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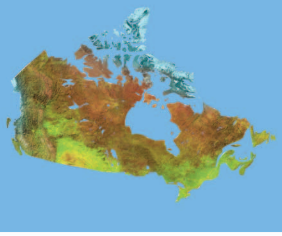

A new temperature, capacitive-resistivity, and magnetic-susceptibility borehole probe for mineral exploration, groundwater, and environmental applications

Q. Bristow and C.J. Mwenifumbo

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Critical review

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Abstract: A new borehole-logging probe has been developed and field tested for the simultaneous recording of high-resolution temperature, capacitive-resistivity, and magnetic-susceptibility logs. The resistivity parameter is measured with a capacitive sensor. The probe was developed by the Borehole Geophysics Group at the Geological Survey of Canada in Ottawa. Applications documented in detail include mineral exploration, groundwater and environmental monitoring, and geotechnical studies. The probe is expected to soon be commercially available.

Résumé : Une nouvelle sonde a été mise au point pour la diagraphie des sondages, et mise à l'essai sur le terrain. Cette sonde permet l'enregistrement simultané à haute résolution de la température, de la résistivité capacitive et de la susceptibilité magnétique. La résistivité est mesurée avec un capteur capacitif. La sonde a été mise au point par l'équipe de la géophysique des sondages de la Commission géologique du Canada, à Ottawa. Les applications documentées en détail comprennent l'exploration minérale et les études dans les domaines des eaux souterraines, de la surveillance environnementale et de la géotechnique. La sonde devrait bientôt être disponible dans le commerce.

INTRODUCTION

The Borehole Geophysics Group of the Geological Survey of Canada (GSC) has been developing borehole geophysical instruments since the 1970s. The most recent development is a probe with three sensors that measures temperature, resistivity, and magnetic susceptibility. These measurements are considered very useful in mineral exploration and groundwater and environmental studies.

The variables from the three sensors are recorded continuously in a single logging run. All three sensors provide continuous outputs as frequencies that are processed at the surface by a small interface unit connected to a laptop. A key feature of the probe is a unique frequency measurement system that allows very high-resolution samples of the variables to be acquired over 200 ms or 400 ms sample times. Another key feature of this ‘triple-sensor probe’ (TSP) is that the electrical resistivity is measured with a capacitive sensor in contrast to the standard galvanic resistivity measurement with contact electrodes. In addition, a new unique coil has been designed for magnetic susceptibility measurements. All three of the sensors address some serious limitations in other techniques of measuring temperature, resistivity, and magnetic susceptibility.

Example borehole logs are presented to illustrate the use of the triple-sensor probe in a variety of applications. The logs discussed in this paper were recorded either by sensors and processing electronics identical to those incorporated into the new probe or by the triple-sensor probe itself in the course of the evaluation. Some of the logs in the application section were recorded with conventional galvanic resistivity and magnetic susceptibility coils for comparison to the triple-sensor probe measurements.

DESIGN FEATURES OF SENSORS

Temperature measurement

In the early 1980s, the Borehole Geophysics Group pioneered very high-resolution measurements of borehole temperatures (Bristow and Conaway, 1984). They demonstrated that if the sensor noise levels were low enough, resolution of temperature measurements of the order of one millidegree Celsius could be achieved. This temperature-measurement resolution was made possible by using a frequency measurement technique developed at that time. A sensor using this technology is used in the new probe.

From these high-resolution temperature measurements, small changes in temperature gradients can be calculated using deconvolution or inverse filtering (Conaway, 1977). In a borehole with a geothermally stable fluid column, the temperature gradients reflect changes in the thermal resistivity of the formations intersected by the hole. Figure 1 shows the rock formation column and five temperature-gradient logs recorded over a period of several years in a borehole in the Ottawa area. The temperature log acquired in 2004 was recorded with the sensor that is on the triple-sensor probe. This example illustrates the very high spatial resolution and excellent repeatability of data. There is also excellent correlation of the temperature gradients with the lithology. The alternating low and high gradients in the Rockcliffe and Oxford formations are siltstone and carbonate layers, respectively

Capacitive resistivity

Resistivity logs are widely used in many applications. The standard technique for acquiring borehole resistivity logs involves the use of probes with galvanic contact electrodes to measure potentials generated by a current source; however, this galvanic method cannot be used in air-filled or in plastic-cased boreholes, where reliable electrical contact cannot be established between the electrodes and the rock formation. Most boreholes drilled for geotechnical and environmental studies are in unconsolidated sediments that require plastic casing to prevent them from collapsing. One solution to acquire electrical logs in plastic casing has been the use of probes based on the inductive technique (McNeill, 1990, McNeill et al., 1990). The inductive techniques are best suited for measuring high conductivity (i.e. low resistivity). A major limitation in inductive conductivity measurements is the rapid fall off in sensitivity with increasing resistivity. A realistic upper resistivity measurement limit for most

