# Geophysical signatures of the Ni-Cu-PGE mineralization in the Stillwater West property, Stillwater Complex, southern Montana, USA

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# Abstract

Ground Induced Polarization (IP) surveys can be expected to play a growing role in discovering new mineral deposits under cover and at greater depths (> 500 m). The standard deliverable products from IP surveys are 2D/3D chargeability and resistivity inversion models. In many cases, the chargeability anomalies can be used to identify disseminated sulphides directly. However, chargeable mineralization can occur in conductive as well as resistive hosts. In the former case, the Metal Factor (MF) is more suited for targeting potential mineralization/deposits while in the latter case, the Resistivity Scaled Chargeability (RSC) is more appropriate. In this contribution, we will demonstrate the effectiveness of using the MF and RSC data in identifying potential sulphide and chromitite mineralization in the Stillwater West property in famous Stillwater Complex, southern Montana, USA.


# Introduction

Schodde (2020) showed that geophysics accounts for nearly 22% of all prospect-scale (drilling stage) discoveries and it can be expected to play a growing role in discovering new mineral deposits under cover and at greater depths (> 500 m). We believe that the success of geophysics at the prospect-scale can be credited largely to the ground/borehole IP/EM methods used to follow-up the airborne magnetic and electromagnetic (EM) anomalies.

In general, the standard final deliverables of a ground Induced Polarization (IP) survey are chargeability and resistivity inversions and, in many cases, for example, in the exploration for porphyry copper systems, the chargeability anomalies correlate directly with disseminated sulphide bodies and can be used to site the test drillholes. However, high chargeable responses can be found in conductive as well as resistive hosts, and in some cases the chargeability and resistivity inversions have proved to be inadequate in identifying the sought mineral targets. Müller, Kwan & Riaz (2021) have shown that the Metal Factor (MF) is more effective in the search for vein and breccia hosted high sulphidation polymetallic Au-Ag mineralization in the Stikinia terrane in northwestern BC, Canada.

The MF in IP was first introduced by Marshall & Madden (1959) to highlight chargeable zones in conductive host. MF correlates well with the metallic mineral content (Hallof, 1964). In frequency-domain IP, MF is defined as the ratio of the percent frequency effect ($PFE$) over the resistivity multiplied by 1000 (Sumner, 1979). In the time-domain IP, the $PFE$ is replaced by the chargeability $m$, and for $PFE \ll 1$, $m \approx PFE$. Therefore, in the time-domain IP, the MF is defined as the ratio of the chargeability $m$ in (mV/V) and the resistivity $\rho$ in (Ohm-m) multiplied by 2000, i.e.,

$$MF = 2000 * ({}^{m}/_{\rho}) \text{ in (mS/m)}. \quad (1)$$

The MF helps to increase the signal-to-noise ratio between the effect of well mineralized zones and the effect of only slightly mineralized zones, but it also favors the rocks having conductive electrolytes in the pores, and therefore it is not so useful when dealing with clays (Marshall & Madden, 1959 and Sumner, 1979).

An innovative IP parameter called RSC is created to help the identification of chargeable zones in resistive terrains. The RSC is defined as the product of LOG10(resistivity) and chargeability, e.g., let $\rho = resistivity\ \ and\ m = chargeability$,

$$RSC = \mathrm{m}{*}\log_{10}(\rho) \quad (2)$$

The RSC is called the resistivity-scaled chargeability in mV/V*Ohm-m, which is a variant of the Cole-Cole time-constant TAU scaled chargeability introduced in Kwan et al. 2018.

In this contribution, we will demonstrate the effectiveness of the MF and RSC data in identifying potential Ni-Cu sulphides and chromitite hosted PGE at the Stillwater West property in Stillwater Complex, southern Montana. RSC can highlight chargeable zones in the resistive terrains.

The Stillwater West property, 100% owned by Group Ten Metals Inc. (Group Ten Metals) and centered near 45° 25’ N and -110° 058’ W, is located approximately 45 kilometers SW from Livingston, and 22 kilometers from Nye, Montana, along the ridges of Chrome and Iron Mountains (Fig. 1). Access to the Stillwater West property is by trails from Nye.


Figure 1: The location of Stillwater West property in southern Montana.

# Alpha IP$^{TM}$ System

The Alpha IP$^{TM}$ – a 2D/3D Wireless Time Domain Distributed System is the world first wireless Induced Polarization system, where a minimum amount of wire is being used and can be expanded to as many channels and eliminates the concept of limited “n” values. Alpha IP$^{TM}$ provides full waveform data with 24-bit digital sampling and advanced signal processing. The chargeability and resistivity components provide an excellent means of delineating target mineralization.

In resistivity surveying, information about the subsurface distribution of electrical conductivity is obtained by examining how currents flow in the earth. DC (direct current) resistivity methods involve injecting a steady state electrical current into the ground and observing the resulting distribution of potentials (voltages) at the surface or within boreholes.

Chargeability is a physical property that is related to resistivity. The module about DC resistivity shows that potentials measured in a DC resistivity survey can be related to charges that accumulate when current is made to flow. However, when the transmitter current is switched off, the measured voltage may take up to several seconds to reach zero. Similarly, when the current is switched on, there may be a finite time taken for the voltage to reach a steady state value. In other words, current injected into the ground causes some materials to become polarized. The phenomenon is called induced polarization, and the physical property that is measured is usually called chargeability, which quantifies the material's capacity to retain charges after a forcing current is removed. The following figure illustrates the measurable effect.

Time domain IP is a rather complex phenomenon but easy to measure. When a voltage applied between two electrodes is abruptly interrupted the electrodes used to monitor the voltage do not register an instantaneous drop to zero but rather records a fast-initial decay followed by a slower decay. This phenomenon is known as IP (Fig. 2). The technique is mostly concerned with measuring Disseminated sulphides have strong IP responses. Clay minerals may also produce significant IP responses. The IP technique is often used to distinguish between clay and for example water saturated media which have similar resistivities but different chargeability.

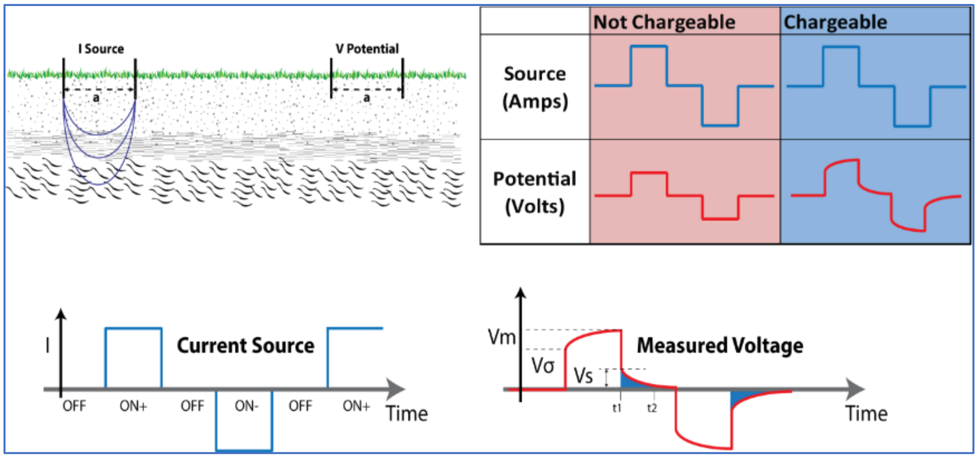


Figure 2: Example of Time Domain IP Measurement Sequence and Parameters.

