Emerging deep penetrating geophysical technologies for exploring under cover. Porphyry and Skarn Examples.

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1. Summary

The oil industry has utilized an image before drilling exploration process for years, with huge success rates, thanks in part to seismic deep imaging capability in sedimentary units. The mineral industry, faced with significantly more complex formations is starting to realize the benefits of advances in data acquisition and data processing and inversion routines that have just evolved over the last 20 years.

The recent advances in deep electrical earth imaging are starting to have a profound impact on our ability to investigate the subsurface prior to drilling. Deep imaging surveys have practical applications for mapping deep structure, alteration and mineralization. In addition the use of these surveys for near mine exploration continues to grow. Mining applications include planning and condemnation studies as well as pre-tailings planning.

A brief discussion of the evolution of deep electrical imaging systems followed actual recent 2D and 3D survey results will be shown from a number of recent discoveries and active exploration situations in Peru, chile and Mexico. Case studies show increased depth of penetration and increased resolution and highlight the ability of these technologies to provide a tangible means for imaging before drilling in many exploration situations.

2. Introduction

Advanced imaging in the medical world developed in the 1950's through the 1970's thanks to new applications of physics to measure key parameters related to internal aspects of the human body. This involved imaging methodologies, and sophisticated software and data manipulation. Damadian was the first to perform a full body scan of a human being in 1977 to diagnose cancer with Magnetic Resonance Imaging (MRI) technology. Today, MRI's are used routinely by doctors to perform investigations and diagnoses prior to any invasive further steps, including surgery.

Advances in the geophysical world have followed a similar timeline. Recently, advances in large scale deep multi-parameter 3D earth imaging technologies are coming close to providing the geoscientist with the equivalent of an MRI. The ORION3D DCIP & MT system provides large scale deep imaging to depths of 800 m for IP and 2000 meters for MT. Large, detailed cubes of information are now available for interrogation and planning prior to drilling.

3. Deep Earth Imaging technology

3.1. Distributed array systems

In the mid to late 1990's there were some early indications showing up in annual mining statistics that highlighted some potential problems in the exploration world. Discovery rates were on the decline. (Figure 1.) There was recognition within the industry that perhaps new deposits may be found in deeper terrains as many of the deposits found to date were nearer to the surface. Although drilling was capable to investigate great depths, associated costs would rise significantly for thorough deep exploration by drilling alone. At the time, most traditional geophysics technology was somewhat depth limited. Several innovative groups recognized a need to provide more effective targeting at depth.

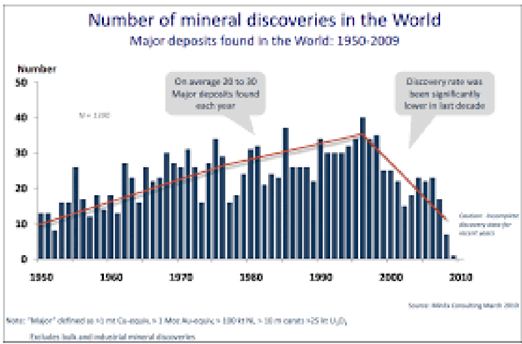

Figure 1. Exploration Discovery rates decreasing significantly from 1990's through 2010. (Shodde, R. 2010)

John Kingman (1994) introduced digital signal processing (DSP) concepts that would require a paradigm-shift in instrumentation. In a (1998) presentation, Sheard et al. while at MIM, introduced the distributed acquisition system (MIMDAS) with time-series acquisition, current-monitoring, available MT and telluric cancelation. In 1999, John Kingman began working with EMI and Quantec to produce the second generation MT-24 acquisition system and the first survey work was performed in August 2000 with the TITAN 24 system. The distributed acquisition approach to geophysical data collection had been commonplace with seismic methods for many years. The multi-channel acquisition approach basically consists of large network of computers and sensors that avoids multiplicity of cables and subsequent capacitive coupling problems, but allows for quick data acquisition and offers noise cancellation benefits. Large array geometries, previously not possible due to noise and signal issues, could now be deployed over great distances (2-5 km). These large geometries or spreads allowed the deeper sensing capabilities of 500 m to 1000 m for IP.

3.2. Advanced 2D imaging [level 2]

The cost of these new surveys were higher due to the new advanced equipment, the sophisticated computing power needed for processing and the large field crew deployment required to carry out the survey. The industry was slow to embrace the technology. Unlike the millenial generation and their phones, the mining industry always requires proof. Eventually, as some very early case studies became avaialble uptake of these surveys began.

