Multiparameter petrophysical characterization of an orebody: an exploration case history

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ABSTRACT: We present results from petrophysical studies to characterize a Zn-Pb-Ag deposit in Nash Creek, New Brunswick. The measurements are part of an integrated study that includes geological and geophysical data acquired on the property. Measured core densities (thirty-two boreholes) demonstrate that high densities (>3.2g/cm^3) correlate strongly with Zn-rich mineralization zones (low resistivity). Compression and shear wave velocity measurements from representative core samples of the regional geology range from ~2.91 (highly altered) to ~6.41 km/s and from ~1.41 to ~4.20 km/s respectively. Porosity estimates range from 0.35% to 11.78%. Results from induced polarization (IP) measurements suggest that chargeability and resistivity information can be combined to adequately identify conductors associated with mineralization in electrical survey data.

Information on these physical parameters and their 3D statistical distribution have serious implications on aspects of mineral exploration that include: resource estimation, choice of geophysical data acquisition and interpretation, and information for preliminary rock stability assessment.

1 INTRODUCTION

In this paper, we present results from petrophysical data analysis aimed at characterizing a sulfide orebody (Zn-Pb-Ag) in Nash Creek New Brunswick. The Nash Creek deposit is located along the western margin of the Jacquet River Graben in northeastern New Brunswick (Dostal et al. 1989), Figure 1. The Nash Creek exploration area is mainly underlain by the Lower Devonian sequence of the Dalhousie Group rocks (Brown 2007) comprising volcanic breccias, siltstones, limestones, mafic flows, rhyolites, tuffs and pillow lavas. The tectonostratigraphic setting may represent a failed continental rift system with shallow water to marginal marine environment (Brown 2007). The volcanic and sedimentary rocks were deposited in a half-graben that is fault bounded to the west.

Rock physics measurements were performed on core samples to help characterize the 2D/3D distribution of the Nash Creek deposit. Understanding the variation and correlation between these physical properties is vital for every exploration project. The petrophysical data is very handy for rock physics modeling especially for determining how the changes in elastic properties relate to changes in mineralogy and in predicting these elastic parameters in areas with no borehole logs. In the present case study, the petrophysical database is useful for resource estimation and also provides invaluable background information for other geophysical data acquisition and interpretation programs being conducted on the property and aimed at delineating the ore deposit.

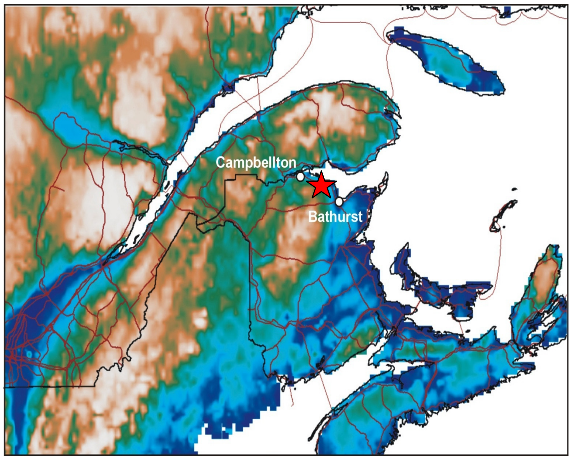


Figure 1: Map showing the location of Nash Creek.

2 ELASTIC PROPERTIES

Contrast in elastic properties is a fundamental factor governing the seismic response of an orebody. Individual velocities and densities are controlled by factors like mineralogical content, damage, pressure and fluid saturation especially in insitu conditions. Various methods such as borehole logging and laboratory measurements are used to constrain these parameters. Studies on hard rock samples indicate that sulfide ores and host rocks have high velocities compared to silicate rocks (Salisbury et al. 1996). Though the velocities of these sulfide ores are variable, they generally have high densities. Thus, sulfide ores have high impedances, which provide ideal contrast for imaging them via seismic methods. Constraining these elastic parameters provides necessary information for adequate assessment of the potential for using seismic methods and gravity methods for imaging this shallow but blind massive sulfide deposit.