Typical 2D IP surveys use the so-called distributed system, using wired or wireless receivers with full waveform recording, with the simultaneous deployment of unlimited receiver dipoles along any length of profile using 25/50/100/200 m long dipoles. Each receiver is fully independent, with its power source, GPS synchronization, and memory for data recording. The post-survey processing includes quality check and the extraction of resistivity and chargeability parameters at each plot point of a pseudo section, all carried out in the time-domain. After that, 2D inversions of the resistivity and chargeability parameters are produced as final deliverables, and they form the database for subsequent geophysical interpretation with the ultimate objective of identifying potential mineralization targets and siting of test drillholes.

Alpha IP$^{TM}$ system can be deployed in many configurations – Pole-Pole, Dipole-Dipole, Pole-Dipole, Gradient Array, and Simcoe's Dipole-Pole-Dipole Array. The accuracy of dip and strike positions of structures is decreased (side shift) if only pole-dipole (PDR) or (PDL) is used, combining the PDR and PDL overcome misleading positions of structures, so the choice of Simcoe's Dipole-Pole-Dipole configuration is highly recommended (Fig.3).

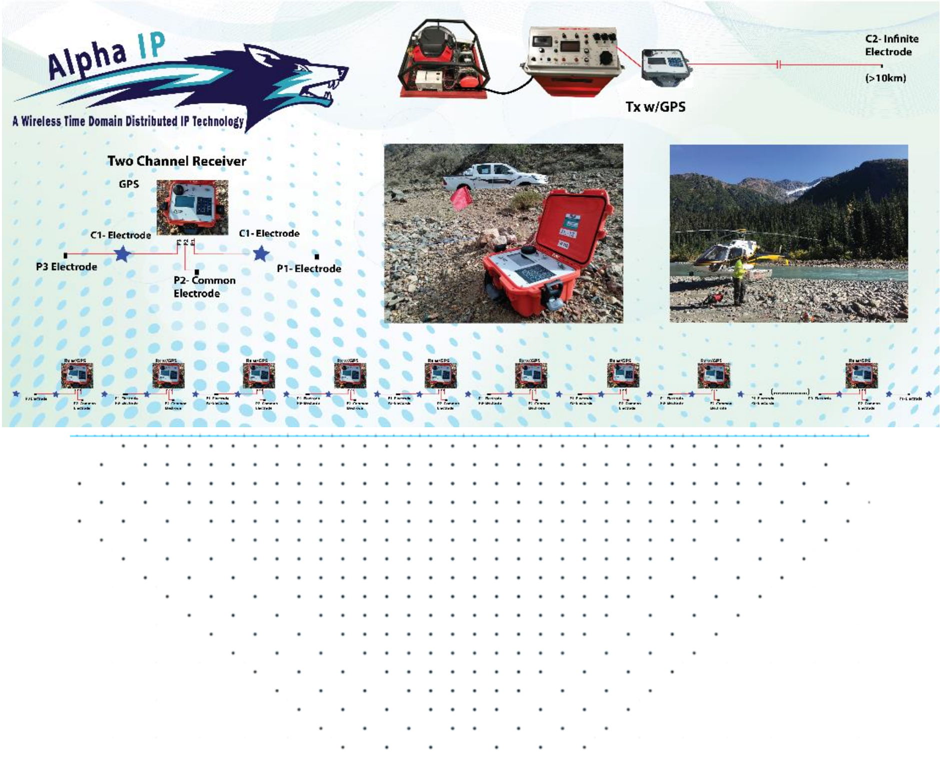


Figure 3: Alpha IP Dipole-Pole-Dipole Schematic Spread Setup with Current Injection Offset

# Stillwater West Property

**The Platinum-Group Elements (PGE)**

The platinum-group elements consist of a group of siderophile to chalcophile metals including osmium (Os), iridium (Ir), ruthenium (Ru), rhodium (Rh), platinum (Pt), and palladium (Pd). Platinum possesses a unique set of physical, chemical and mechanical properties, such as high melting point (1769˚C), high catalytic activity and mechanical strength and malleability, thus making it an important industrial and high technology metal and being used in automobile catalytic converters, magnetic hard drives, optical fibres, Liquid Crystal Displays (LCDs), turbine blades and fuel cells (Misra, 2000).

Significant PGE deposits are hosted in ultramafic rocks. According to Misra (2000), two types of PGE deposits account for nearly 98% of the world's PGE resources: (1) stratiform or stratabound deposits in large layered intrusive complexes, e.g., Bushveld (South Africa) and Stillwater (USA), exploited mainly for PGE; and (2) Ni-Cu sulphide deposits mined primarily for Ni-Cu but containing recoverable amount of PGE as by-products, e.g., the Sudbury (Canada) and Noril'sk-Talnakh (Russia). The distinctive characteristics of stratabound PGE mineralization include: (a) their occurrence as relatively weak disseminations of sulphides in silicate rock layers at specific horizons or "reefs" within layered intrusions; and (b) their association with chromitite.

The Bushveld Complex accounts for nearly 80% of the world's PGE resources, and about 2/3 of total world production of PGE comes from the Bushveld Complex. Stillwater Complex is relatively smaller in size compared with the Bushveld, but caries a much higher PGE grade, 22.3 g/t for J-M Reef in Stillwater versus the average of 8.5 g/t for Merensky Reef, UG-2 Chromitite and Platreef in Bushveld (Misra, 2000). South Africa is the largest platinum producing country (~130 metric tons in 2019), followed by Russian (~20 metric tons in 2019 (www.statista.com).

**Stillwater Complex**

The Stillwater Complex is well documented in Zientek & Parks, 2014. The Stillwater Complex is a Neoarchean (2704$\pm$5 Ma) mafic to ultramafic layered intrusion exposed in the Beartooth Mountains in south-central Montana, Fig. 4. Over 5500 m of layered igneous rocks are exposed and can be traced for nearly 50 kilometers along strike. The John Manville (J-M) Reef deposit has been traced for 42 kilometers of the 50-kilometer strike-length of the complex, at least 2 kilometers down the dip of layering and open at depth. The J-M Reef is the sole source of primary PGE production and reserves in the US as of 2014. The Stillwater Complex also contains stratabound chromitite resources and nickel and copper in contact-type PGE deposits.

