Reducing Geotechnical Risk through Waterborne Geophysical Solutions – Closing Data Gaps on Water

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ABSTRACT
Geotechnical information beneath rivers and lakes like water bottom mapping and bedrock location and rigidity can be critical to numerous types of operations such as construction, directionally drilled river crossings, and where conventional deployments are not suitable for various reasons such as logistical and environmental considerations. Options are available to increase the understanding of a site in the form of waterborne geophysical approaches such as sub-bottom profiling, reflection and refraction, resistivity, electromagnetic methods, and GPR surveys.

This paper will use a variety of case studies from Canada and abroad to illustrate solutions available for obtaining sub-bottom information for geotechnical sites including estimation of: Vp/Vs ratios, rippability, soil stability, soil type, sedimentary layering, paleo-scours, and bathymetry to name a few. A variety of sites will be presented including harbours, lakes, and pipeline river crossings. Included will be results from an R&D project to develop a water-borne TEM system capable of providing high density electrical resistivity information to depths of up to 100m below the water bottom.

RÉSUMÉ
Les informations géotechniques sous les rivières et les lacs, comme la cartographie du fond de l'eau et la localisation et la rigidité du substratum rocheux, peuvent être essentielles pour de nombreux types d'opérations, comme la construction, les traversées de rivières par forage dirigé, et lorsque les déploiements conventionnels ne conviennent pas pour diverses raisons, comme des considérations logistiques et environnementales. Des options sont disponibles pour améliorer la compréhension d'un site sous la forme d'approches aquatiques telles que le profilage de sous-fond, la réflexion et la réfraction, la résistivité, les méthodes électromagnétiques et les levés GPR.

Cet article utilise une variété d'études de cas du Canada et de l'étranger pour illustrer les solutions disponibles pour l'obtention d'informations sur le fond marin pour les sites géotechniques, y compris l'estimation des rapports Vp/Vs, des ondulations et de l'impact sur l'environnement : Les rapports Vp/Vs, l'ondulation, la stabilité du sol, le type de sol, la stratification sédimentaire, les paléoscours et la bathymétrie, pour n'en nommer que quelques-uns. Une variété de sites sera présentée, y compris des ports, des lacs et des traversées de rivière par pipeline. Les résultats d'un projet de R&D visant à développer un système TEM aquatique capable de fournir des informations sur la résistivité électrique à haute densité à des profondeurs allant jusqu'à 100 m sous le fond de l'eau seront également présentés.

1 INTRODUCTION

Among the problems that engineers face during the construction of structures in marine environments is lack of geotechnical information of the subsurface under water bodies. Boreholes are drilled for that purpose but the cost of drilling in a marine environment is often one order of magnitude higher than drilling on land. Geophysics can be a useful tool for solving this problem by providing the engineer/geologist an indication of the depth to bedrock, the hardness of the bedrock and the overburden, as well as information about some of the possible obstacles that may be encountered on the water-bottom. This paper discusses how marine geophysical methods can be used to help provide a better understanding of the subsurface under marine environments.

2 METHODS

2.1 Sub-Bottom Profiling

Sub-bottom profiling is used to map of bedrock surface, sedimentary horizons and structure beneath the waterbottom. The sub-bottom profiling method involves creating a medium frequency sound wave (200 Hz to 16 kHz) at the water surface and recording the sound that has echoed off of the layers beneath the instrument. Echoes are created where the sound wave travels across a seismic impedance contrast. Seismic impedance is the product of the seismic velocity and density of a material. The relative strength of the reflection is dependent on the reflection coefficient of the two layers according to the following equation:

$$R = \frac{Z2 - Z1}{Z2 + Z1}$$

Where: R = reflection coefficient, Z1 and Z2 are the impedances of the two layers.
Typical reflection coefficients for geologic interfaces normally encountered in marine surveys are shown in Table 1.