2.1 *Density Measurements*

Thirty-two boreholes were logged for density information. Commonly these small diameter boreholes were very unstable. The use of a nuclear sourced gamma-logging tool is not possible; therefore all density measurements were performed by manually logging each bore core at intervals ranging from 0.5m-1.5m. The density of each core sample was computed from two measurements of mass, one with the sample suspended in air and a second with the sample suspended in water. Assuming the water has a density of 1.0 g/cm^3, this simple procedure provides an estimate of the dry density of the rock. Though these rock samples were no longer in insitu conditions, we assumed densities would not have changed significantly over time and the measurements were a close representation of the insitu conditions of both the sulfide mineralization and the host rocks. The Nash creek sulfides occur as matrix replacements mineralization in laterally extensive statabound volcanic fragments and as vein mineralization in fractured (low density) zones. A total of 5981 measurements were made with an average density of 2.76 g/cm^3 (Fig. 2a). The low densities (<2.5 g/cm^3) and the high densities (>3.2 g/cm^3) correlate very well with alteration zones and Zinc-rich mineralization zones respectively. Figure 2b shows the correlation between measured density and mineralization (assay data). Boreholes intersected by zones with high grade sulfides (high densities) correspond to low resistivity zones obtained from Vertical Resistivity Profiling (VRP, Milkereit et al. 2008). Detailed analysis of the borehole data suggests most of the mineralization is hosted within felsic and mafic material (Fig.

2c). A subset of the 32 boreholes (17 boreholes) constitutes two intersecting borehole profiles. The good correlation between the density and the assay data in these 17 boreholes can be used to obtain a 3D geophysical model of the ore.

