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# Delineation of hydrothermal dolomite on Cape Donovan, Southampton Island, Nunavut, Canada using magnetotellurics

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## Summary

A 26-site magnetotelluric (MT) survey was conducted on Cape Donovan, Southampton Island, Nunavut in July 2018 as part of the Canadian GEM 2 Project to determine whether the MT method can detect and delineate a fault-controlled hydrothermal dolomite (HTD) deposit. The MT results resolve a small conductor at the location of the deposit, although with quite low resolution. At a larger-scale the MT resistivity models also resolve enhanced conductivity on the fault system that is thought to have contributed to the formation of the HTD deposit.

## Introduction

A focus of the GEM 2 Hudson-Ungava Project is examination of fault-controlled hydrothermal dolomite (HTD) in the Hudson Bay Basin. HTD deposits form important hydrocarbon reservoirs in intracratonic settings (Lavoie et al., 2013). In this study, the magnetotelluric (MT) method is used to investigate an occurrence of HTD identified on Cape Donovan, Southampton Island in Nunavut, Canada (Figure 1).

The MT method uses fluctuations in the Earth's magnetic field as a virtual transmitter. Its depth of exploration depends on signal period and ranges from tens of metres in audiofrequency MT (AMT) surveys to hundreds of kilometres in low-frequency MT studies. MT receivers and sensors are portable and use low power, so can be deployed in remote locales by a crew of two or three persons. Structurally-controlled HTD deposits are often formed by fluid movement associated with faulting and fracturing and are often more porous than host carbonates. When pores are mineralized or brine-saturated, deposits are electrically enhanced relative to their host rocks and therefore suitable for mapping with geophysical methods such as MT.

The capability of MT for generating information on prospectivity of hydrocarbon systems was shown previously in the GEM project through MT mapping of porous *versus* tight shallow carbonate units near Churchill, Manitoba (Roberts and Craven, 2012). In the current study the MT survey is used in the evaluation of HTD-related hydrocarbon potential of Hudson Strait and Foxe Basin and to help understand the fault systems associated with the HTD.

## Geological background

Cape Donovan hosts a small area (15 by 10 km) of Paleozoic sedimentary rocks of the Hudson Bay Basin, with interpreted thickness of up to 200-300 m, overlying Proterozoic metasedimentary and plutonic basement rocks (Figure 1; Heywood & Sanford, 1976; Zhang 2010; Chakungal et al., 2008). The Paleozoic rocks record multiple phases of faulting. The primary Precambrian-Paleozoic contact is interpreted as being associated with uplift of the Bell-Boothia Arch during Silurian-Devonian time (Heywood & Sanford 1976; Sanford and Thompson, 1984). Transverse faults display intensely sheared Paleozoic and Precambrian rocks (Heywood & Sanford, 1976). Similar structures are seen on White Island, 140 km to the northwest, where the

Precambrian-Paleozoic contact is offset by steeply-dipping reverse and normal faults trending at high angle and sub-parallel to the main contact (Jefferson & Hamilton 1987). Seismic surveys in the Foxe Basin reveal deformation related to the North Southampton Fault, which is interpreted to be of Cretaceous age (Figure 1, Pinet et al., 2013). It is possible that some of the deformation on Cape Donovan and White Island is of this age. For example, a late normal fault extending the length of White Island truncates the reverse faults there (Jefferson & Hamilton, 1987).