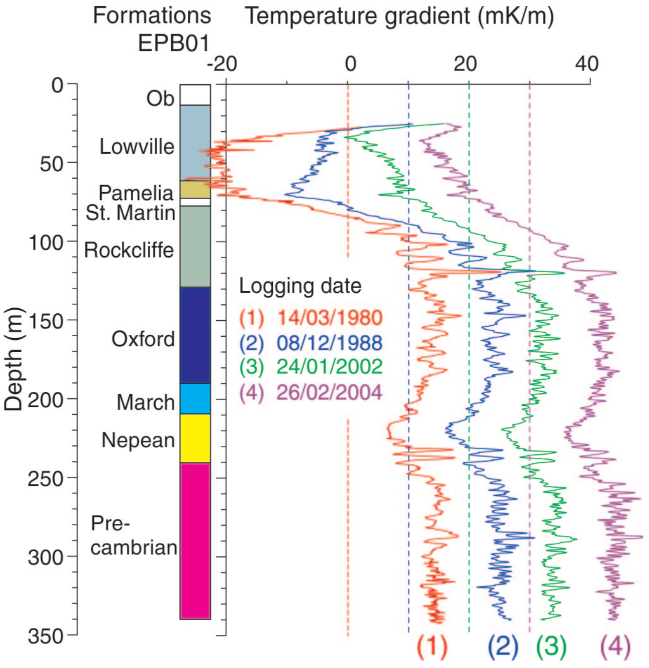
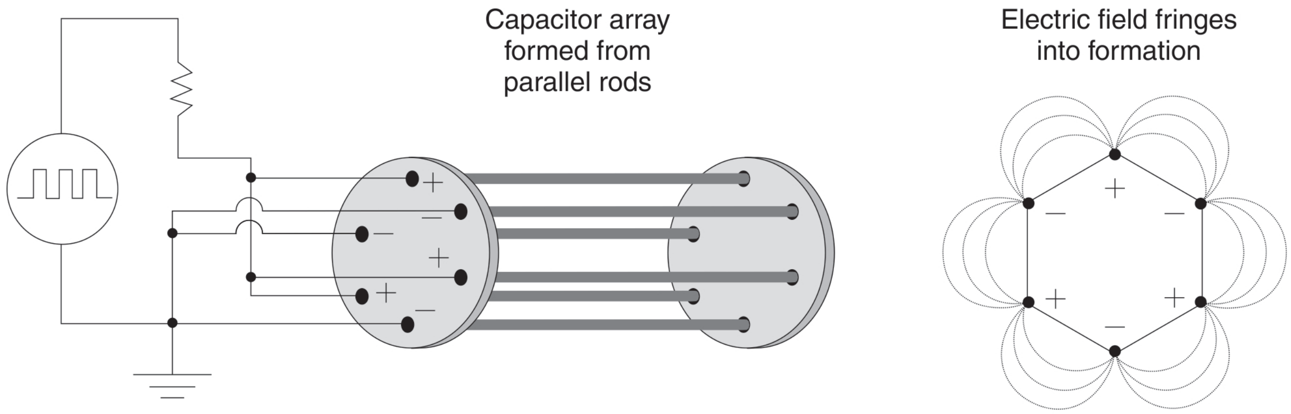


Figure 1. Temperature-gradient logs acquired from a borehole in the Ottawa area, Ontario, over a period spanning several years. The logs are offset by 10 mK/m for clarity. The logs show excellent repeatability. The alternating low and high gradients in the Rockcliffe and Oxford formations are siltstone and carbonate layers, respectively. Dates are in dd/mm/yyyy format.



[This sensor is covered by U.S. Patent 7,183,777 B2 dated Feb 27. 2007]

Figure 2. New capacitive resistivity sensor. An oscillator drives the capacitor array, producing an electric field between the rods.

inductive-resistivity probes is less than 1000 Ω•m. Therefore, this method does not work well in most aquifers, which are resistive (Mwenifumbo et al., 2009).

A capacitive technique for measuring electrical resistivity in boreholes using a dual-capacitor arrangement consisting of a transmitter and a receiver was described by Timofeev et al. (1994) and Bristow and Mwenifumbo (1998). A new innovative and simplified version of the above capacitive-resistivity scheme has been developed and patented. This new design combines the transmitter and receiver into a single sensor. The principle is shown in Figure 2 and this capacitive sensor has been incorporated into the triple-sensor probe. The resistivity logs obtained with this single sensor correlate very closely with conventional, 40 cm normal array galvanic resistivity logs (Fig. 3). There is a significant improvement in the spatial resolution of the lithology (*see* for example, 77–90 m). Unlike the galvanic method, this capacitive method does not require any electrical contact between the probe electrodes and the borehole wall. Because it is also capable of recording resistivity logs through plastic casing, it is a real advantage for environmental studies, where holes are plastic cased; however, neither method will work in steel casing or drill rods.