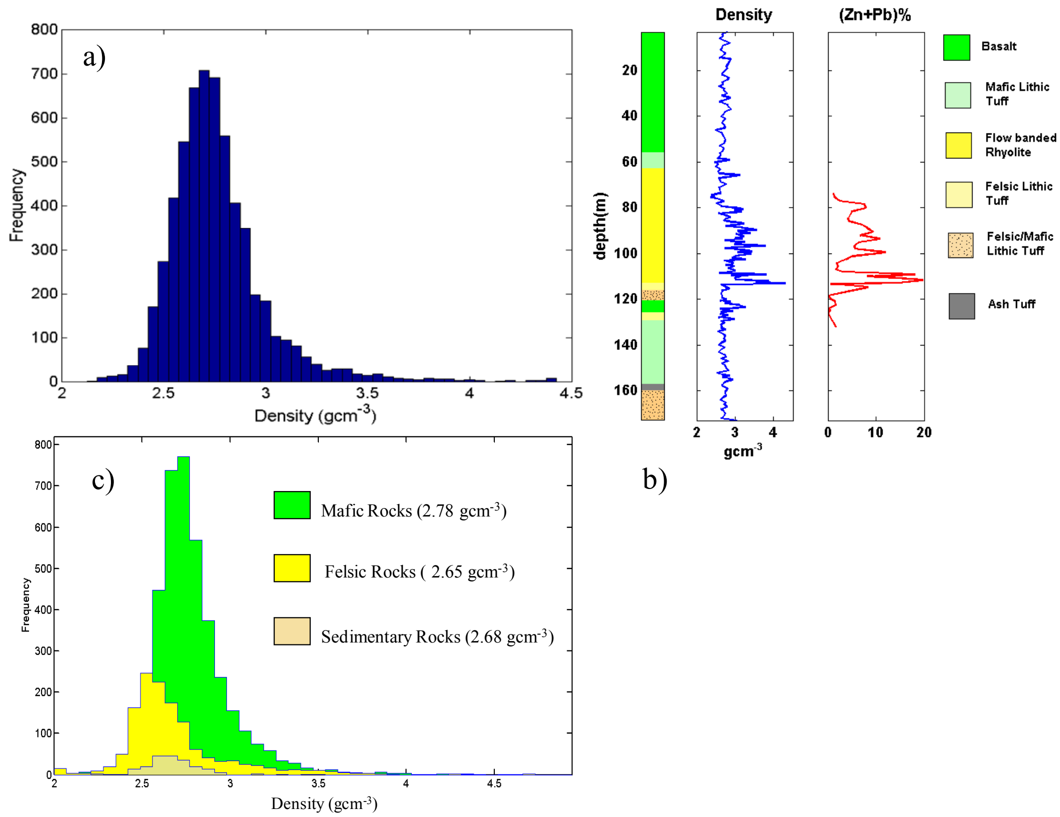


Figure 2: a) Density distribution from systematic measurements done on 32 boreholes (5981 measurements). b) Density log and assay data (%Zn +Pb) from one of the boreholes surveyed. c) Density distribution based on lithology (24 boreholes).

2.2 *Velocity and Porosity Laboratory measurements*

The velocities were determined from a suite of 18 micro cores of ore and host rock with dimensions ranging from 18-70mm in length and 25-48mm in diameter. These cores were representative of the characteristic lithology found in Nash Creek. After the micro core densities were determined, the compressional wave velocities were measured using the pulse transmission method: a pair of piezoelectric sensors placed on opposite ends of the cylindrical rock sample such that one sensor triggers an acoustic pulse that propagates through the sample and is recorded by the second sensor at the opposite end. The measurements were done under standard conditions.

Porosity was measured by using the caliper technique described by Franklin et al. (1977). The method requires measurements of the dry and the saturated masses as well as bulk volume calculated from caliper readings for dimensions of each rock sample. The rock samples were dried by putting them in an isotemp vacuum oven whereas saturation was achieved by water immersion in a vacuum for a period of five days. Assuming that the total pore space volume forms a percentage of the bulk volume of the rock sample and that the air in the pore space is completely replaced by water when the rock is fully saturated, pore volume was obtained from the relative difference between the measured dry and saturated masses. Hence, porosity for each rock sample was measured as a percentage ratio between the pore volume and the bulk volume.

The compressional and shear velocities range from ~2.91 to ~6.41 km/s and ~1.41 to ~4.20 km/s respectively. The low velocity values correspond to rocks with a high degree of alteration. As expected, the porosity for most of these crystalline rocks is less than 10%. However, some of the measured core samples have high porosities (>=10%) and we think that this is strongly correlated with the low velocity values (< 4 km/s) measured for these rock samples due to fractures and brecciation. Table 1 summarizes the dynamic rock property measurements from the cores used in this study. Additional mechanical properties (Young's modulus) were also estimated from theoretical relations between V_p, V_s, and density. These mechanical properties come in handy when characterizing the rock mass for seismic stability and for mine design.

Table 1. Acoustic properties of Nash Creek sedimentary, felsic and mafic rocks at room temperature

Sample ID	Density (g/cm^3)	V_p (km/s)	V_{s1} (km/s)	V_{s2} (km/s)	Porosity n (%)	Young's Modulus E_{s1} (GPa)	E_{s2} (GPa)
A	3.00	5.18	3.04	3.06	2.31	68.61	69.35
B	2.76	3.89	×	×	×	×	×
C	2.65	×	×	×	×	×	×
D	2.71	3.70	2.34	2.34	6.98	34.67	34.62
E	2.47	3.47	2.27	2.25	11.47	28.61	28.37
F	2.58	4.64	2.85	2.90	×	50.18	51.17
G	2.68	4.73	2.79	2.78	4.48	51.62	51.37
H	2.67	4.07	1.61	1.55	×	19.43	18.09
I	2.56	×	×	×	×	×	×
J	2.67	2.91	1.43	1.41	×	14.66	14.24
K	2.59	3.68	2.18	1.84	11.78	30.27	23.44
L	2.41	4.53	2.44	2.39	×	37.24	35.94
M	2.78	6.41	3.57	3.57	0.35	90.56	90.41
N*	3.00	5.80	3.35	3.37	×	84.26	85.05
O*	3.28	4.89	2.83	2.85	×	65.52	66.18
P*	3.21	5.79	3.26	3.49	×	86.68	94.97
Q*	3.27	4.74	2.96	2.93	×	67.57	66.84
R*	3.96	6.26	4.11	4.20	×	150.05	152.37