The Stillwater Complex was emplaced in the Archean at a depth of 10-15 km, and the Laramide deformation and subsequent erosion have exposed the basal hornfels and a thick but incomplete section of the complex (McCallum, 1996).

The general geology of the Stillwater Complex comprises mainly of Banded Series (Upper, Middle, and Lower), Ultramafic and Basal Series (McCallum, Raedeke & Mathez, 1980 and Todd et al. 1982). The complex intruded deformed metasedimentary rocks of the Wyoming Archean province and was intruded by Late Archean quartz monzonite plutons and is unconformably overlain by Paleozoic sediments on the north side (Thompson, 2008). The J-M Reef is hosted in the Lower Banded Series.

The geology of the Stillwater West property consists of mainly the Archean metasediments and the Ultramafic and Basal series. The Archean metasedimentary rocks consist of iron formation, quartzite, greywacke, and argillite (Thompson, 2008). The Basal Series is a laterally persistent but heterogeneous unit made up of bronzite-rich cumulates containing minor segregations of noncumulate mafic rocks, coeval sills of diabase, sulphide-rich mafic norite, and inclusions of Archean metamorphosed sedimentary rocks. The Ultramafic Series consists of a Peridotite Zone of interlayered dunite, harzburgite, orthopyroxenite and chromitite overlain by a massive Bronzitite zone (Aird & Boudreau, 2013). The Peridotite zone is made up of cycles of cumulus olivine with conformable layers of chromitites in the lower parts of each cycle.

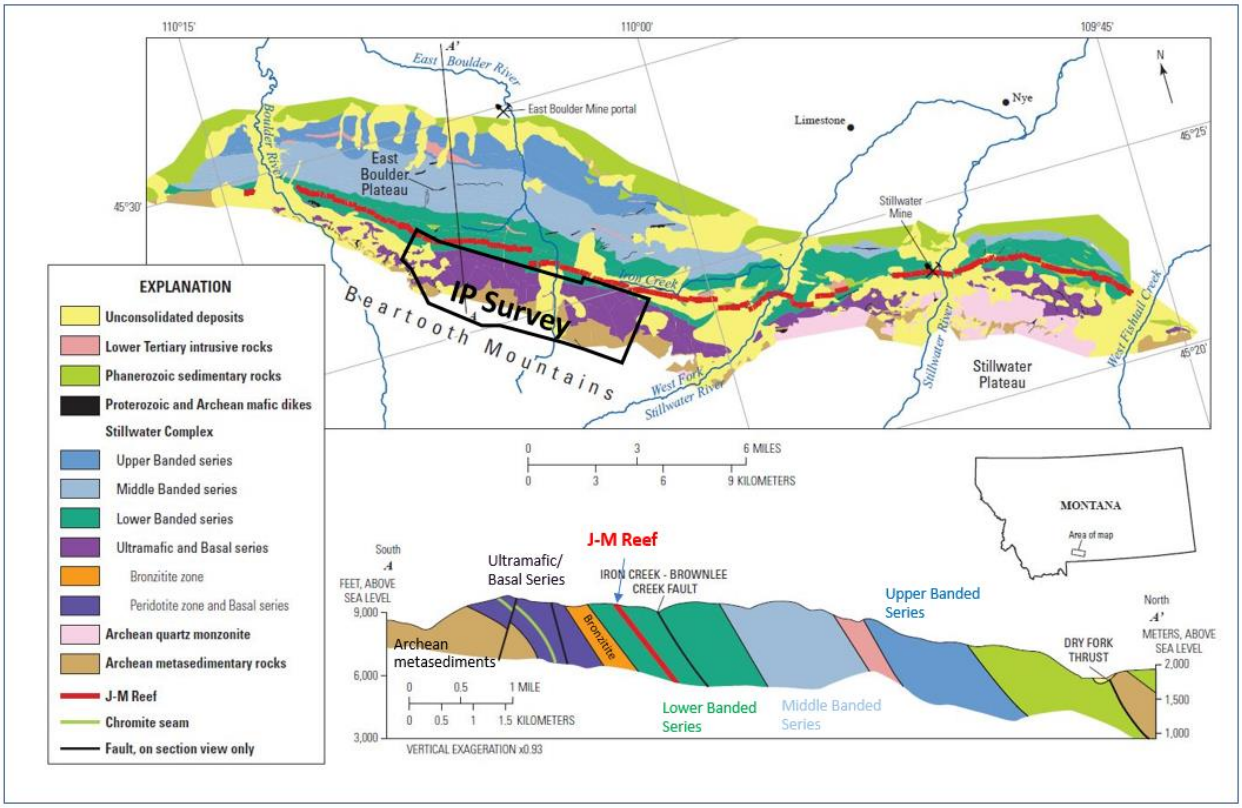


Figure 4: Stillwater Complex geology and the geological section along AA' profile (from Zientek & Parks, 2014); the IP survey area is marked by a polygon.

**Local Geology, Chromitite and PGE Mineralization**

More detailed geological map of the Stillwater West IP survey area is shown in Fig. 5. The area is underlain mainly the Peridotite and Bronzitite members of the Ultramafic Series and the Basal Series of the Stillwater Complex exposed mainly in the Chrome and Iron Mountains, and the Archean hornfels. The hornfels is composed of quartz (0-51%), plagioclase (1-15%), orthopyroxene (10-40%), cordierite (20-76%) and biotite (0-7%). The Basal series locally contains pods or blebs of pyrrhotite, pentlandite, and chalcopyrite. The Ultramafic series also contains chromitite cumulates with subordinate amounts of cumulus olivine, and intrusive dunite and harzburgite cross-cutting cumulate layers.

The compositions and tectonic settings of chromitite deposits through geological time are documented in Stowe 1994. Podiform chromitite orebodies are hosted in peridotites mostly regarded as the remains of obducted ophiolite complexes. They imply ocean spreading at their sites of original crystallization, and plate convergence where subsequently re-emplaced by thrusting. Chromitite deposits range in age from the Archean greenstone hosted in Zimbabwe (~3.5 Ga) to the Miocene (~10 Ma) ophiolite-hosted in New Caledonia. Stratiform chromitite seams of the Bushveld-Stillwater type are hosted in layered mafic to ultramafic complexes within the stable continental shields. Those of economic grade date between about 2.9 and 2.0 Ga. The stratiform chromitite sheets in the Stillwater Complex were emplaced about 2740 Ma (Stowe, 1994) and the mapped chromitite zones in the Stillwater West property are shown in Fig. 5.