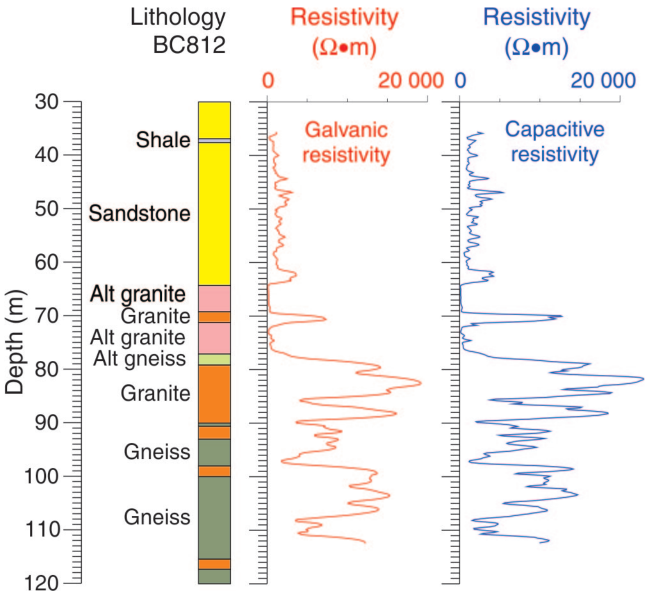


Figure 3. Comparison of galvanic normal resistivity log and the capacitive resistivity log acquired with the triple-sensor probe at the Bells Corners Geophysical Test Site in Ottawa; Alt = altered.

The capacitive resistivity technique is also well suited to fluid-filled holes and for best results requires that the probe diameter be greater than or equal to 60% of the diameter of the borehole (e.g. a 60 mm BQ-hole, the probe diameter should be ≥36 mm or a 76 mm NQ-hole probe diameter should be ≥48 mm). The current resistivity sensor in the triple-sensor probe has been calibrated, empirically against the normal array galvanic resistivity at the Bells Corners Geophysical Test Site in Ottawa, Ontario.

Magnetic susceptibility

The conventional technique used to measure magnetic susceptibility is based on frequency changes caused by changes in the inductance of a solenoidal coil coaxial with the probe. Magnetic susceptibility measurements in the triple-sensor probe use a unique and novel coil design which causes a disc-shaped radial field to be generated. This field has greater radial penetration and higher spatial resolution than the field from a conventional coil. Figure 4 compares the signals obtained by moving a piece of ferrite material past the triple-sensor probe coil and the conventional coil. As with the capacitive resistivity measurements, the best results are obtained when the probe diameter is at least 60% of the borehole diameter. The high-resolution measurement of the frequency allows very small signals (of the order of 10 μSI) to be resolved. Figure 5 shows a comparison of a triple-sensor probe magnetic susceptibility log recorded at the Bells Corners Geophysical Test Site in Ottawa and magnetic susceptibility a log made in the same hole with the conventional GeoInstruments THC-3 probe (Bristow and Bernius, 1984; Bristow, 1985). There is excellent correlation between the two logs.

One of the short comings of the two-coil magnetic susceptibility probes such as the Geonics system is their inability to resolve thin layers and the complex responses to layers thinner than the coil separation. Figure 6 compares the magnetic susceptibility log acquired with the triple-sensor probe and that acquired with the Geonics probe through a sedimentary sequence in the Fraser River delta area. The broad susceptibility high from the Geonics probe around 47–49 m can be resolved into several thin layers with the triple-sensor probe. Also the thin magnetic susceptibility highs around 53.5 m and 55.3 m on the triple-sensor probe log show up as 'rabbit-ear' responses on the Geonics log. Resolving them is significant in unravelling the stratigraphy, depositional characteristics, and provenance of the sediments.

APPLICATIONS

Temperature, resistivity, and magnetic susceptibility are important geophysical measurements in geoscience applications including mineral exploration (Mwenifumbo, 1993b; Mwenifumbo and Elliott, 2002)), and groundwater (Wilson et al., 1996), environmental (Mwenifumbo,