Overall, deep 2D imaging has proven to be extremely successful over the last 19 years. Goldie showed the superiority of the methodology for deep IP (figure 2) in 2007. (Goldie 2007).

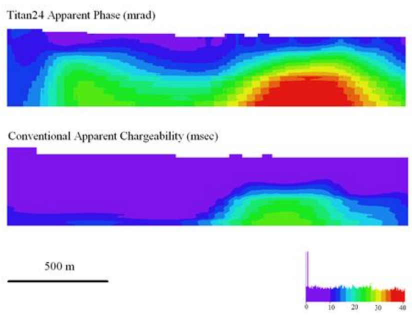

Figure 2. Deep imaging technology vs. conventional technology.

The coupled use of MT being run simultaneously and on very tight centres (100m) provided corroborative information in the top 700 metres but extended the imaging of resistivity down to useful depths of 1500 to 2000 meters and more. (Figure 3 bottom)

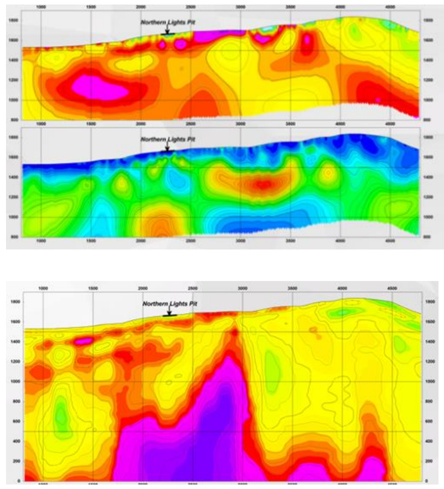

Figure 3. (top) DC resistivity inversion model from 2D TITAN24 distributed array survey. (middle) IP Inversion model. Note how the DC model sees a near surface horizontal layer, senses a second deeper feature and also senses something at the bottom of the section. (Bottom) The MT corroborates the DC in the near surface but pulls out more definition on a sub parallel layer and also highlights the deeper structure central to the area. Data courtesy Newmont, Nevada USA.

However, the 2D paradigm for geophysics has been a significant hindrance over time. Simply speaking a single line of geophysics across the surface does not tell a complete story in terms of the features that exist below that line. This is due, in part to the fact the sensors along the surface also detect information off the line. This issue has been traditionally addressed by running relatively closely spaced parallel lines and making a survey grid. However, line spacing is typically determined by cost considerations vs. geologic significance. Drilling features simply based on information on the lines, led to many unanswered questions and drill holes that have missed targets. (See figure 4.) The advent of borehole EM methods has addressed the issue with respect to strong conductors existing off section and off hole, however, borehole IP methods have not advanced to the same level.

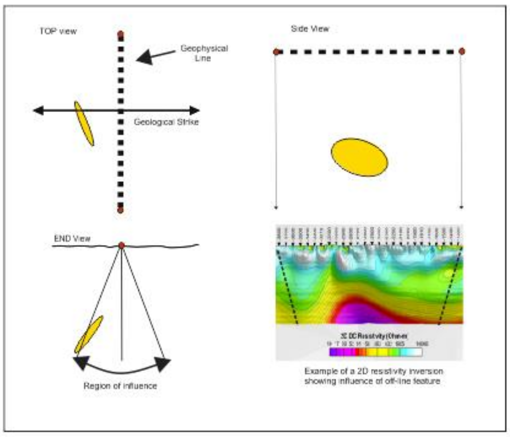

Figure 4. Example of 2D interpretation. The target which exists off the line occurs as a "false" anomaly on the section.

3.2. Advanced 3D imaging

With the advances in 3D data inversion techniques in the early 2000's for single point data collection techniques such as Mag, Gravity and subsequently IP & MT the natural progression was to develop methodologies for collecting full 3D DCIP data to address limitations in 2D data acquisition techniques as described above. The development of this new technology was based the solid and proven foundation of the 2D multi-parameter TITAN 24 distributed acquisition system which was introduced in 2002. (Gordon 2006). The new 3D technology called ORION 3D was the first distributed acquisition multi-parameter (DCIP&MT) technology system. (Sharpe 2017).

There are several unique features of the system including a large footprint of 2 x 2 km which helps to optimize DC and IP depth of investigation in the 600 m to 900 m depth range as well as an equal number of in-line and cross-line receiver dipoles that maximize coupling with any target.

