The Role of Borehole EM in the Discovery and Definition of the Kelly Lake Ni-Cu Deposit, Sudbury, Canada.

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Summary

On October 22, 1997, Inco announced the discovery of a new deposit located at the south end of the Copper Cliff offset, a dike extending south from the Sudbury Igneous Complex (SIC) near the city of Sudbury, Ontario. The deposit was detected in 1992 as an off-hole borehole EM anomaly in a hole drilled from surface under Kelly Lake. A subsequent hole, 93670 targeted this off-hole conductor intersected 51 feet of ore grade mineralization; the first of the Kelly Lake deposit.

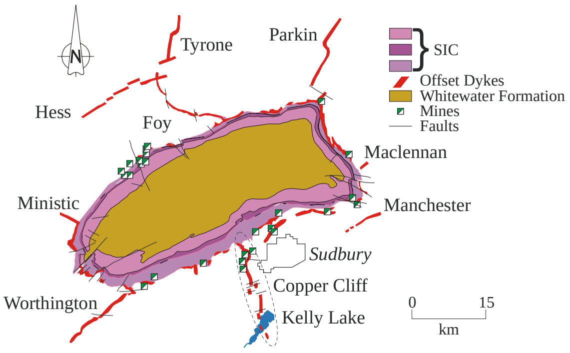
Since this initial intersection an integrated program of geology and borehole EM (BHEM) has continued to expand the Kelly Lake deposit. Three component borehole EM has contributed significantly to the efficiency of this process. The story of this exploration program and the technology behind it serves to illustrate the evolution of the borehole EM technique from its use in an exploration role to a mineral definition tool.

Introduction

The Kelly Lake deposit is located near the town of Copper Cliff, a few kilometers from the City of Sudbury Ontario in Canada. The Sudbury mining camp has been a prolific producer of nickel copper (Ni-Cu) sulphide ores over the last 100 years. Most of the Sudbury ore is hosted along the periphery of the Sudbury Basin at the base of a sequence of mafic-ultramafic rocks called the Sudbury Igneous Complex (SIC) (Figure 1). The SIC is generally believed to be associated with the effects of a meteor impact, either through the resulting direct melting of the existing rocks, and/or by the subsequent stimulation of magmatic activity. The Sudbury Basin structure itself is considered to be a deformed remnant of the original impact crater.

Most sulphide occurrences associated with the main SIC are found at the base of the main mass of the SIC, or within the brecciated country rock which formed as a result of the impact. However, the Kelly Lake deposit belongs to a group of deposits which occur outside the main SIC in quartz-diorite (QD) dikes radiating outward from its center. These, so called “offset dikes” are located at a number of places around the Sudbury structure (Figure 1). They originate at the main contact with the SIC in deep troughs which have been themselves productive reservoirs of sulphide mineralization.

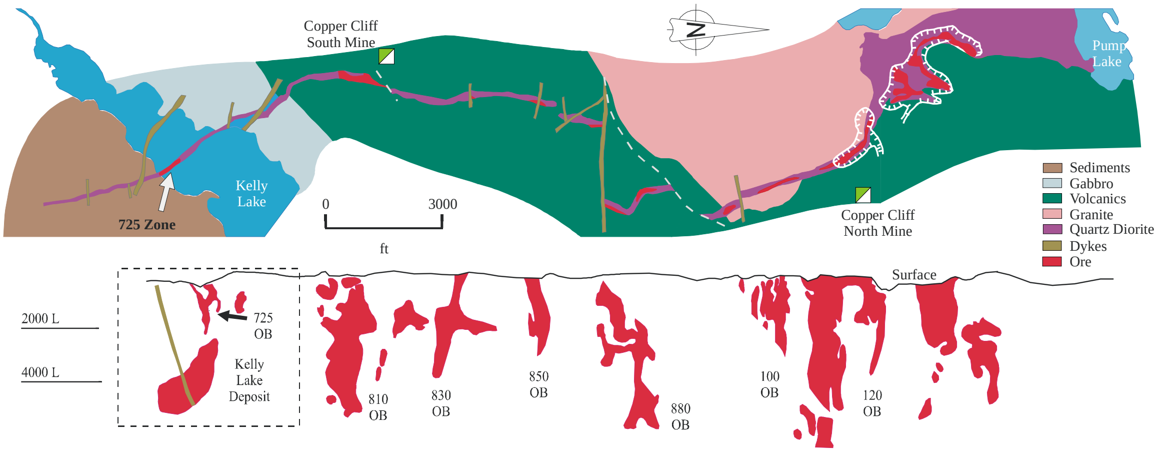
Figure 1: Sudbury Igneous Complex (SIC), with offset dikes.