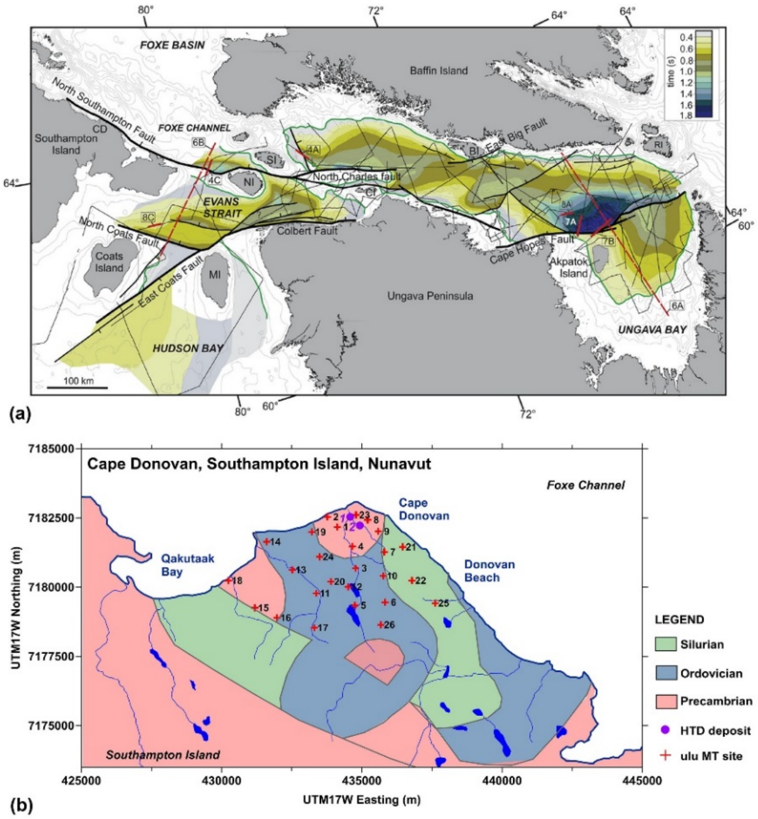


**Figure 1.** Maps of MT survey area. **(a)** Regional map showing major faults and time of seismic depth to Precambrian basement (from Pinet et al. 2013). CD=Cape Donovan. **(b)** Map of Cape Donovan showing geology from Heywood et al. (1969) and Zhang (2010).

Two HTD deposits occur on Cape Donovan. Both deposits lie in 10-15 m thick zones and are associated with fractures and faults (Figure 1; Zhang 2008, 2010; Lavoie et al., 2011). They include massive dolomite breccia and dolomite and limestone clasts cemented by coarse-grained dolomite cement (Lavoie *et al.* 2011). Dolomite cement fills pore spaces between carbonate clasts irregularly with visually estimated porosities of 5-25%. At the first HTD location, the highly fractured zone has a general orientation of N187/70 (Lavoie *et al.* 2011).

## MT survey and data processing

The 2018 "*ulu*" MT survey provided coverage of the Paleozoic rocks at Cape Donovan and included sites near the HTD (Figure 1; Craven et al., 2018; Marks 2019). The area is quite rugged with steep slopes at the coastline and deep indentations along larger streams, so MT sites were chosen in areas as flat as possible. The ground consisted of cobble terraces formed from underlying Paleozoic rocks. In order to provide reasonable levels of electrode contact resistance it was necessary to choose sites where surface materials were as conductive as possible. These sites were characterized by patchy vegetation consisting of moss, lichen, and stunted shrubs.

The survey area is accessible only by helicopter as it is quite remote (70 km from the hamlet of Coral Harbor). The survey used both AMT and broadband MT equipment. Most recordings were made for one-night's duration providing ~12 hours of time series. On each night there were at least two sites recording AMT data, enabling remote-reference signal processing. Electric fields recorded during AMT data acquisition were used with broadband MT data imported from a nearby site to determine the broadband MT response.

Recorded data were processed using robust spectral analysis and optimal responses were obtained using an electric field remote reference. Following final editing, good quality MT responses spanned a period range of $10^{-4}$ s to between 30 and 100 s. Results are examined using the apparent resistivity and impedance phase, with phases of <45° indicating increasing resistivity with depth and phases >45° indicating the reverse.

## MT responses

At short periods (azimuthally-averaged) apparent resistivity and phase responses show strong lateral variations spatially correlated with topography. High phase and low apparent resistivity in the north-central part of the survey area is interpreted as being due to conductive unconsolidated sediments overlying resistive Paleozoic bedrock. The two sites nearest the HTD deposits, ulu23 and ulu08, exhibit phase of ~45° and low apparent resistivity (<200 Ω.m) at periods <0.1 s indicating a significant zone of enhanced conductivity. The response at intermediate periods is more spatially uniform, with high phase and low apparent resistivity indicating a broad-scale conductive feature at relatively shallow depth beneath the survey area.