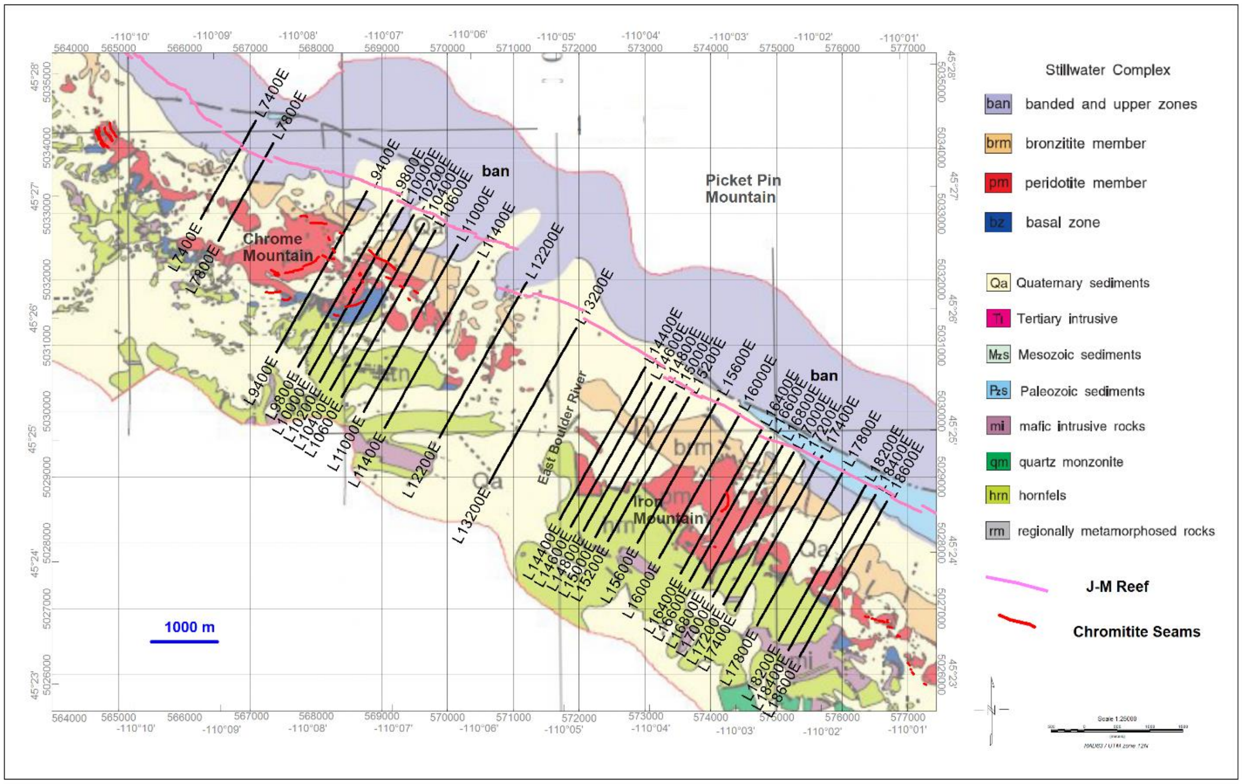


Figure 5: Local geology of the Stillwater West IP survey area (from Page & Nokleberg, 1974), and the IP lines.

The chromitite cumulates in the Ultramafic Series contains mineral-graded layers generally occurring in lower parts of olivine cumulate in the cyclic units, (Fig. 6); the cumulates contain 5-95% chromitite, 0-40% olivine, 1-20% bronzite, and locally host platinum-group minerals with maximum grade of approximately 3.3 g/t (Page & Nokleberg, 1974). According to Talkington & Lipin (1986), The platinum-group minerals are present as inclusions in both disseminated and massive chromitite and distributed randomly within the chromitite host. The PGE mineralization may also occur with silicate and base metal sulphide inclusions in an unfractured chromitite host. The basal chromitites of most of the cyclic units in the Critical Zone of the Bushveld Complex are anomalously enriched in PGE (Cawthorn, 1999).

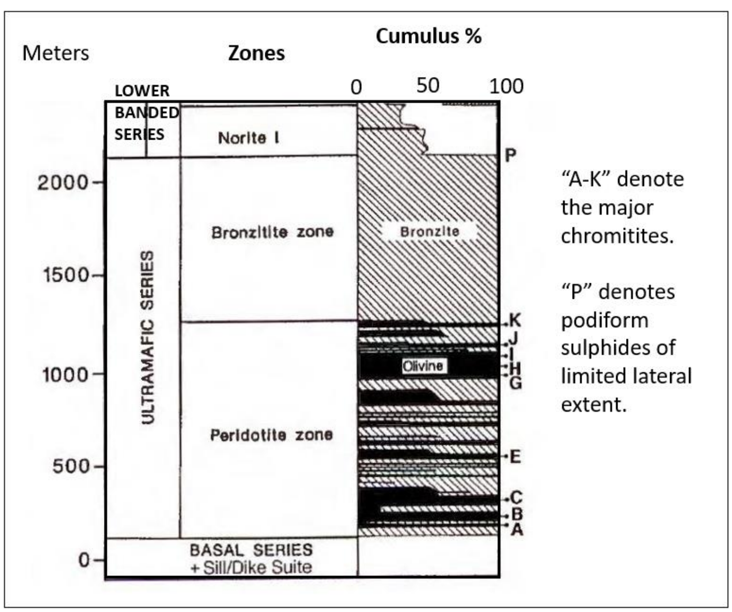


Figure 6: Composite stratigraphic sections of the Ultramafic Series (modified after McCallum, 1996).

The mineralogy of the Stillwater Complex is documented in McCallum 1996. The most abundant primary minerals in the Stillwater Complex are olivine, orthopyroxene, clinopyroxene, plagioclase, and chrome spinel. Minor primary minerals are quartz, amphibole, apatite, magnetite, ilmenite, and sulphides. Sulphides may occur as interstitial minerals in any assemblage of the Stillwater Complex. Olivine occurs as a cumulus mineral in peridotites and harzburgites and is the major constituent in dunite masses. Alteration of olivine in the Ultramafic series varies from the formation of a few veins of serpentine (+ magnetite) to complete replacement of entire outcrops of serpentine + magnetite. The more Fe-rich olivines are from the lowermost cycles of the Peridotite zone while the Mg-rich olivines are associated with chromitites.

The Stillwater Complex contains important reserves of base and noble metals. Sulphide-rich rocks associated with the Basal series, adjacent hornfels, and the lowermost Ultramafic series have been extensively explored for nickel and copper since the later 19th century. Furthermore, Stillwater Chromitite s represent about 80% of the identified chromium reserves in the US, (McCallum, 1996).