* *Rock samples with veins of sulfide mineralization (pyrite, sphalerite, and galena)*
V_p: *Compressional wave velocity*
V_{s1} & V_{s2}: *Shear wave velocities (SV & SH respectively)*

In order to further characterize the acoustic velocities, the measured values were plotted against the Nafe-Drake curve that highlights the velocity-density field (Salisbury et al. 1996) of sulfide ores and silicate host rocks at confining pressure of 200MPa (Fig. 3). Velocity properties are severely affected by microcracks and the measured values will increase to the crack free value with pressure as the cracks are progressively closed (Schmitt et al. 2003, Salisbury et al. 1996). Thus, owing to the fact that our measurements were obtained under conditions where confining pressure were slightly above 0MPa, the data have lower values than expected at the given pressure conditions (200MPa). This difference in pressure was accounted for by considering a rock physics database of acoustic velocity measurements under several confining pressures from a host of rocks samples around the world (Salisbury et al. 1999). Analysis of the rock physics database suggests that velocities should increase on average by 9% for pressures changing from 10MPa to 200MPa. Densities change very slightly over same pressure range. Note most of the sulfide rich samples in this study plot correctly within their respective subfield of the Nafe-Drake curve (mixed sulfides).

As compressional velocities increase with pressure, densities also increase slightly with pressure, causing acoustic impedance differences to be invariant with pressure (Salisbury et al. 1996). This suggests reflection coefficients are pressure independent even if velocities change. Thus, from our measurements, we can obtain reasonable estimates of the impedance contrast between the orebody and the host rocks. A close examination of Figure 3 suggests the sulfide ore are acoustically distinguishable from the host rocks since R=0.06 (reflection coefficient) is the threshold for producing a reasonable reflection after allowing for noise.