The choice of frequency for this method depends on the requirements of the survey; higher frequencies give better resolution but poorer exploration depths, and lower frequencies give poorer resolution but greater exploration depths.

Material	Reflection Coefficient
Water/air	-1.0
Water/limestone	0.5
Water/sand	0.3 – 0.4
Water/clay	0.1 – 0.2
Water/mud	0.05 – 0.1
Mud/clay	0.1
Clay/sand	0.1
Sand/limestone	0.2
Clay/limestone	0.3
Sand/granite	0.4

Table 1: Typical reflection coefficients (modified from Sylwester, 1983)

2.2 Bathymetry

Bathymetry is used to map the water bottom surface. Bathymetry data is collected using either a single-beam or multi-beam fathometers, depending on the scale of the project. A single beam system produces a high frequency sound wave from a transducer at the surface, which is reflected off of the water-bottom and detected by the transducer. Taking the travel-time of this signal and the speed of sound in water (1500 m/s), a water-bottom depth is calculated. Because of the high frequency of the sound wave produced (100-200 kHz), the accuracy of water-bottom measurements are typically in the range of +/- 0.03 m, but the signal cannot penetrate the water-bottom.

2.3 Side-Scan Sonar

The side-scan sonar method uses wide angle bathymetry to efficiently image large areas of the water-bottom on either side of the survey device. It operates in a similar fashion to traditional fathometers, which are narrow-beam depth-sounders. The side-scan sonar system directs sound waves from a transducer suspended beneath the instrument in a fan shape towards the water-bottom. Reflections are recorded to provide an image of the water-bottom to the left and right of the instrument's path as seen in Figure 1.

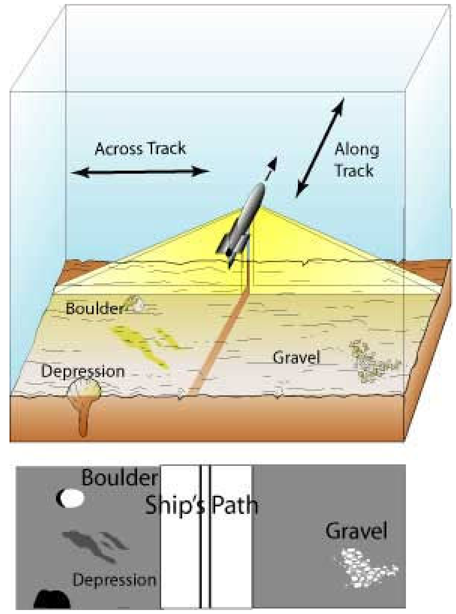

Figure 1. Schematic of side-scan sonar system.

(source:http://woodshole.er.usgs.gov/operations/sfmapping/images/sonartracktextnotow.jpg)

2.2 Time Domain Electromagnetics (TDEM)

The Time Domain Electromagnetic (TDEM) method is a geophysical technique that resolves the resistivity of the earth's subsurface. Instrumentation consists of a transmitter to impart current to a loop of wire laid on the ground surface. A receiver coil and logging unit measure the resulting magnetic field flux (Figure 2).

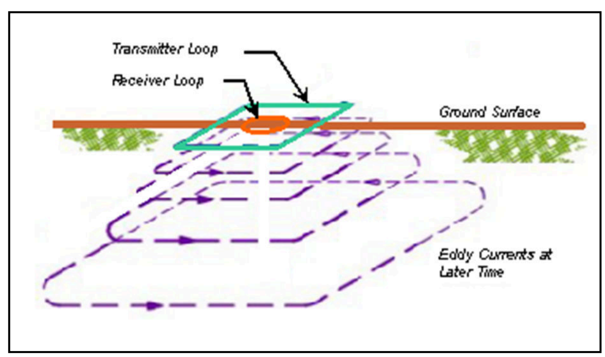

Figure 2: Simplified TDEM schematic.