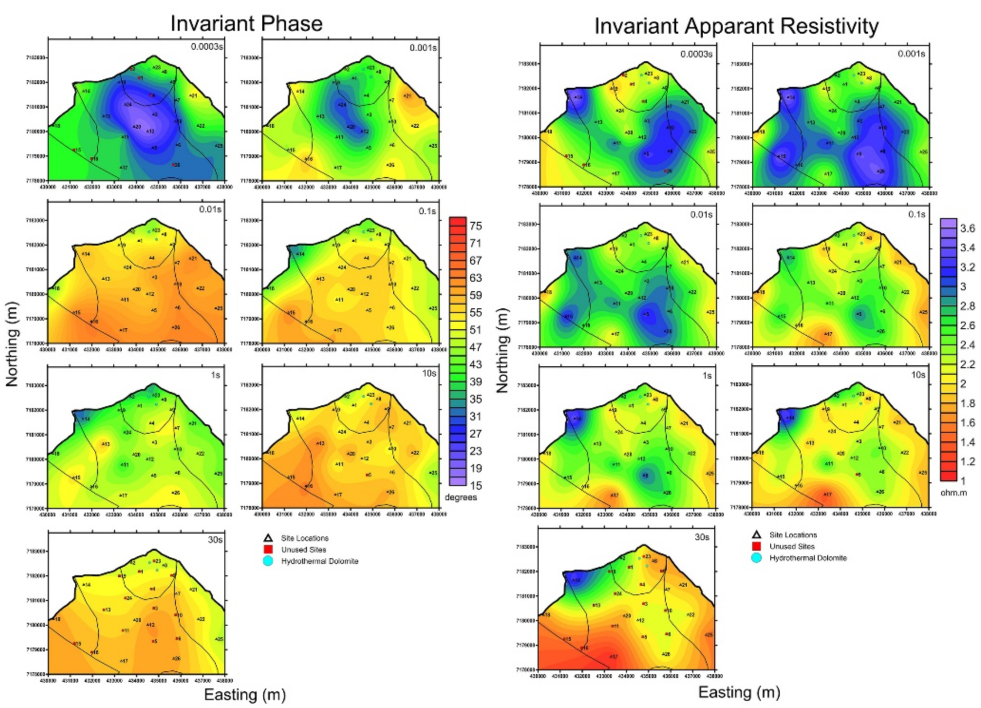


**Figure 2.** Invariant (azimuthally-averaged) log apparent resistivity and phase responses.

The MT responses were analyzed using depth-dependent Groom-Bailey decomposition (McNeice & Jones, 2001) to determine geoelectric strike and dimensionality (Figure 3). The resulting strikes show good spatial coherence with the azimuths being consistent with the sites lie on the conductive side of a NW-SE trending contact. The strike azimuth is parallel to local magnetic field lineations, larger-scale magnetic and gravity features, regional-scale MT responses (Spratt et al. 2012) and the North Southampton Fault. Dimensionality responses define a localized 3-D conductive feature at the HTD location.