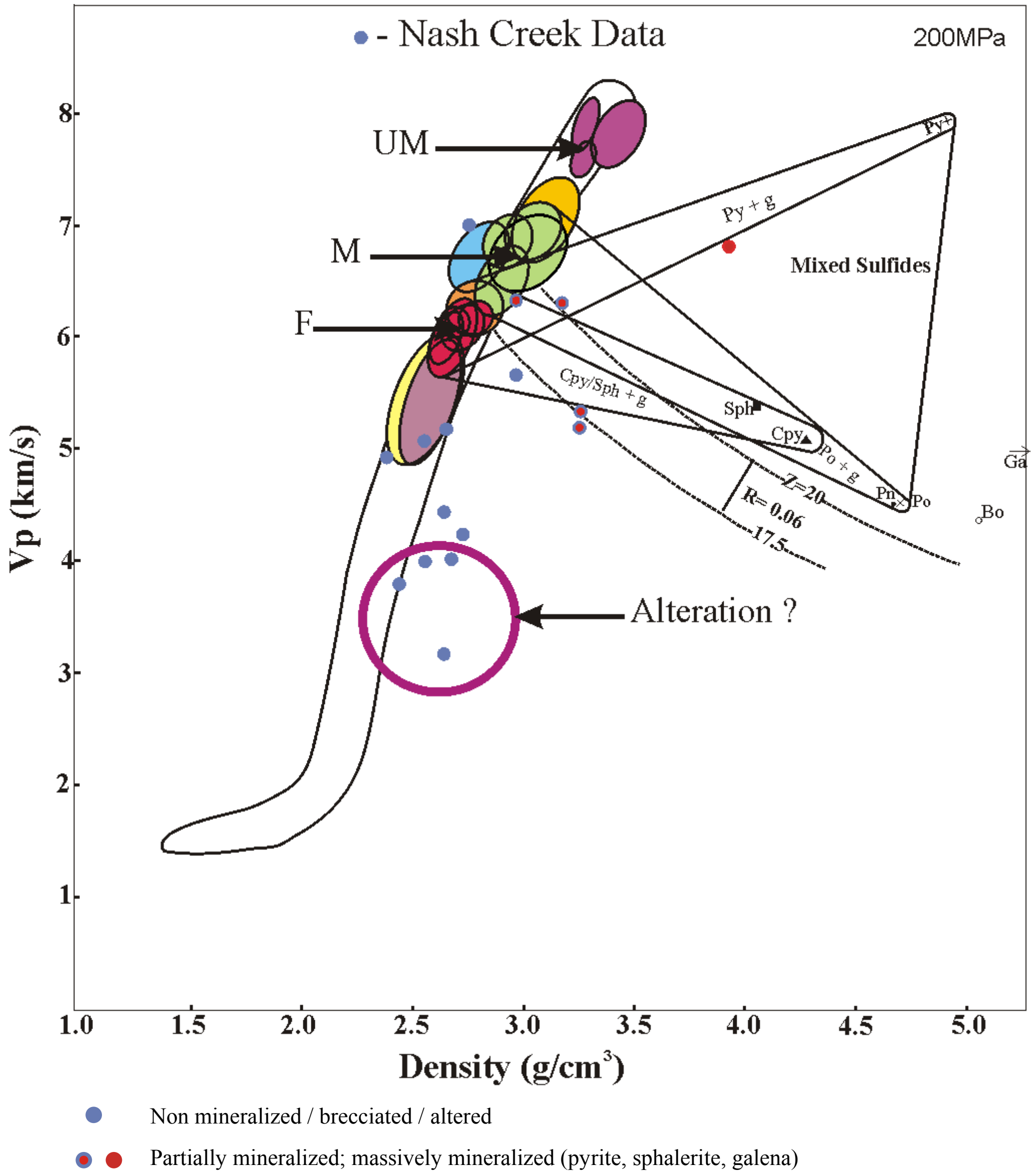


Figure 3: Projected Compressional wave velocity versus densities for Nash Creek rock samples superimposed on the Nafe-Drake curve for common silicate rocks, hardrocks and selected base metal ore minerals (after Salisbury et al. 1996, Salisbury et al. 2003). Dashed lines represent lines of constant impedance; bar shows minimum impedance constrast required for strong reflection (R=0.06). Abbreviations: Bo, bornite; Cpy, chalcopyrite; g, gangue; Ga, galena; Pn, pentlandite; Po, pyrrhotite; Py, pyrite; Sph, sphalerite; F, felsic; M, mafic; UM, ultra mafic.

3 ELECTRIC AND MAGNETIC PROPERTIES

Measurements were done using 25mm-diameter by 18-24mm-long samples. The lab measurements for electric properties focused on the electric induced polarization (IP) response of the core samples. The IP response of a rock sample was derived from a record of the transient response (voltage change) induced by a 2 sec square wave electrical current. A schematic representation of an example of a measured transient response is illustrated in Figure 4. The IP opposes the build up or collapse of the potential difference between the voltage electrodes when current is switched on or switched off. The change in voltage depends on the degree of polarizability of the sample. There is a vast literature that covers the electro-chemical mechanisms explaining the IP phenomenon as well as case histories highlighting the application of IP methods for base metal exploration (Bertin & Loeb 1976, Fink et al. 1990).

The transient voltage response is associated with both metallic and non-metallic effects. This consequently poses a problem for the effectiveness of IP methods in ore prospecting where the IP phenomenon due to the metallic and non-metallic effects of the rock is indistinguishable. For ore prospecting, interest is usually in the IP response owing to the metallic effects of the rock.