Several configurations of TDEM are possible, the choice of which depends on the objectives. In this case the objective was to map generally flat-lying layers so a central loop sounding was used. In this configuration, the receiver is placed in the centre of the transmitting loop and both Rx and Tx are moved together to different sounding locations.

The depth of exploration is governed by a number of factors including loop size, number of turns of the loop, current in the loop and the underlying geology. The larger the loop size, and greater the current, the deeper an investigation is possible. Conductive regions tend to concentrate the current and limit penetration to deeper layers.

The result of a TDEM sounding is a set of voltages measured within given time gates after the transmitter is shut off. The voltages are then inverted to determine a possible geo-electric earth model that fits the data. A number of models can be found which fit the data equally well (the principal of equivalency, ref). TDEM surveys are most sensitive to conductive layers however, and therefore, can be mapped with increased certainty, particularly with a priori knowledge of the lithology of the layer.

3 CASE STUDIES

3.1 Riverbed Scour-Hole Detection

One of the risks facing bridges is the formation of riverbed scours at the base of their support pillars. These riverbed scours are one of the major causes of bridge collapse throughout the United States (Murillo, 1987). Scour-holes can develop during periods of high flow, and then can fill in with unconsolidated sediment during periods of low flow (Trent and Landers, 1991). These filled-in scours cannot be easily distinguished from the surface.

DMT conducted a survey to detect scour-holes around a bridge in southern Alberta. The survey started with side-scan sonar and a bathymetric survey. A sample side-scan sonar section from the survey is displayed in Figure 3. The scour-holes appear as shadows near the bridge pillars.

The bathymetric data was compiled, contoured and a map of the water-bottom elevation is presented in Figure 4. The scour-holes are clearly visible at each bridge pier.

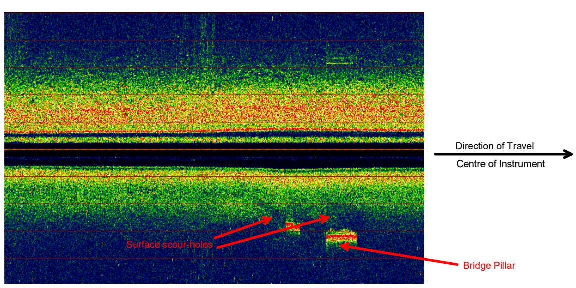

Figure 3: Sample side-scan sonar section, showing surface scour-holes near bridge piers.

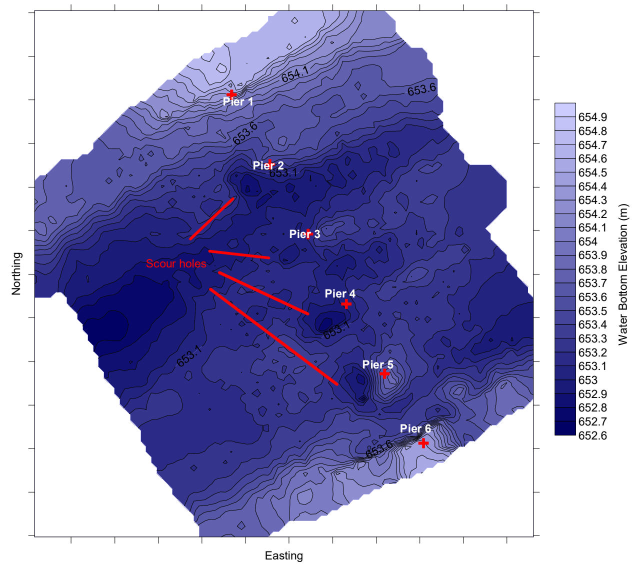

Figure 4: Water-bottom elevation map showing scour holes around bridge piers.

For sediment-filled scour-holes, the side-scan sonar section might show subtle changes, but cannot be reliably used to map them. Due to a density contrast between the sediment that is filling up the holes and the water-bottom material, sub-bottom profiling (marine seismic reflection) was used to map these filled in scour-holes. Since sub-bottom profiling surveys generally employ a single source and a single receiver, the survey must be conducted in a grid pattern with relatively tight line spacing. Sample sections showing filled in scour-holes are presented in Figures 5 and 6.