**Airborne magnetic and frequency-domain EM data**

Airborne magnetic and frequency-domain eromagnetic data were acquired over the Stillwater West property in 2000 (Rudd, 2000). The geophysical data were provided by Group Ten Metals for this study. The first vertical derivative of the Reduced To Pole (RTP) data are shown in Fig. 7, along with the inferred magnetic highs. Most of the high magnetic anomalies are in the Basal Series and its contacts with the Ultramafic Series and the adjacent hornfels. In general, the magnetic responses are related to the magnetite content in the ground, assuming no remanent magnetization. The magnetite could be resulted from the serpentinization of the abundant olivine in the Ultramafic Series.

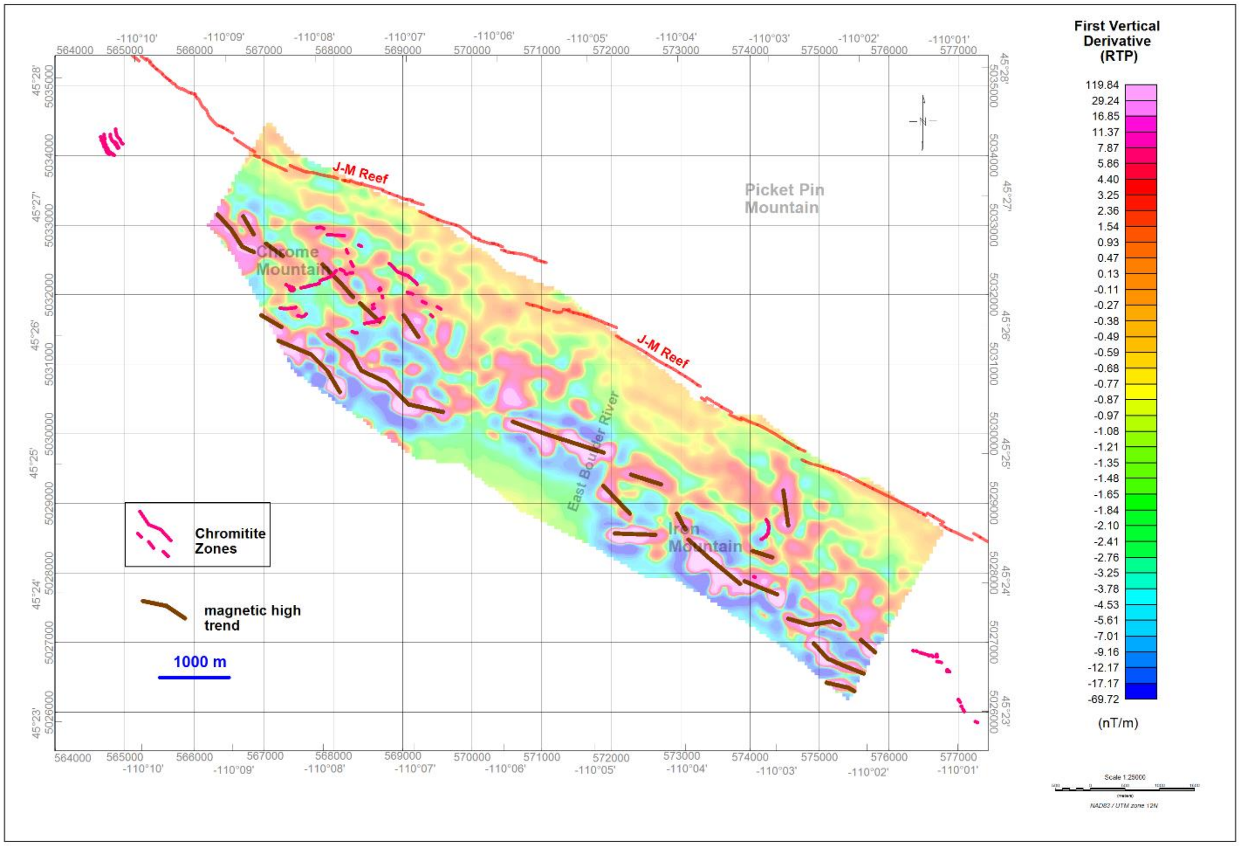


Figure 7: First vertical derivative of the RTP data over the Stillwater West property.

The 900 Hz coplanar resistivity data are shown in Fig. 8. The conductive zones (resistivity lows with hot colors) are located mainly in the Basal Series and its contacts with the Ultramafic Series and the adjacent hornfels. Most of the conductive zones are also coinciding with the magnetic highs. The resistivity lows could be associated with sulphides. The known chromitite zones are located in moderately conductive or resistive terrains.