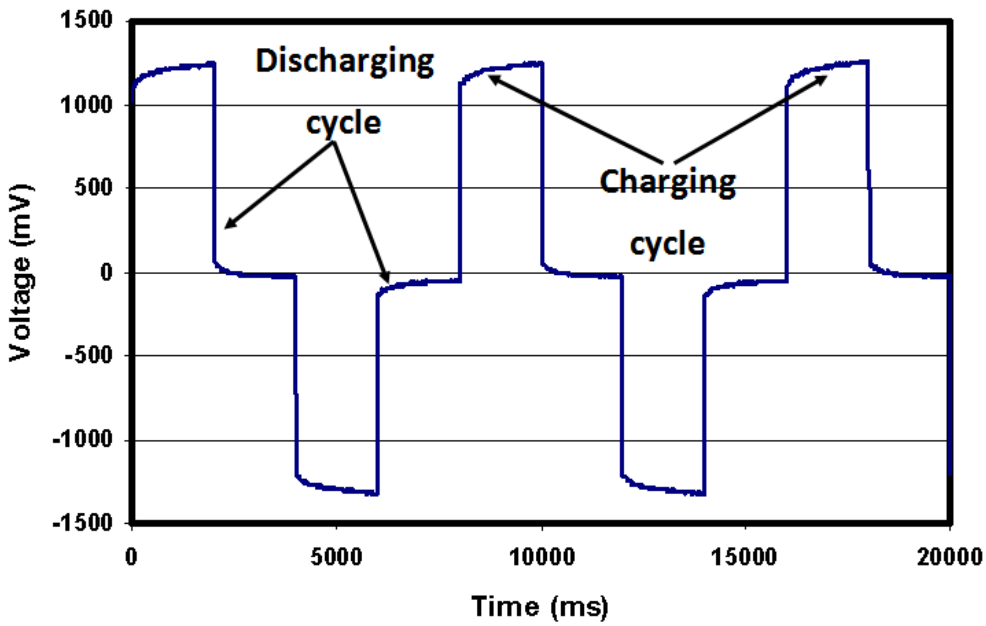


Figure 4: Sample of measured induced polarization charge-discharge curve.

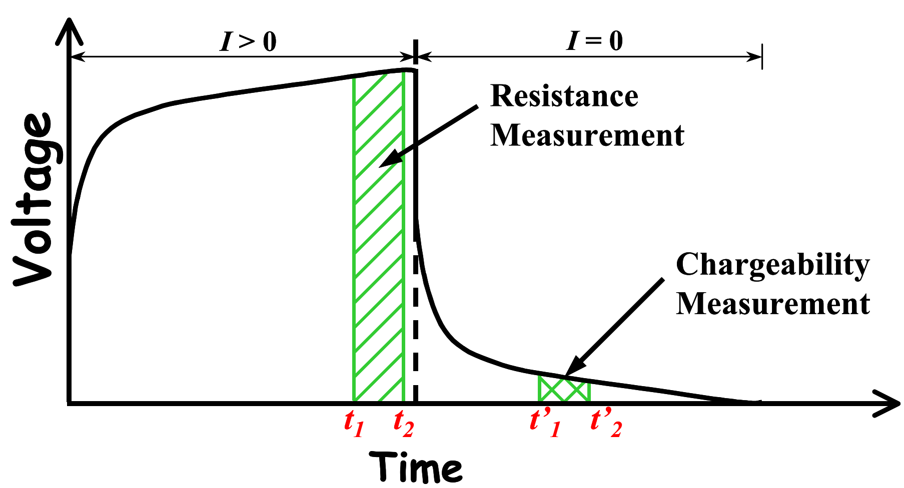


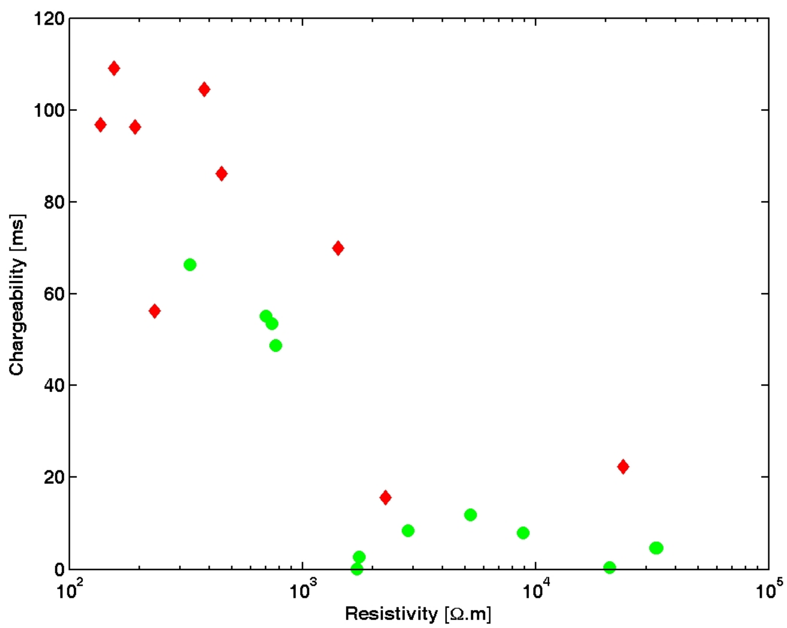
Figure 5: Schematic representation of how resistivity and chargeability are computed from the IP curve.