The Kelly Lake Deposit occurs in the Copper Cliff offset dike (Figure 1). Figure 2 shows plan and west-facing longitudinal of the Copper Cliff Offset dike and shows the deposit in relation to others in the dike. The dike is on average 100-200 feet wide.

The principal geophysical tools for mapping the Ni-Cu sulphide mineral deposits of the Sudbury Camp have been borehole EM techniques utilizing large loop transmitters on the surface with down hole sensors. A good description of

Figure 2: Plan and longitudinal view of the Copper Cliff Offset dike, showing major mineral deposits



single axis BHEM applied to the deposits of the main SIC is given by King, 1996.

The Copper Cliff offset is in many ways an ideal setting for EM methods. The QD dike crosscuts Huronian metasedimentary and metavolcanic rocks as well as the Creighton Granite. These are all very transparent from an electromagnetic point of view, with conductivities less than one 10^{-3} S/m. In contrast, the ore is highly conductive, as is common for Ni-Cu sulphides, with conductivities of individual pyrrhotite-rich samples ranging up to 10^{5} S/m. The confinement of the mineralization to the dike further simplifies matters by constraining the geometry of the ore bodies to one orientation, allowing complete coverage of an area of the dike with only a single transmitter loop location.

Exploration History of the Kelly Lake Deposit

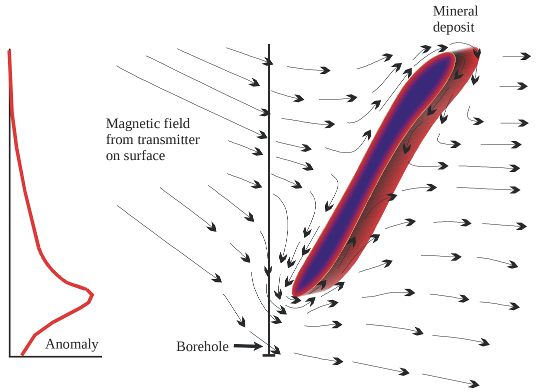
Mineral discoveries and exploration in the Copper Cliff Offset dike dates back to the late 1800's when the Murray Mine was discovered near Pump Lake where the dike meets the main SIC (Figure 2). Exploration since has moved southward to the more distal portions of the dike. Between the 1940's and the 1970's the 725 was the target of shallow drilling to depths of 1000 feet in the portion of the dike near Kelly Lake. The deposit proved to be difficult, lacking continuity and consistent grades. In the 1980's, deeper drilling was undertaken to explore beneath the 725 deposit to the 3000 foot level. These holes encountered largely sub-economic mineralization.

In the early 1990's borehole EM was first used to evaluate the potential of the 725 at depth. In 1992 a quality off-hole conductor was observed at a depth of 3300 feet at a range of 90 feet from the hole. This anomaly was followed up in 1995 with the discovery hole which intersected 51 feet of high grade mineralization in what is now called the Kelly Lake deposit. Between 1993 and 1996 13 holes were drilled into the deposit guided in part by a program of single (axial) component BHEM. Since 1996 an accelerated program of mineral resource definition has been closely integrated with 3-component BHEM. In 1997 the completion of a 2000 level exploration drift from neighboring South Mine permitted the definition of the deposit to proceed both from underground and from surface. Currently the definition drilling is complete and development planning is in progress.

The 3-Axis Borehole EM Method

Borehole EM systems use a magnetic field established by a large transmitter loop antenna lying on the surface of the earth (Figure 3). The primary field flows from the transmitter into the ground in a predictable pattern that can be computed precisely at any point. Due to their extreme conductivity, the field is prevented from flowing through zones of quality Ni-Cu mineralization by current systems induced on their surfaces and hence must flow around these obstacles, much as water flows around an obstruction in a stream. The 3-axis down-hole measurement system senses the direction and strength of the total magnetic field. Differences between these observations and those expected from the known location and orientation of the transmitter and receiver are attributed to the deflection caused by mineralized zones. It is the job of the interpreter to find the location, orientation and size of the surfaces needed to cause the observed magnetic field deflections. The most reliable parameters available from these analyses are the distance and direction to the nearest edge of the mineral zone as well as its overall size and attitude.

Figure 3: schematic showing primary field and interaction with conductor.

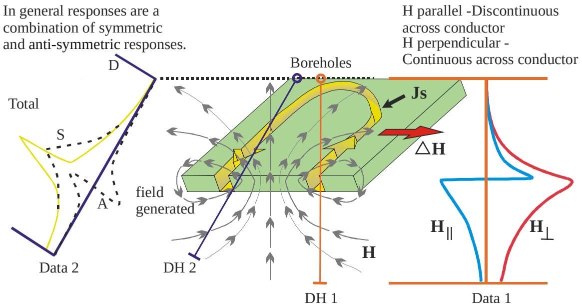


The process of total exclusion of the magnetic field from an excellent conductor described above is EM induction in the *inductive limit*. Eddy currents located on the surface of the conductor are in phase with the transmitter current and they create a magnetic field which opposes the normal component of the incident magnetic field. When the transmitter current is zero, there are no eddy currents at the inductive limit. For this reason transient EM techniques that rely on transient magnetic field measurements during the transmitter off time are ineffective at mapping the Ni-Cu ore. The on-time transient step response system, UTEM (West et al, 1984), has been the tool used in the program.