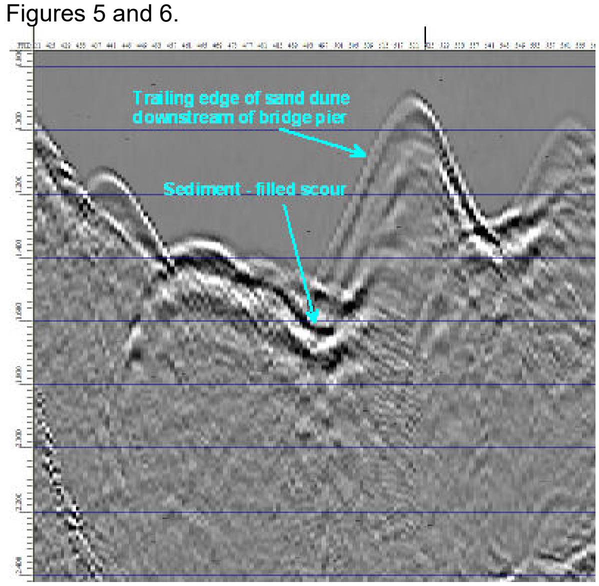

Figure 5: Sample sub-bottom profile showing a sediment-filled scour hole near a bridge support.

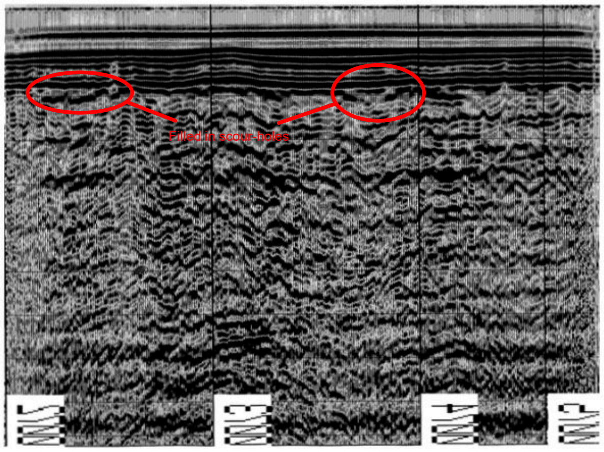

Figure 6: Sample sub-bottom profile showing two filled in scour-holes.

3.2 Road Expansion Engineering Application

This case study presents a roadway expansion that runs along the edge of a lake in southwest British Columbia. Due to extreme changes in topography on the land side of the roadway, the only option available for the expansion of the roadway was for the construction to extend into the lake. In order for this to be done the engineers needed a better understanding of the subsurface to determine the viability of the construction plan. Figure 7 shows the outline of the site along the lake edge

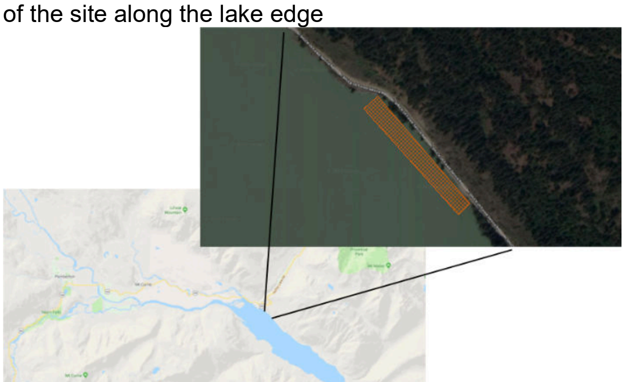

Figure 7: Location map of lake edge survey. Extent of the survey is indicated by an orange rectangle.