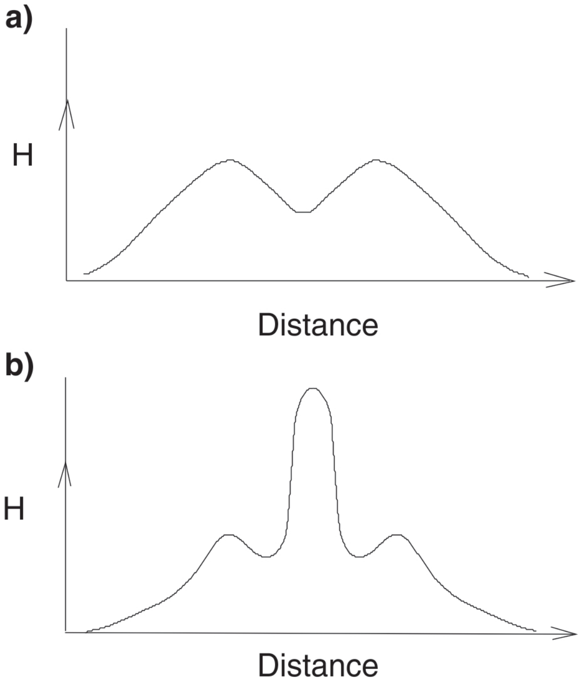


Figure 4. Responses to ferrite bead moving past a coil. A comparison of the magnetic-field patterns and intensity distribution between the **a)** conventional solenoidal coil, and **b)** the new coil design.

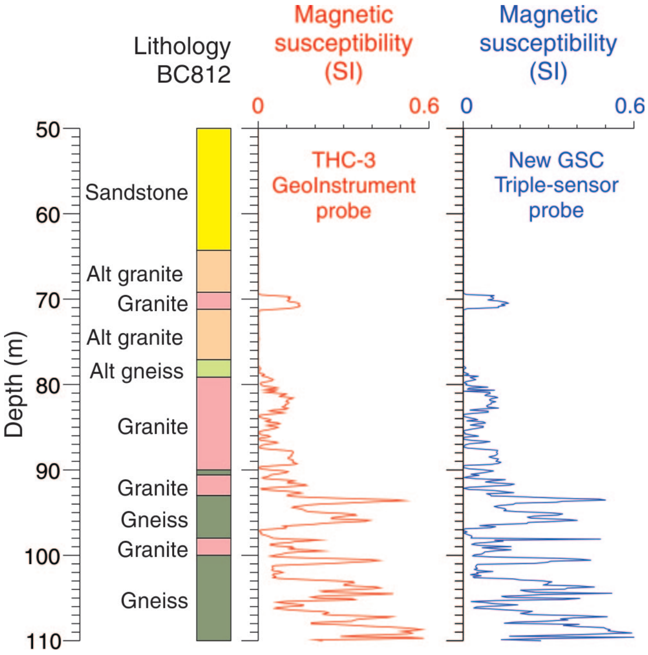


Figure 5. Comparison of magnetic-susceptibility log acquired with the GeoInstruments THC-3 probe with log acquired with the new coil design in the triple-sensor probe; Alt = altered.

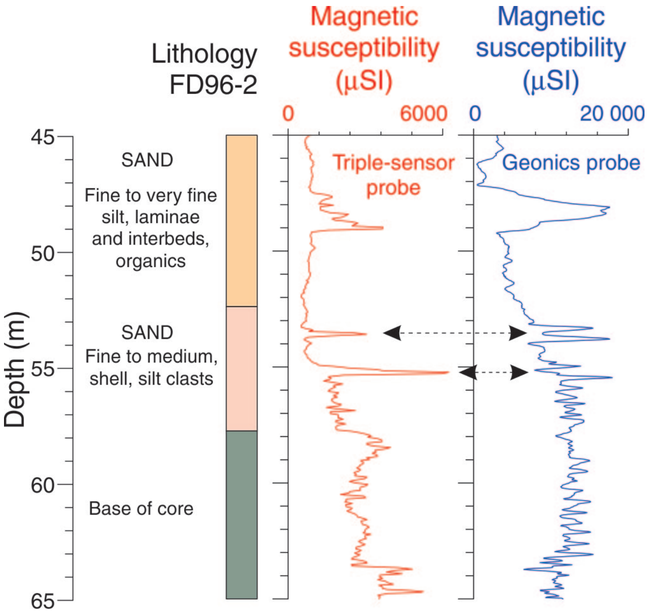


Figure 6. Magnetic-susceptibility log recorded the new coil design in the triple-sensor probe is compared to the two-coil Geonics probe (0.5 m coil separation).

1993a; Abbey et al., 1997), and geotechnical studies. Borehole electrical and magnetic susceptibility logs have been effectively used to map and delineate lithology, mineralization, and alteration associated with mineralization (Mwenifumbo et al., 2006). They also provide physical rock properties to aid in the interpretation of ground and airborne electrical and magnetic surveys. In groundwater and environmental applications, the three measurements from the triple-sensor probe can be used to characterize aquifers, map fractures and flow zones, and to map and monitor contaminant migration. The following are some application examples where the triple-sensor probe has been successfully evaluated.