BHEM Interpretation in Resource Definition

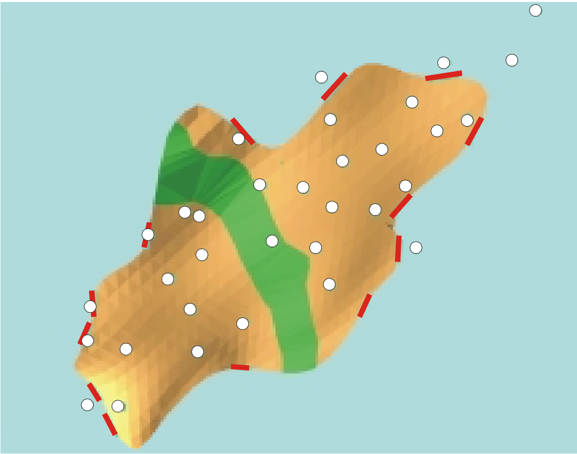
Most accounts of 3-axis BHEM interpretation describe its use as an exploration tool where a deposit has been missed by the drill and the three component response provides a direction and range to the target (Dyck, 1991, King, 1996). In a mineral resource definition role, most holes intersect the target. At the surface of the deposit, the eddy currents near the hole penetration are sheet-like. The surface current density results in a step discontinuity in the magnetic field vector across it (**ΔH**) which is parallel to the surface and perpendicular to the surface current vector (**Js**). Since the surface current is constrained to flow parallel to the nearest edge, **ΔH** points towards (or away from) the nearest edge. The EM component directions are not necessarily related to the principal directions of the mineral zone; therefore each of the three EM component responses can be considered to be composed of a symmetric and anti-symmetric part (Figure 4).

Figure 4: Symmetric and anti-symmetric responses



The anti-symmetric part of an EM component represents the component of **ΔH** in the direction of the sensor. Thus **ΔH** can be derived from very robust observations, the discontinuities in the responses of the three axes. The distance from the penetration point to the edge in the direction of **ΔH** is related to the ratio of the symmetric to anti-symmetric response amplitudes. Obtaining the normal vector to the conductor (defining its dip and strike) is more difficult since it depends on the symmetric part of the response which is due to the current distribution at a distance within the conductor and in other conductors.

Figure5: Geophysically constrained model of the Kelly Lake deposit showing intersections (white points) and interpreted edges (red lines). The cross cutting Olivine diabase dike is in green.



In practice the entire response is studied more completely by computer modeling using simple rectangular plates. The response of a plate model of a mineral deposit is calculated from an exact digital reproduction of the survey specifications (transmitter location, transmitter waveform, receiver sampling, receiver orientation and hole trajectory). The model is adjusted interactively until its simulated response matches as closely as possible the observations (Figure 8). Particular care is taken to simulate the discontinuity responses in the vicinity of the target. The response in the interior of the deposit, where the field is essentially zero, is not properly simulated by the thin sheet model, so these points are ignored for the purposes of fitting the data.

The geometry of the mineral system is generally modeled using the latest delay time channel in the transient step response. The recovered geometry corresponds to those parts of the deposit with a conductance high enough to render the zone opaque to magnetic field penetration for frequencies at or higher than the base frequency of operation. Better discrimination between high and low grade/thickness zones within the deposit can be realized by lowering the base frequency. Recent advances have permitted operation at base frequencies as low as 2 Hertz.

A different plate model of the deposit is generally obtained from each hole. The parameters of the model geometry best constrained by the data are noted for each hole and are used to build an estimate of the complex 3D shape of the deposit. Figure 5 shows a wireframe of the deposit constrained by intersections and by geophysically interpreted edges.