The objective of the survey was to determine the water depth, depth to bedrock, and estimate the condition of the water-bottom sediments to aid in the upgrading of the road. A high frequency sub-bottom profiler survey and seismic refraction survey was conducted on a dense grid of the area. An example sub-bottom profile is shown in Figure 8 below.

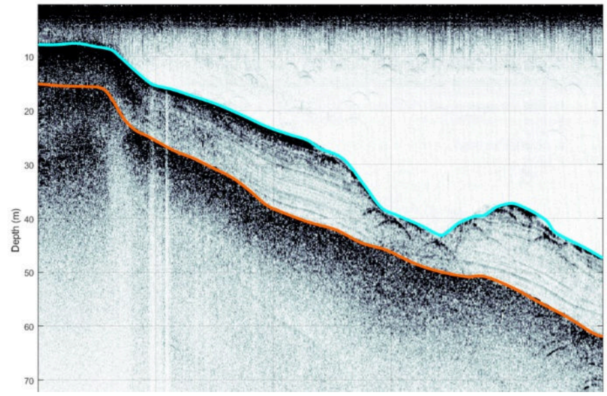

Figure 8: Sample sub-bottom profiling data collected perpendicular to the shore approximately 60m away from shoreline with water bottom show in in cyan and bedrock show in in orange.

The seismic refraction analysis indicated that the seismic velocities of the sediment layer between the bedrock and the water-bottom is approximately 1600 m/s, which is slightly higher than the velocity for water (1500 m/s) and at the low end of the range expected for saturated sediments (1500-2000 m/s). The relatively low velocity of the sediments suggests that it is poorly consolidated and likely compressible.

Maps showing the depth to the water-bottom, depth to the bedrock, and thickness of the sediment layer are presented in Figure 9, 10 and 11, respectively.

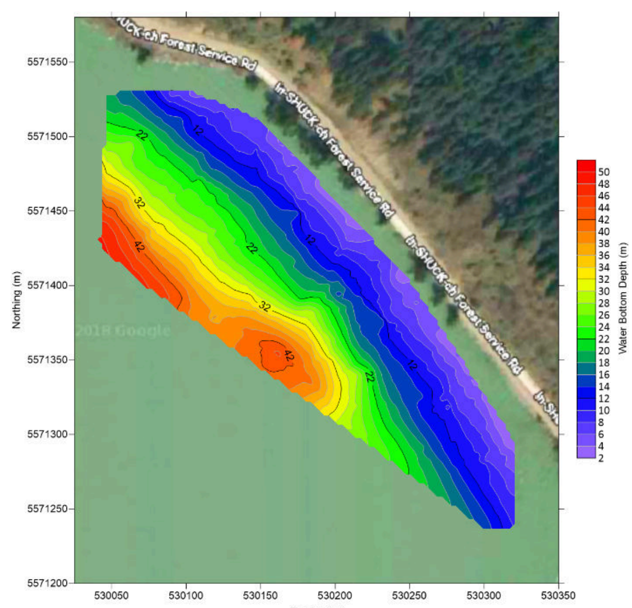

Figure 9: Water-bottom depths.

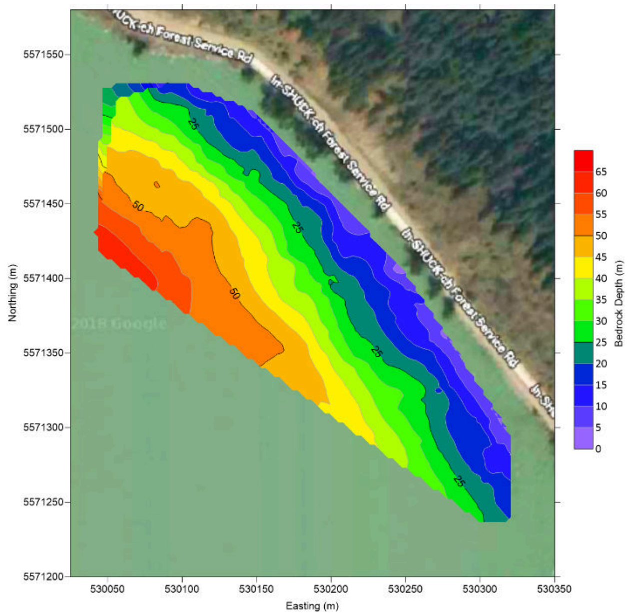

Figure 10: Bedrock depths.