Mineral exploration

Borehole electrical and magnetic susceptibility logs can be effectively used in exploration for base metals including Cu-Pb-Zn massive-sulphide and nickel-sulphide deposits. Although temperature logs are not used routinely in base-metal exploration, they have been shown to be quite effective in mapping massive-sulphide deposits as the thermal conductivities of sulphide minerals are much greater than those of the host rocks (Mwenifumbo, 1993b).

Figure 7 shows logs from the triple-sensor probe illustrating the typical mineralization and host-rock responses (i.e. signatures) at the Calumet Cu-Pb-Zn massive-sulphide deposit. The Calumet deposit occurs within altered carbonate amphibolite, siliceous quartz-biotite gneiss, and calc-silicate minerals. The siliceous gneiss hosts the sulphide mineralization. High susceptibilities observed in mineralized zones are primarily due to the presence of pyrrhotite and correlate with low resistivities. Magnetite is prevalent in the amphibolite minerals and biotite gneiss, which shows up as high magnetic susceptibility. These high-susceptibility zones with high magnetite content may be distinguished from the pyrrhotite-rich mineralized zones by their higher resistivities (*see* Fig. 8).

The temperature logs show an unusual high-temperature anomaly between 110 m and 150 m (Fig. 7) that is due to the proximity of the drillhole to abandoned mine workings. The temperature in the rocks within a few metres of the mine workings increases with time as the heat disperses away from the warmer underground openings. This type of observation has also been made at Les Mines Selbaie (Reed et al., 1997).

Pyrrhotite-rich and magnetite-bearing massive-sulphide deposits are good candidates for the three measurements included in the triple-sensor probe. Figure 9 shows the three logs recorded at a Cu-Ni sulphide deposit in the Sudbury area. The drillhole intersects norite, Sudbury breccia, gneiss, and diabase. The felsic norite and felsic gneiss exhibit low magnetic susceptibilities, whereas very high susceptibilities are observed in the mafic gneiss, diabase, and Sudbury breccia units. The low resistivities accurately delineate sulphide mineralization. The typical temperature response through a massive-sulphide zone is observed in this drillhole (i.e. low temperature gradients and a flattening in the temperature log (*see also* Mwenifumbo, 1993b)). Figure 10 shows another

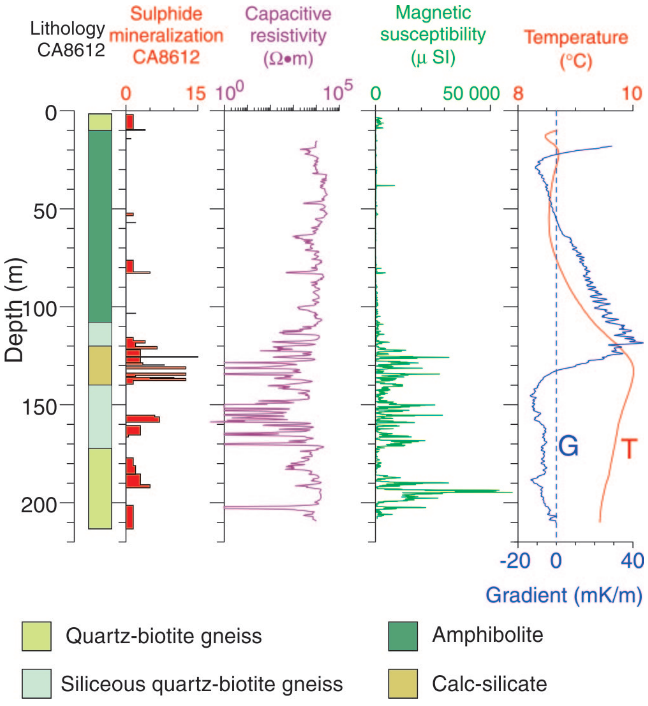


Figure 7. Capacitive-resistivity, magnetic-susceptibility, and temperature logs from the new triple-sensor probe with the sulphide intersections included on the left track.