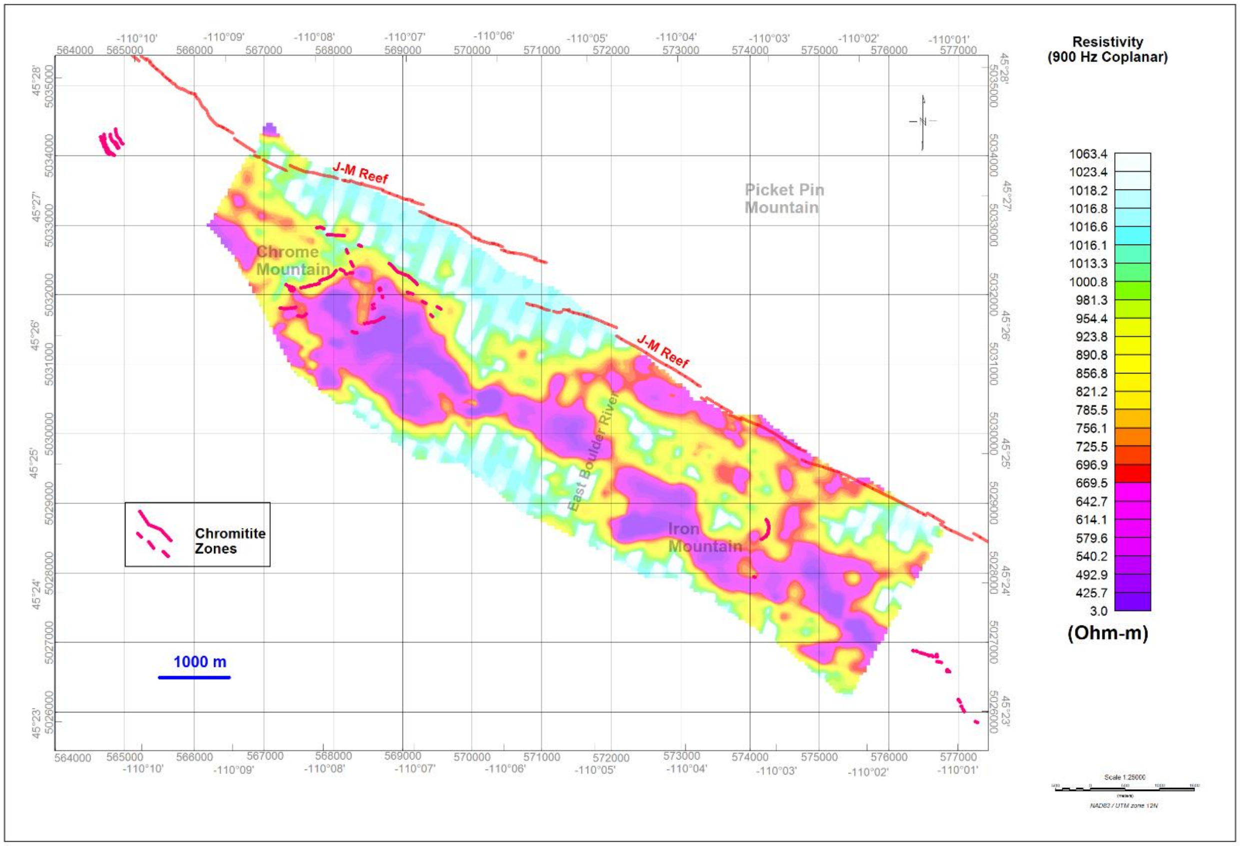


Figure 8: The calculated resistivity from 900 Hz co-planar coils.

**Interpretation of the IP data**

The line L9800E (the fourth line from the western end of the IP survey and on the east side of the Chrome Mountain) overlies, from SW to NE, the hornfels, the Basal Series, the peridotite and possibly the bronzitite zones of the Ultramafic Series (Fig. 5). The geological section underneath the line is shown in Fig. 9. Two priority target zones are the intrusive dunite enriched in sulphides and the hybrid unit enriched in PGE and gold. The sulphides in the intrusive dunite will be very conductive and chargeable. However, the unaltered ultramafic rocks in the hybrid unit hosting chromitite (Fig. 6) are resistive and chargeable.

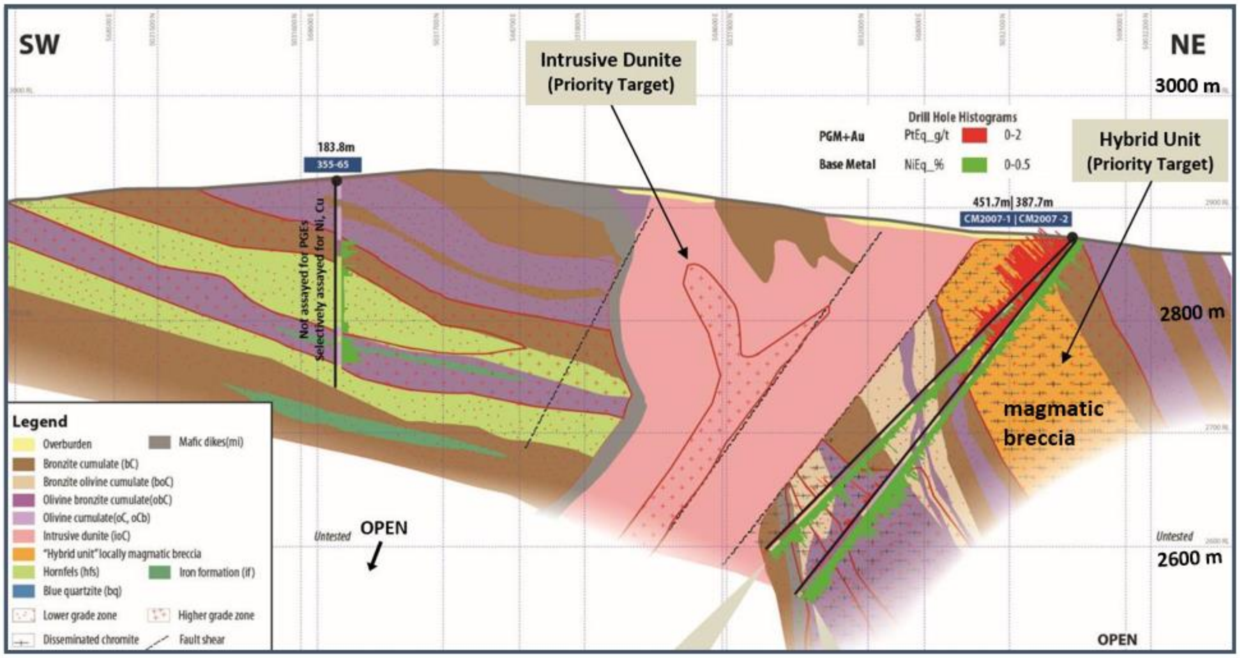


Figure 9: Geological section under L9800E of the Stillwater West property (provided by Group Ten Metals).

The 2D chargeability and resistivity sections of L9800E are shown in Fig. 10. The inferred hybrid unit and intrusive dunite are outlined. The inferred contacts between the major lithological units are also displayed. The intrusive dunite is conductive and chargeable and can be better mapped by the MF data. The hybrid unit is resistive and chargeable, and it can be mapped effectively by the RSC data.