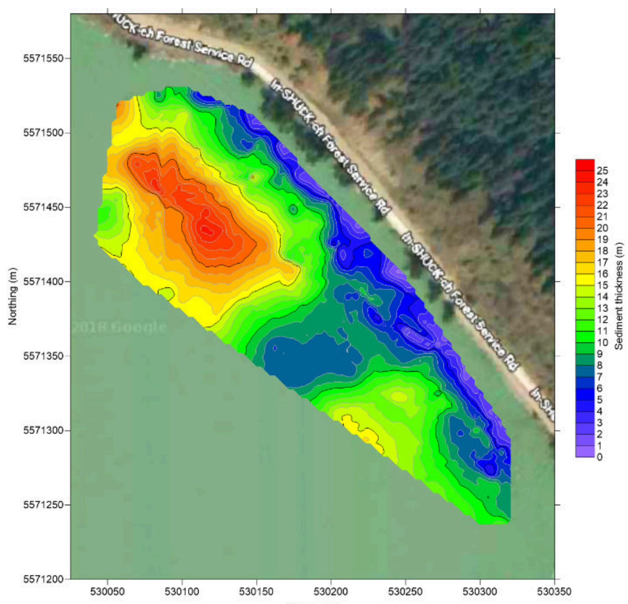

Figure 11: Sediment layer thickness.

3.3 Kimberlite Pipe Mapping

This case study presents an exploration project of a potential kimberlite pipe underneath a lake in a remote location in the Northwest Territories. Figure 12 shows the survey line plan.

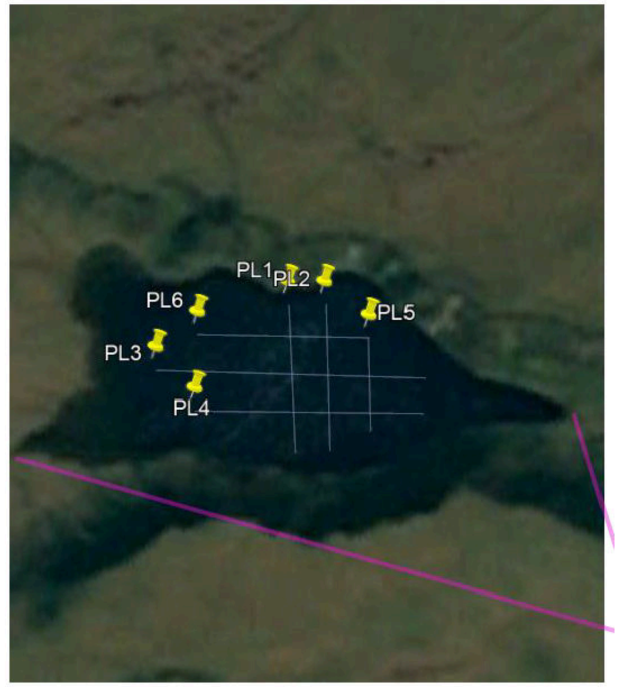

Figure 12: Survey line location map.

The objective of the survey was to collect TDEM data as a follow-up of a magnetic anomaly found in a previous survey. The property surveyed in this case is a lake, which suggests using a model similar to diamondiferous kimberlite pipes in the Slave Craton in NWT, as shown in Figure 13 (McConnell, 1996). In the Slave Craton region, the top of kimberlite pipes have a soft, friable conductive clay or lake sediments layer. This top layer differentially eroded with respect to the hard, cratonic host-rocks during the Pleistocene glaciations, resulting in topographic lows that became lakes (Power, Belcourt, & Rockel, 2004) (Raiche, 2001) (Smith, Annan, Lemieux, & Pedersen, 1996) (Kamara, 1981) (Jansen & Witherly, 2004).