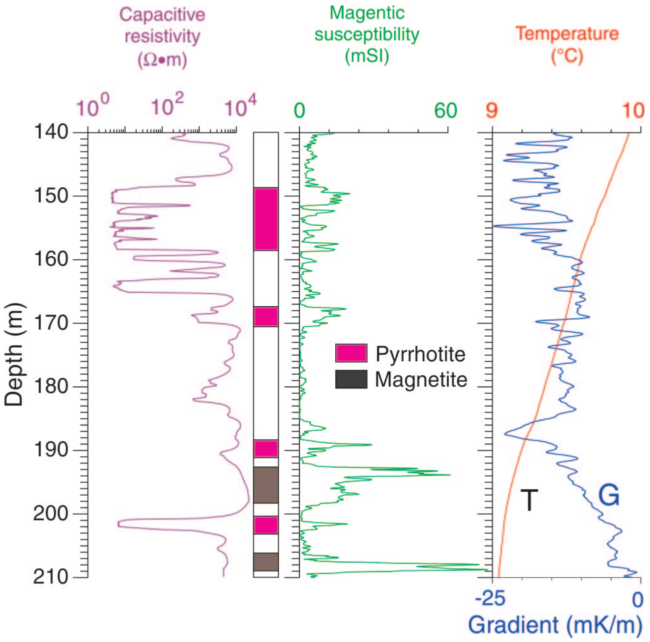


Figure 8. Capacitive-resistivity, magnetic-susceptibility, and temperature logs from the triple-sensor probe. Pyrrhotite-rich zones exhibit high magnetic susceptibilities and low resistivities. Magnetite-rich zones are indicated by high magnetic susceptibilities and high capacitive resistivities.

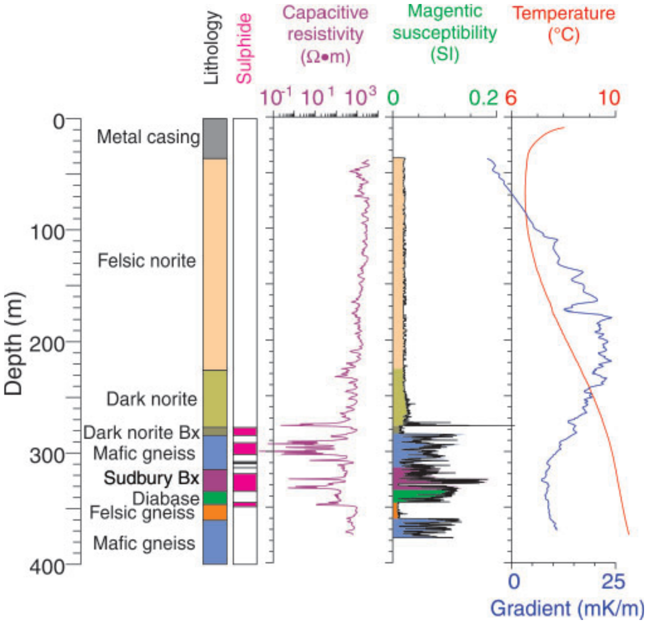


Figure 9. Capacitive-resistivity, magnetic-susceptibility, and temperature logs from a drillhole at a Cu-Ni sulphide deposit in Sudbury. Also shown are the lithology and sulphide columns. Bx = breccia.

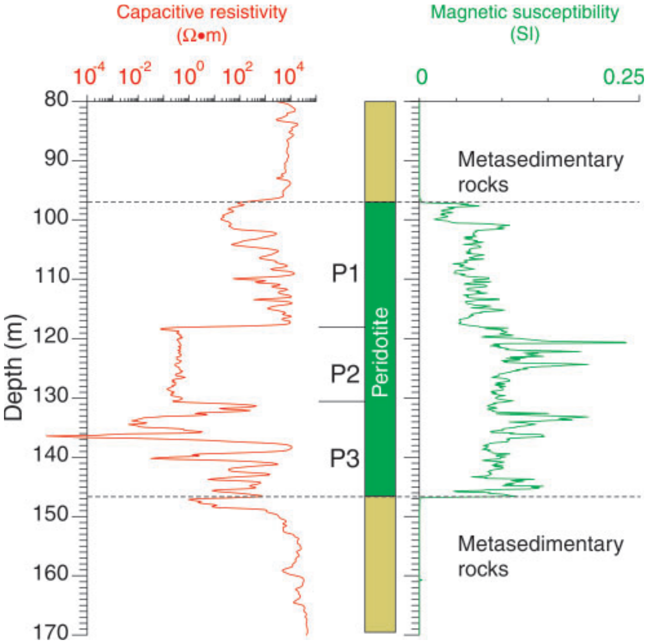


Figure 10. Capacitive-resistivity and magnetic-susceptibility logs recorded with the triple-sensor probe at a Cu-Ni-PGE deposit illustrating the use of these logs in refining the lithology. The drillhole intersects highly magnetic peridotite which hosts the mineralization. The peridotite intrusion has been subdivided into three zones (P1, P2, and P3) based on the resistivity and magnetic-susceptibility signature. These zones may be correlated with sulphide content and distribution.

example of capacitive resistivity and magnetic susceptibility logs from the triple-sensor probe in a Cu-Ni-PGE deposit. The peridotite intrusion that hosts the mineralization is clearly distinguished from the enclosing metasedimentary rocks on both the resistivity and magnetic susceptibility logs. There are, however, very prominent variations in both resistivity and susceptibility within the peridotite intrusion that may have some significance in terms of the distribution of the economic minerals within the unit. The peridotite intersection has been subdivided into three major sections based on the geophysical logs.