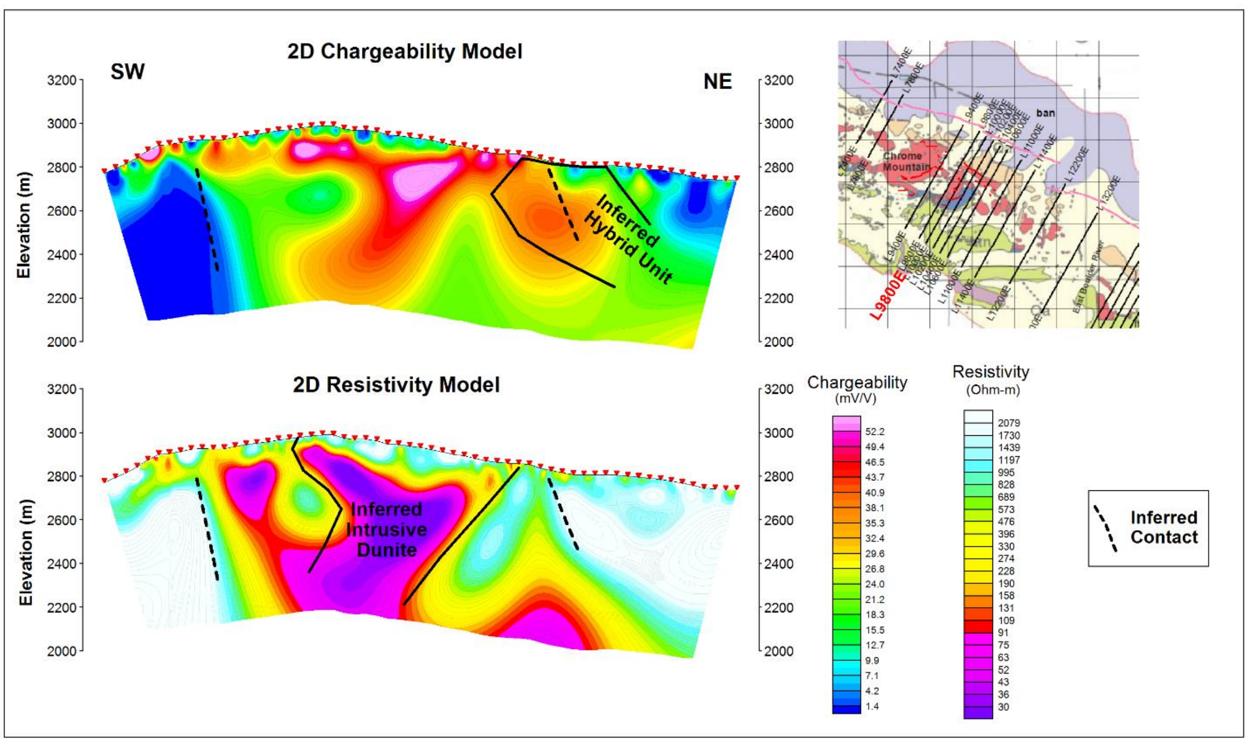


Figure 10: 2D chargeability and resistivity sections, and inferred contacts, Hybrid unit and intrusive dunite.

The RSC and MF data from L9800E are shown in Fig. 11. The inferred hybrid unit has the highest RSC values. The RSC data in the Stillwater West property are used to identify potential chromitite targets in the Ultramafic Series. The inferred intrusive dunite enriched in sulphides has the strongest MF values. The MF data are used to identify sulphide targets in the Stillwater West property.

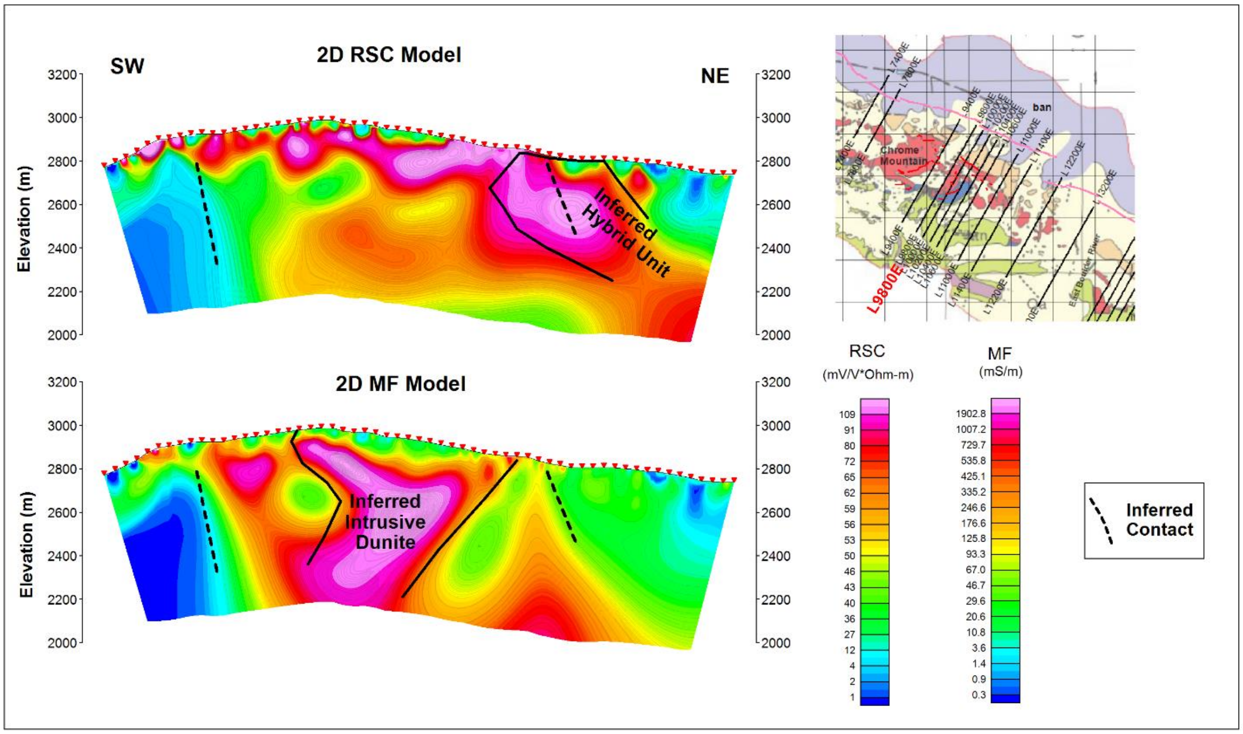


Figure 11: 2D RSC and MF sections, and inferred contacts, Hybrid unit and intrusive dunite.

**The Chromitite and Sulphide Targets**

3D inversions were carried out for two blocks, the western block covered by lines L9400E to L13200E and the eastern block surveyed by lines L14400E to L18600E. Depthslices were extracted from the 3D voxels. The RSC -300 m depthslice overlain with the known chromitite seams and the selected chromitite targets are shown in Fig. 12. The RSC data covers the known chromitite seams in the Chrome Mountain really well. In addition, the data identified two more zones with chromitite potential.