In our experimental setup, the measureable is the transient voltage response from which we obtain chargeability and resistivity parameters. To measure resistance, the average of the voltage values (Primary voltage) within a small time window shortly before current turn off (Fig. 5) was used. The chargeability measure was obtained from a normalized integral of the voltage values over a small time window some time after the current turn off (Fig. 5). The normalization coefficient for the integral is the primary voltage. Resistivity was obtained by using the mathematical relation:

$$\mathrm{Re}sistivity = \frac{\mathrm{Re}sis\tan ce \times Area}{length} \tag{1}$$

A cross plot of the chargeability and resistivity is shown in Figure 6. Low resistivities were recorded in samples visually identified with some veins rich in sphalerite, pyrite and galena mineralization. The figure shows an inverse relation between resistivity and chargeability whereby low resistivity correlates with high chargeability and vice versa. The resistivity contrast existing between mineralized and non-mineralized rock samples provides a valuable tool for quality control on resistivities characterizing known conductors from surface DC sounding (Milkereit et al. 2008). Nowadays, it is common practice to use IP sounding sections in constraining the interpretation of any conductors obtained in surface resistivity (DC) sounding. Based on the chargeability results from the suite of Nash creek rock samples, IP sounding combined with surface DC sounding will be adequate for delineating the sulfide-mineralized zones.

Magnetic susceptibility of the rock samples was also measured. Given that measurements were done on a few samples, more magnetic susceptibility measurements are needed to better constrain the magnetic properties of the different lithologic units. However, there was no significant difference in values obtained from most of the rock samples. This suggests probing for the ore deposits by magnetic methods will be inefficient. It is noteworthy that the degree of magnetization of sulfides is very sensitive to composition; more analysis of magnetic susceptibility using other mineralized samples can help to better constrain the relative magnetic properties of the ore and the host rocks.



◆ Samples with veins hosting sulfide mineralization (pyrite, sphalerite, and galena)
Figure 6: Cross plot of measured chargeability and Resistivity from the Nash Creek Rock samples.

4 CONCLUSIONS AND IMPLICATIONS

From the results of the petrophysical study on core samples, we conclude that the average host rock density is 2.7 g/cm^3 while the Zn-Pb-Ag sulfide ore show densities that are atleast greater than 3.0 g/cm^3. There is a good correlation between the high densities of the sulfide and the assay data. By using multi-drillhole density and assay data, a 3D-earth model of the ore deposit can be developed.

Laboratory measurements of some physical and elastic wave properties under standard conditions (velocities, porosities, and dynamic Young's modulus) have been used to predict that the sulfides and fault zones on the Nash creek property can be imaged using acoustic methods. The high impedances from the sulfides is controlled by their high density contrasts with respect to the mafic, felsic and sedimentary host rocks while the low impedances in host rock are associated with low velocities measured from altered rock samples that could have come from fault zones. Moreover, the sulfides show a sharp resistivity and chargeability contrast with respect to the host rock. Taking this into account and the fact that the deposits in the present case are shallow, it can be possible to probe the ore deposit with electrical methods such as DC surface surveys. An integrated approach for electrical surveys combining IP sounding and surface DC sounding will be efficient in delineating the orebody. On the other hand, seismic methods in this case will be more suitable for deep targets.