Groundwater and environmental applications

In groundwater and environmental investigations there are several problems that can be addressed with geophysical logs from the triple-sensor probe. These include: 1) mapping fractures that provide storage for groundwater in fractured bedrock aquifers, or in environmental applications, they provide pathways for the migration of contaminated fluids; 2) identification of lithology and stratigraphic correlation; 3) estimation of porosity; and 4) monitoring fluid migration through porous and permeable strata.

Fractured rock is electrically more conductive than unfractured rock and therefore can be effectively mapped by resistivity. These rocks exhibit low resistivities on a resistivity log because of increased porosity (Fig. 11). Detection of fracture zones with groundwater flow is made possible with the use of temperature logs. In Figure 11 the authors note that there is no flow in a major fracture zone in the metasedimentary rocks between 140 m and 150 m. This is probably a consolidated fracture zone; however, the temperature gradients indicate fluid flow in a fracture zone between 80 m and 100 m and between 10 m and 60 m. Although the rhyolite between 100 m and 120 m has relatively high resistivities compared to the metasedimentary rocks, there are fracture zones that exhibit fluid flow. There is relatively high magnetic susceptibility in the altered and fractured rocks that is most likely due to the presence of pyrrhotite, which constitutes one of the most prominent sulphide mineralizations. Although this example is from a site that is atypical of groundwater and/or geotechnical environment, it shows the kind of responses to be expected in fractured bedrock from the three sensors.

Figure 12 shows the triple-sensor logs acquired in a hole drilled through soft sediments in the Fraser River delta area, British Columbia. The magnetic-susceptibility log shows variations within the sand that may provide information for refining the lithology and deposition environment. The fine to very fine sand between 28 m and 35 m shows lower susceptibilities compared to those between 38 m and 52 m. The low resistivity

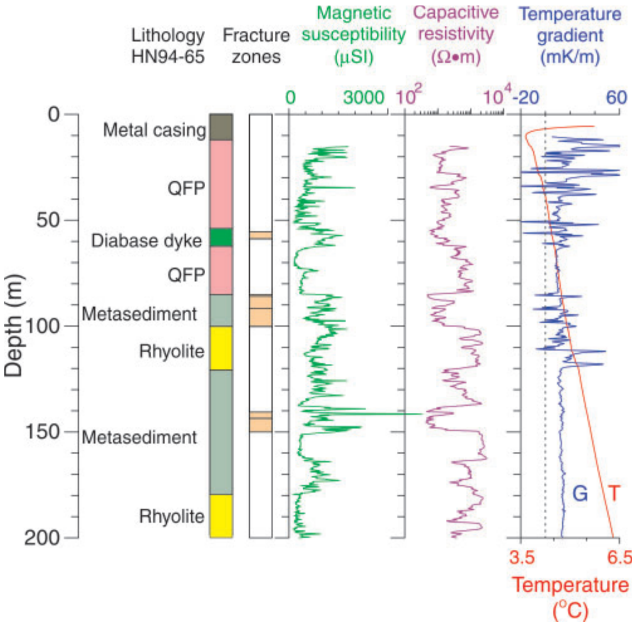


Figure 11. Magnetic-susceptibility, capacitive-resistivity, and temperature logs showing low-resistivity fracture zones. Open fractures with fluid flow are indicated by the high-frequency temperature gradients. The fracture-zone column indicated the location of fractures observed in the drill core. QFP = quartz-feldspar porphyry.

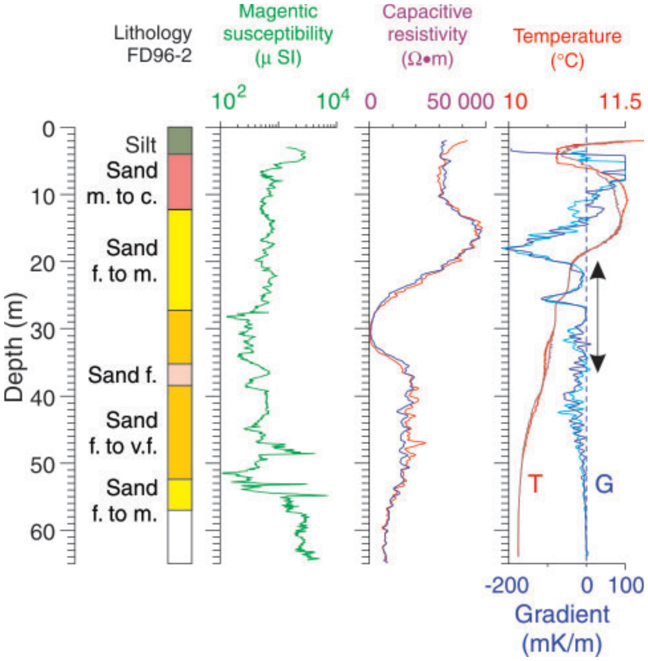


Figure 12. Capacitive-resistivity, magnetic-susceptibility, and temperature log recorded through a plastic-cased hole in the Fraser River delta. The lithology column is presented on the left column. The borehole intersects primarily sand with fine to very fine interbeds of silt. Two repeat logs are presented for both the resistivity and temperature. m. to c. = medium to coarse; f. to m. = fine to medium; f. to v.f. = fine to very fine.