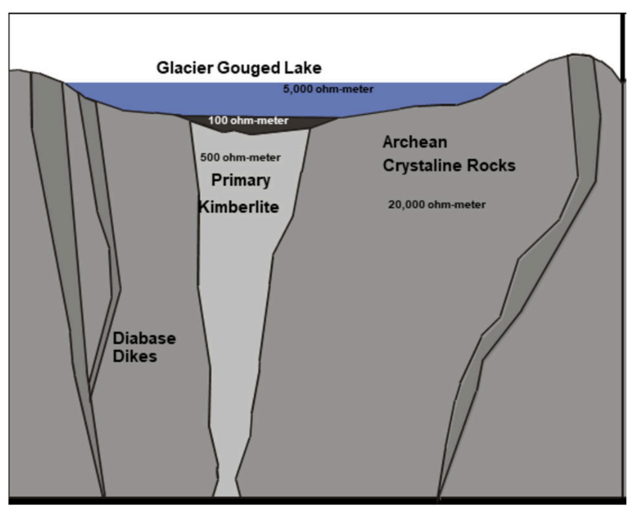

Figure 13: Conceptual Electrical Properties of a kimberlite pipe in the Slave Province NWT (McConnell, 1996).

The location for this investigation is within the interior platform geological region on the edge of the western Canadian fold and thrust belt, and therefore the setting may be more like kimberlites in the western Canadian sedimentary basin (WCSB) rather than kimberlites in the Slave Craton. The magnetic and EM responses of kimberlites relative to host rock are variable in WCSB basin settings (Dufrense, et al., 1996). Ashton Mining of Canada reported finding kimberlite pipes in Alberta (Skelton, et al., 2003) where the conductive, clay-rich bedrock in the Buffalo Head Hills region contrasts sharply with the more resistive kimberlitic rocks and some pipes were magnetic and others non-magnetic. In this survey location, without knowledge of the specific electrical and magnetic properties of the host rock, coincident EM and magnetic anomalies in any sense near diamond indicator mineral finds could be considered a primary target for a kimberlite.

The soundings collected along each profile line were used to create 1D resistivity models at each sounding site. These 1D models were combined to create 2D sections. Figure 14 is the 2D section for Profile Line 2. It runs in a north-south orientation through the centre of the lake. The conductive structure highlighted by the 10 ohm-m contour is 250 metre wide and 40 metres thick. The top of the conductive structure is at a depth of 90 metres, which is similar to the maximum recorded depth of the lake of 80 metres. The conductive structure is below a resistivity of 10 Ohm-m which is consistent with the expected conductivity of clay.

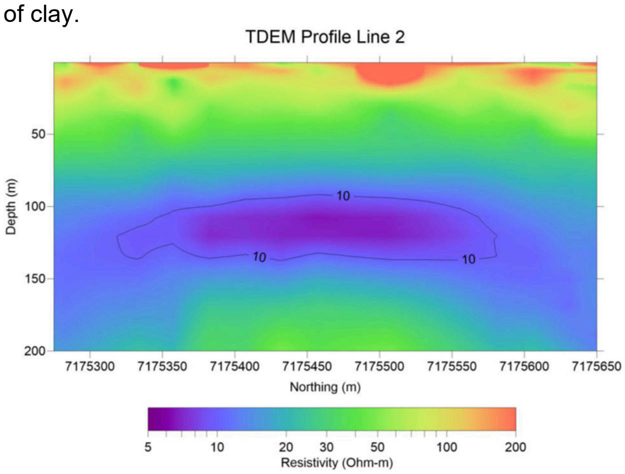

Figure 14: TDEM Profile Line 2 showing a conductive body at about 125 metres depth and 200 metres wide.