Kelly Lake Mineral Resource Definition Program

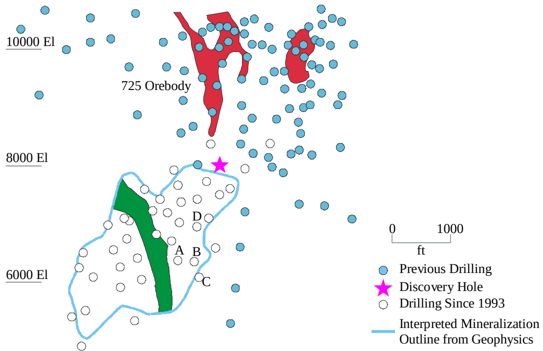
In the Kelly Lake program BHEM provided information on the geometry of the mineral zone and its continuity between holes. As the drilling expanded the resource, the geophysical information allowed subsequent holes to be deployed in the most effective manner. The most valuable information provided in this context was on the location of the nearest edge of the deposit relative to the hole. This information was used to ensure that each hole intersected mineralization thereby maximizing the resource added with each hole drilled. A knowledge of the overall size of the deposit ahead of the drilling also permitted the potential resource to be assessed early so that the merits of the project could be evaluated against others. Finally, the location of the edges of the deposit using BHEM made it unnecessary to locate large numbers of blank holes outside the locus of mineralization as a means of mapping the deposit perimeter.

The advantage gained by use of BHEM is shown clearly in Figure 6. The figure shows a longitudinal of the Copper

The Kelly Lake Deposit

Cliff Offset dike with the pierce points of the drillholes completed to date. The holes drilled into the shallow 725 deposit undertaken before the use of BHEM are shown as dark centered points while holes drilled during the recent program of BHEM integrated with drilling are shown as hollow centered points. For reference, the geophysical envelope which corresponds well to the envelope of mineable grade and thickness is shown as the blue outline. It is clear that many of the holes drilled into the upper zone would not have been necessary if BHEM had been used in these earlier programs. In the Kelly Lake program, almost all holes intersected significant mineralization. At least two holes were targeted outside the geophysical envelope intentionally and several were targeted very close to the edges of the geophysically inferred envelope.

Figure 6: Hole distribution vs mineable mineral (longitudinal looking West)



In addition to mapping the outline of the Kelly Lake deposit, the BHEM has shed light on details relating to the mineral distribution and the structure of the hosting dike. A good example involves the region immediately to the north of the cross-cutting olivine diabase dike where Hole B encountered the QD dike at a location displaced 200-300 feet to the east of the overall dike trend (Figures 6 and 7). The section in Figure 7 shows the initial interpretation from drill data with the displacement interpreted as a flexure in the dike and mineral. Hole C did not intersect mineral or QD a fact attributed to a local pinching of the dike. The BHEM plate modeling of these holes (Figure 8) together with the drillhole intercepts indicated a more complex model. (Figure 9). Figure 8 shows the hole trajectories and plate models. The data and best fitting model traces have been displaced from the holes for clarity. Hole C displayed a near-miss off-hole response which placed a conductor edge to the south of the hole. Hole B data showed evidence of a discrete top edge of a second east-displaced conductor as well as a second off-hole response located at the bottom of the hole. The modeling has clearly shown that the displaced QD in Hole B is part of a smaller displaced raft of QD and mineralization sub-parallel to the main dike trend and not a continuous extension of it. The off-hole response at the bottom of Hole B confirms the continuity of mineral in an extension of the main trend untested by the drilling.

Conclusions

Borehole EM can be used to greatly improve the efficiency of mineral resource definition programs. Its role is most important early in these programs where the full potential of a deposit can be quickly assessed with few holes. Late in the project, the ability of the method to map the edges of the mineralization can help to minimize the number of holes drilled to reach the same level of confidence in resource estimates. Geological models can be tested and improved based on careful geophysical modeling.

The cost of the BHEM program at Kelly Lake represented about 4% of the drilling budget. Considering the value it added to the overall program for such a low cost, a strong case can be made for the continuing development of BHEM techniques for data acquisition, interpretation and modeling.

References

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King, A., 1996, Deep drillhole electromagnetic surveys for nickel/copper sulphides at Sudbury, Canada: Expl. Geophys., 27, no. 2/3, 105-118

West, G. F., Macnae, J. C. and Lamontagne, Y., 1984, A time-domain electromagnetic system measuring the step-response of the ground: Geophysics, 49, no. 07, 1010-1026.

Figure 7: Geological model without EM

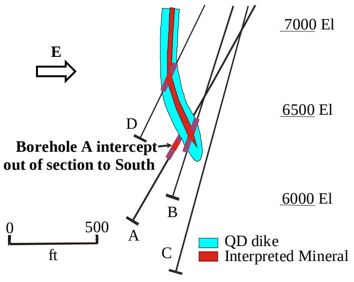

Figure 8: EM plate modeling

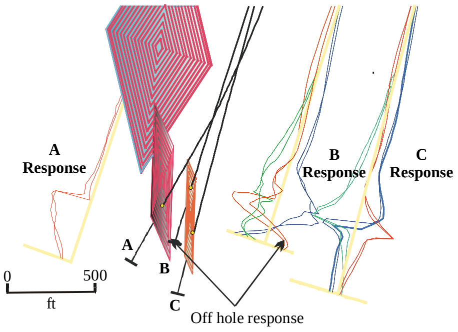

Figure 9: Geological model with EM