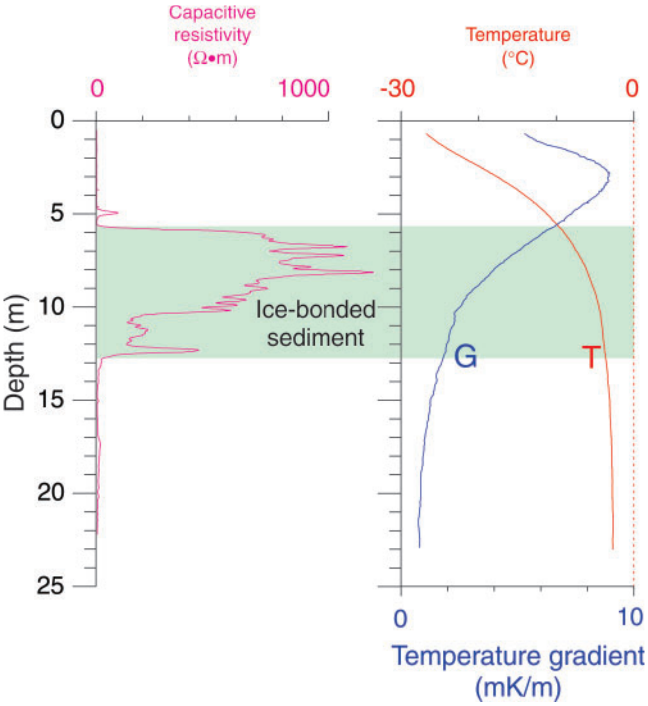


Figure 13. Capacitive resistivity, temperature and temperature gradient logs acquired through permafrost in the Mackenzie Delta. The borehole is dry, air filled, and uncased.

(high conductivity) between 20 m and 35 m is due to the presence of highly saline fluids. There is indication of fluid flow around this region from the temperature and temperature-gradient logs.

Permafrost in the Arctic poses some unique engineering and geotechnical problems. Ice-bonded sediments are prone to thermal and mechanical erosion and thawing is detrimental to infrastructures and pipe lines. Numerous shallow boreholes are drilled to map and/or monitor permafrost. Most of these boreholes are frequently instrumented with thermistors to record the temperatures. Continuous, high-resolution temperature measurements have been acquired in several boreholes in the Mackenzie Delta with a temperature sensor identical to the one used in the triple-sensor probe (Fig. 13). These logs provide a more continuous temperature-depth profile and appear to be superior to those acquired with thermistors fixed at prescribed intervals. The other parameter that is quite effective for mapping permafrost is electrical resistivity. Boreholes drilled through permafrost in the winter are generally dry and plastic-cased which precludes the use of galvanic resistivity. Inductive methods are also not suitable because of the very high electrical resistivities. Figure 13 shows a resistivity log recorded with the transmitter-receiver–type capacitive probe in a dry borehole in the Mackenzie Delta. The ice-bonded sediments are clearly delineated on the resistivity log. The variations in resistivity within this zone may be correlated with the percentage of ice content.

CONCLUSIONS

Although there are a number of borehole geophysical logging tools that are used in mineral exploration and groundwater and environmental investigations, the triple-sensor probe offers a unique set of measurements that are recorded with some unique sensor designs.

High-resolution temperature measurements can be effectively used to detect and map fracture zones, map lithology with different thermal conductivity contrasts, and detect massive-sulphide mineralization with very high thermal resistivities compared to host rocks. Temperature measurements are also useful in piecing together groundwater flow patterns. Temperature anomalies associated with migrating, warm, contaminated fluids are a good candidate for the high-resolution temperature sensor.

Capacitive electrical-resistivity measurements, which can be acquired in fluid-filled, dry, or plastic-cased boreholes, are a significant asset in environmental applications. Here these data can be extremely useful in identifying zones of increased groundwater conductivity that is often indicative of contaminant concentrations, variations in clay content, or variations in porosity and/or fluid saturation in fractured bedrock.

The new magnetic susceptibility sensor has greater radial penetration and finer spatial resolution than conventional sensor designs. This sensor can be effectively used to characterize and map low-susceptibility sediments in groundwater and environmental investigations. The applications in mineral exploration and mining are endless — characterizing lithology, delineating mineralization, and mapping alteration associated with mineralization.

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