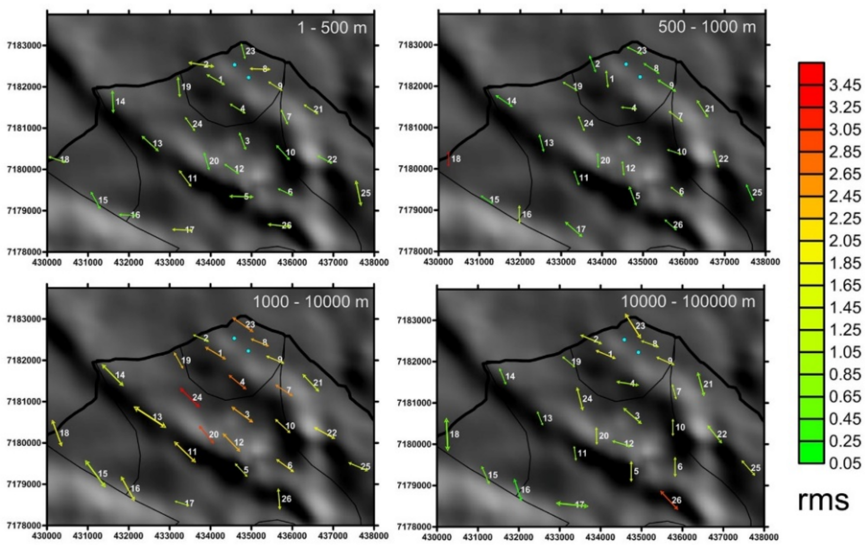


**Figure 3.** Geoelectric strikes (constrained to northwest quadrant) superimposed on a shaded relief map of airborne magnetic data (Natural Resources Canada, 2008)). Colour code indicates the root mean square misfit of the Groom-Bailey model of a regional 1-D or 2-D response with 3-D galvanic distortion. Depths do not represent true depths.

## 2-D inversion

Inversion of the MT data is complicated by resistivity features located outside the survey area but preliminary inversions of shorter period (<0.03 s) data have been done. Unconstrained 2-D inversions using a NLCG algorithm (Rodi & Mackie, 2001) of sites projected onto a southwest-northeast profile reproduce all of the major features in the response. The resulting resistivity model includes 5 to 50 m thick conductive (<100 Ω.m) overburden (Figure 4a). The underlying Paleozoic sequence is ~300 m thick. Its high resistivity of >1000 Ω.m suggests an absence of conductive pore-fluids. The resistive zone is underlain by a series of planar conductors at 200 to 400 m depth. Although, the inversion model indicates conductive rocks at greater depth, constrained inversions show the data are compatible with the presence resistive rocks underlying a continuous listric conductive feature with integrated conductance of 2 S (Figure 4b).

The inversion model includes a shallow zone of enhanced conductivity near the HTD. There are also increases in conductivity at larger depth (20-200 m) beneath the position of linear aeromagnetic features (Figures 3 and 4).

## Preliminary interpretations

The MT data define a 3-D conductive feature in the vicinity of the HTD deposit but provide relatively low resolution. The MT results also define several additional areas of low conductivity which, in association with magnetic data, can be interpreted to represent fault zones. The listric feature at 200-400 m depth in the constrained inversion likely corresponds to the faulted Precambrian-Paleozoic contact. The HTD conductive zone is associated with = a magnetic lineament and a sub-vertical conductive zone suggesting a moderately extensive fault zone. Further 2-D inversions and 3-D inversions are required for final interpretations.

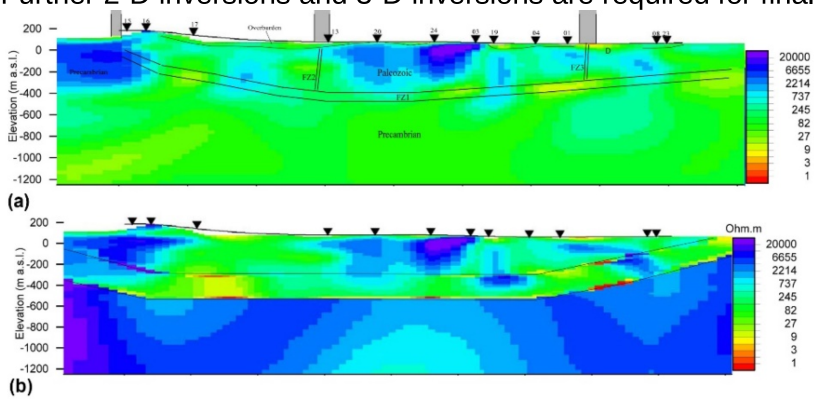


**Figure 4. (a)** Unconstrained and **(b)** constrained 2-D inversion models. For the unconstrained inversion with TE/TM phase and apparent-resistivity error floors of 6%/3% and 24%/12% respectively the root mean square error is 1.77. Grey shaded boxes denote the position of linear aeromagnetic features (Figure 3) and "D" denotes the HTD. In the constrained model, regularization tears (grey lines) have been included and the resulting model shows the inverted MT data are compatible with relatively resistive Precambrian rocks beneath a sub-horizontal conductive feature.

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