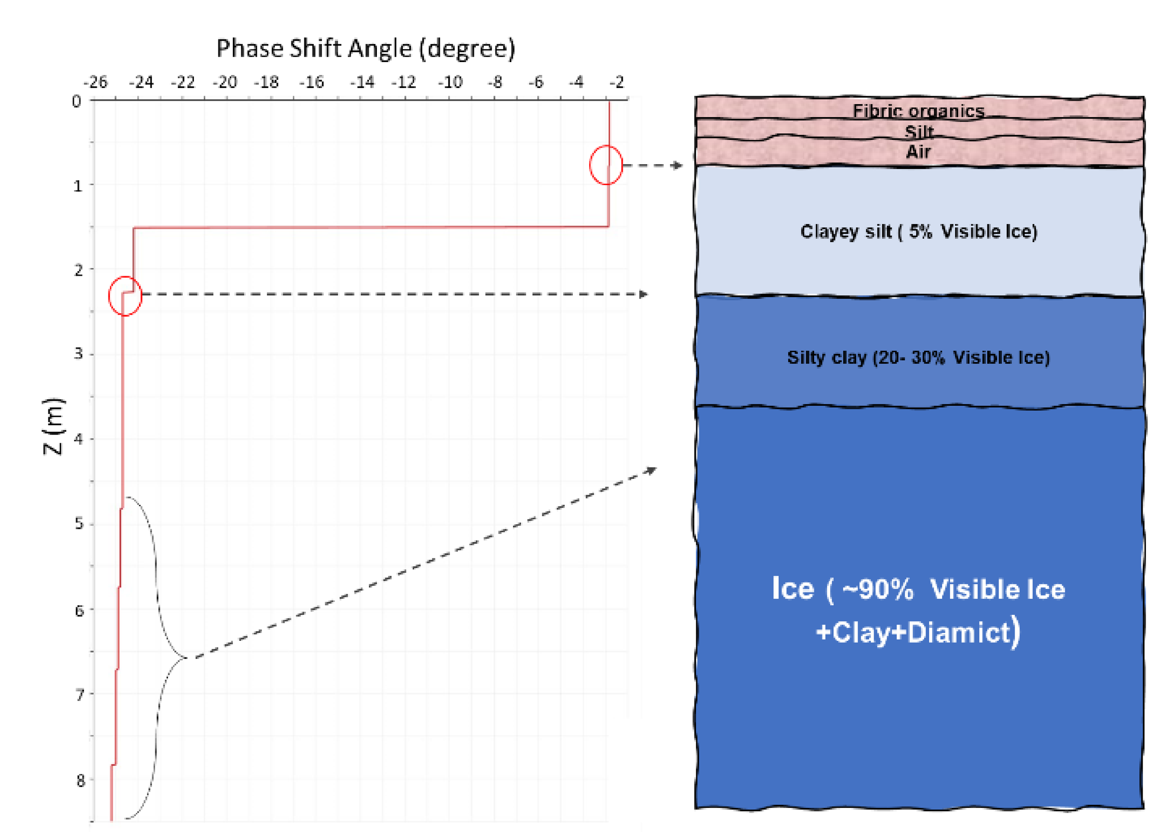


Figure 4. Phase Shift Angle at 40 kHz (extracted for the borehole Location).

Authors

Hosein Fereydooni Department of Earth Sciences - Carleton University, Ottawa, Ontario, Canada
Stephan Gruber Department of Geography and Environmental Studies, Carleton University, Ottawa, ON, Canada
Derek Cronmiller Permafrost Geologist, Energy, Mines and Resources, Yukon Geological Survey, Yukon, Canada.
David Stillman Southwest Research Institute, Boulder, CO, USA

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