The petrophysical database obtained from this study has important implications in the exploration stages and development of the mine, including, choice of geophysical data acquisition and interpretation for ore delineation, resource estimation and information for preliminary rock stability assessment. Integrating the petrophysics from multiple drill holes as well as geologic and geophysical data allows for building an adequate rock physics 3D earth model that characterizes the shallow but "blind" ore deposit.

More lab measurements need to be done by using a wider selection of samples from the property to get better handle on average values for the various petrophysical properties. Pressure dependent measurements of velocity values will also be useful to better constrain the dynamic elastic properties.

REFERENCES

L'Heureux, E., Ugalde, H., Qian W., Milkereit, B., & Nasui, C. 2007. An integrated geophysical study of orebody delineation, *CSEG Recorder Vol. 32*:36-39.

Ugalde, H., L'Heureux, E., & Milkereit, B. 2007. An integrated Geophysical study for Orebody delineation, Nash Creek, New Brunswick, In *Proceedings of Exploration 07: Fifth Decennial International Conference on Mineral Exploration: 1055-1058.*

Qian, W., Milkereit, B., & Gräber, M. 2007. Borehole resistivity tomography for mineral exploration, *EAGE expanded abstract, London, 11-14 June*.

Salisbury, M. H., Milkereit, B., & Bleeker, W. 1996. Seismic imaging of Massive sulfide deposits, part I: Rock properties*, Economic Geology Vol. 91*: 821-828.

Salisbury, M. H., Harvey, C. W., & Mathews, L. 2003. Acoustic properties of ore and host rocks in hardrock terranes. In D. Eaton, B. Milkereit, & M. H. Salisbury (eds), *Hardrock Seismic Exploration*; *Geophysical development series Vol. 10*: 1-19.

Schmitt D. R., Mwenifumbo, J., Pflug, K. A., & Meglis, I. L. 2003. Geophysical logging for elastic properties in hard rock: A Tutorial. In D. Eaton, B. Milkereit, & M. H. Salisbury (eds), *Hardrock Seismic Exploration; Geophysical development series Vol. 10*: 20-41.

Loeb, J., & Bertin, J. 1976. In R.G. van Nostrand & D. S. Parasnis (eds), *Experimental and Theoretical aspects of induced polarization* 1&2; *Geoexploration Monographs* (Series1-No. 7): Geopublication Associates.

Fink, J. B., Sternberg, B. K., McAlister, E. O., Wieduwilt, W. G., & Ward, S. H. (eds) 1990. *Induced Polarization: Application and case histories; Society of Exploration geophysicists press, Investigations in geophysics Vol. 4*.

Milkereit, B., Qian, W., Ugalde, H., Bongajum, E., & Gräber, M. 2008. Geophysical Imaging of a "Blind" Zn-Pb-Ag Deposit, *EAGE expanded abstract, Rome, 9-12 June*.

Salisbury, M. H., & Iuliucci, R. 1999. Geological Survey of Canada/ Dalhousie University rock properties database: http://gsca.nrcan.gc.ca/pubprod/rockproperties/ index_e.php.

Brown, D.F. 2007. Technical report on mineral resource estimate, Nash Creek project, Restigouche County, New Brunswick, Canada: 1-190.

Dostal, J., Wilson, R. A., & Keppie, J. D. 1989. Geochemistry of the Siluro-Devonian Tobique Volcanic Belt in Northern and Central New Brunswick (Canada): Tectonic Implications. *Canadian Journal of Earth Sciences Vol. 26* (No. 6): 1282-1296.

Schon, J. H. 1996. In K. Helbig & S. Treitel (eds), *Physical Properties of Rocks: Fundamentals and principles of petrophysics; Handbook of geophysical exploration Vol. 18*.

Franklin, J.A., Vogler, U. W., Szlavin, J., Edmond, J. M, & Bieniawski, Z. T. 1979. Suggested Methods for Determining Water Content, Porosity, Density, Absorption and Related Properties and Swelling and Slake-Durability Index Properties. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts Vol. 16* (No. 2): 141-156.

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