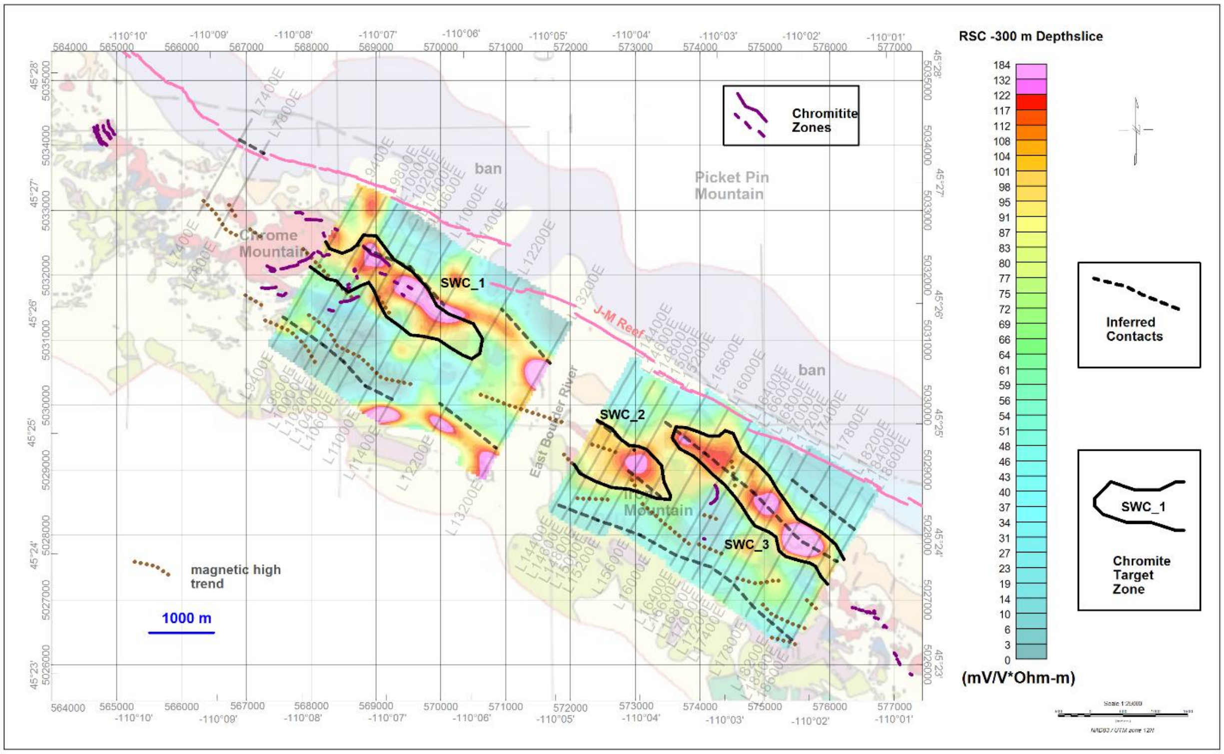


Figure 12: Selected chromitite targets over the RSC -300 m depthslice.

The MF -300 m depthslice overlain with the selected sulphide targets are shown in Fig. 13. The deeper MF -300 m highs are located mostly in the Iron Mountain.

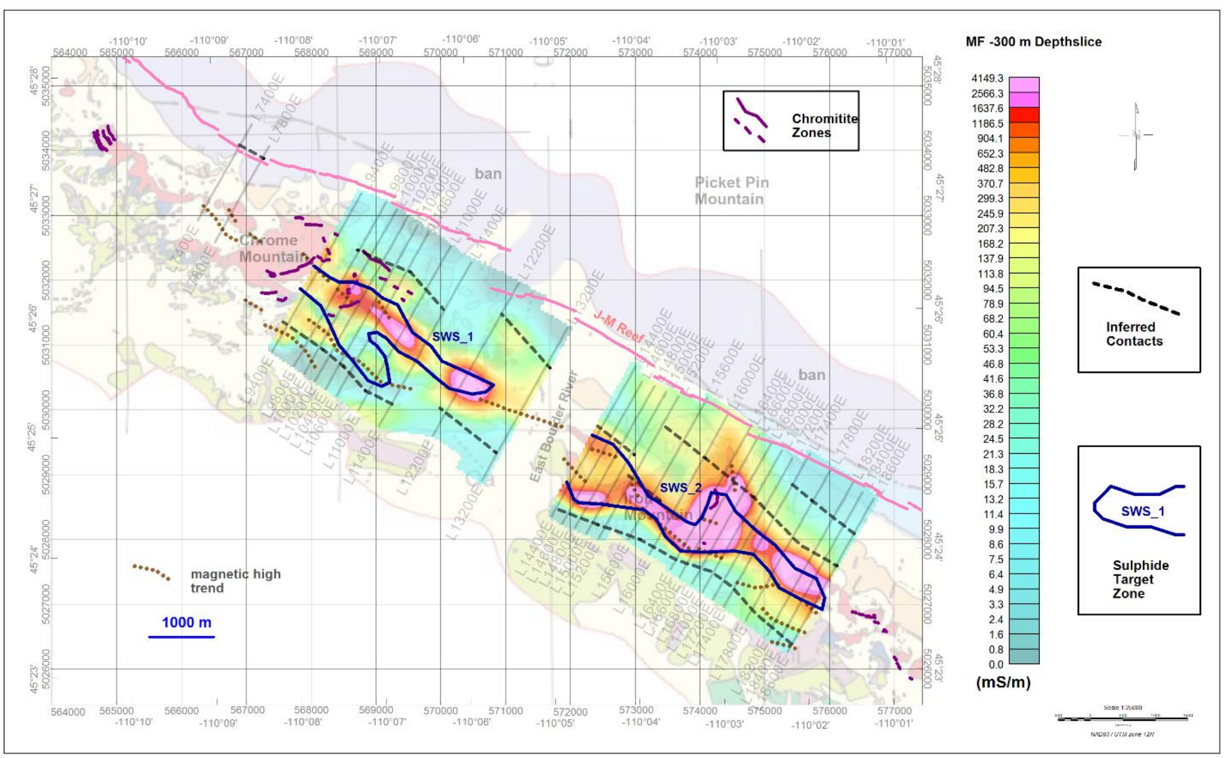


Figure 13: Selected sulphide targets over the MF -300 m depthslice.

**Discussions**

A useful and diagnostic IP parameter that can be extracted from the time-domain IP survey is the relaxation time-constant $\tau$ in the Cole-Cole model (Pelton et al. 1978) shown below.

$$\rho(\omega) = \rho_o \left[1 - m\left(1 - \frac{1}{1 + (i\omega\tau)^c}\right)\right]$$

$\rho(\omega)$: frequency dependent resistivity in Ohm-m.

$\rho_o$: low frequency asymptotic resistivity in Ohm-m.

$m \ (0 \leq m \leq 1)$: dimensionless chargeability.

$\tau$: relaxation time-constant in second.

$c \ (0 \leq c \leq 1)$: frequency factor.

The chargeability $m$ is related to the amount of polarizable material, $\tau$ to the size of the polarizable grains, and $c$ to the distribution of grain sizes, from non-uniform (0) to uniform (1).

The relaxation time-constant $\tau$ alone or in combination with other Cole-Cole parameters, could be used potentially to differentiate the clay (generally fine-grained) from coarse-grained sulphides. The relaxation time-constant $\tau$ has been shown to be potentially useful in the search for Archean greenstone-hosted gold in Ontario Canada by Müller, Kwan & Groves (2021).

The product of chargeability $m$ and time-constant $\tau$ can highlight chargeable zones with coarse-grained polarizable materials. A case is presented by Kwan & Müller (2020) to use $m\tau$ to map the alteration halos around porphyry stocks at Mt Milligan, British Columbia Canada.

# Conclusions

Schodde (2020) pointed out that geophysics can be expected to play a growing role in the exploration for mineral deposits under cover and at greater depths (> 500 m). In order to make it happen, we geophysicists need to provide more relevant and effective geophysical products closely related to geology and mineralization.

In this contribution, we have demonstrated the effectiveness of the RSC and MF data in the exploration for chromitite hosted Ultramafic Series and the sulphides in the Basal Series and the Archean hornfels in the Stillwater West property, Stillwater Complex, southern Montana, USA.

# Acknowledgements

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