Profile Line 3 runs in an east-west direction perpendicular to and bisecting profile line 2. Figure 15 is the 2D section for profile Line 3. The conductive structure, highlighted by a 10 ohm-m contour line, is very similar in character to the structure from profile line 2. It is also 250 metres wide and 40 metres thick. The top is also at depth of 90 metres. The conductive body in profile Line 3 is consistent with the conductive body found in profile Line 2.

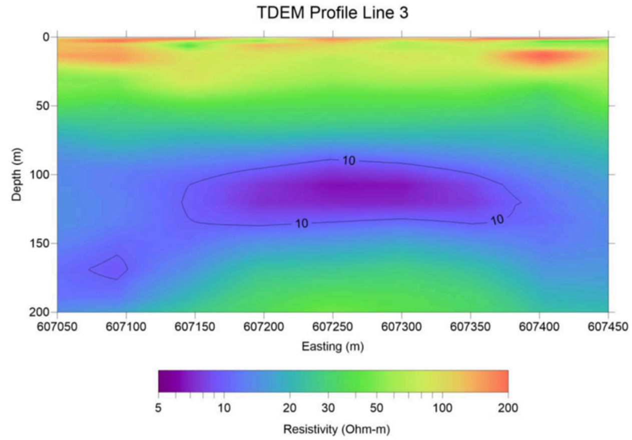

Figure 15: TDEM Profile Line 3 showing a conductive body at about 125 metres depth and 200 metres wide

The remaining four profiles all have conductive structures that are consistent with the example profiles and each other in their location, size magnitude of resistivity.

For every resistivity model, the values at a depth of 120 metres were gridded to visualize the horizontal extents of the conductive body. Figure 16 shows the 10 Ohm-m contour line from the TDEM resistivity models plotted on a colour map of the magnetic field strength. The shape and location of the magnetic anomaly is coincident with the shape and location of the conductive body.

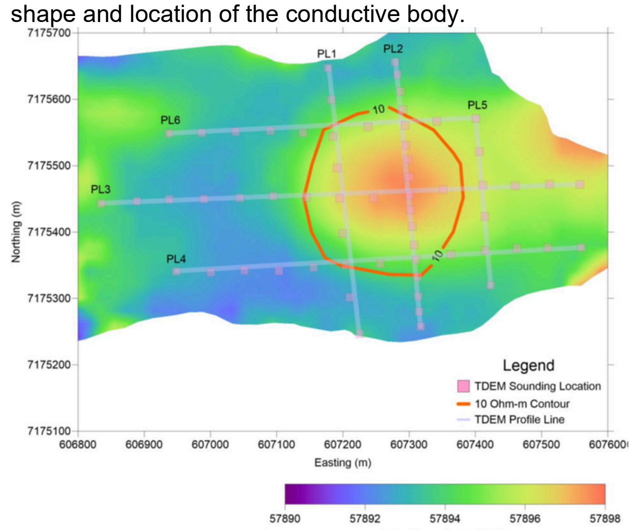

Figure 16: The 10 Ohm-m resistivity contour from the TDEM survey is overlaid on the total magnetic field from the previous survey. Note the coincidence of the magnetic high in orange with the 10 ohm-m contour line.

The conductive body identified by the TDEM survey has a much lower bulk resistivity than is presented in the conceptual model shown in Figure 13. The difference in the geologic setting of this survey, as compared to the Slave Craton, on which the conceptual model was based, can reasonably explain the lower resistivities found in this survey.

4 CONCLUSION

Through a series of case histories, we have shown how marine geophysical investigations can help provide geotechnical information of the subsurface under marine environments at costs significantly less than traditional methods such as drilling. Each geophysical method has its own set of limitations and the limitations need to be clearly presented to the engineer/geologist so that they have a realistic view of what can be anticipated from the survey results.

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