True 3D is defined to mean acquisition where receiver electrodes sample the current in orthogonal directions across a grid with a very large number of receivers (300). The receivers are deployed (using a DAS) to optimize the footprint geometryand allows for simultaneous readings for every current injection. This results in a true omnidirectional coverage for each current injection and gives multiple intersecting current paths over the entire survey with a very large number of data points acquired. The overall result is an enormous volume of data which lends itself to a better coupling with complicated 3D geology and structure which enhances resolution and target detection at both shallow and deep depths. The omnidirectional coverage provides a better 3D inversion result because there is no acquisition directional bias and each cell in the inversion volume is sensitive to multiple omnidirectional current paths.

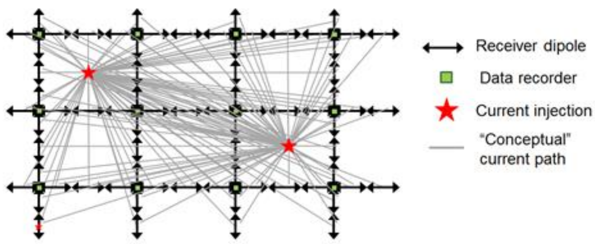

Figure 5 *An example of a 3D deployment of receivers with conceptual current paths for 2 injection points. All receivers will continue to collect data from 100's of additional current injections.*

3.2.1. 2D vs. 3D

The ability to collect more data from all different angles has increased the ability of these geophysical tools to accuratly depict the distribution of physical properties within the subsurface. The volume of data is significantly more as shown in Figure 6.

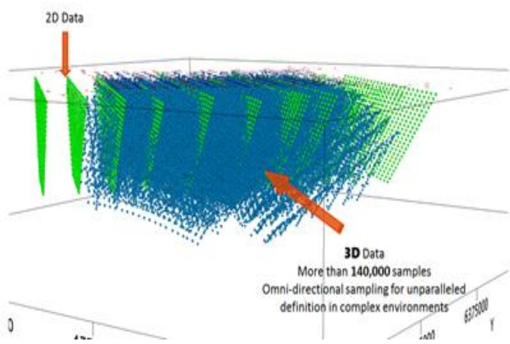

Figure 6 Data points gathered by a deep 2D survey deployment (green) and a 3D deployment of a distributed acquisition system (blue) .

The increase in data volume coupled with the omnidirectional sampling provides the basis for highly data constrained 3D inversions. When the data is inverted we see what in some terrains can be stark differences. In Figure 7 we see significantly more detail extracted from the full "3D" survey.

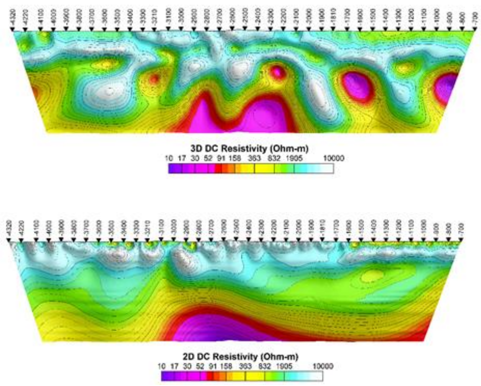

Figure 7. Resistivity inversion models (sections) Depth of the section is roughly 800 meters.(Top) 2D section sliced from a 3D inversion model of 3D data. (Bottom) 2D resistivity section from 2D inversion of single line of receivers.(2D data)

4. Recent Exploration Case Examples of Deep Earth Imaging

Although 2D applications of these technologies have been around since the early 2000's, the industry has been a bit slow to adapt across the board. To many companies the upfront cost of these surveys seems high compared to what they are used to considering during the budget process. However, more and more cases are showing, over time, that upfront imaging has many benefits for explorers. As drilling becomes more effective, success rates should increase. Both 2D and 3D examples of deep imaging has applications across the commodity spectrum.

4.1. Bolivar skarn mineralization exploration

4.1.1. Background and Geology

Sierra Metals owns 100% of the Bolivar mine located in state of Chihuahua, Mexico, Bolívar is a copper-silver-gold underground mine using room-and-pillar mining method. (Figure 8). The property comprises 12 mining concessions covering approximately 6,616 hectares within the municipality of Urique, in the Piedras Verdes mining district of Chihuahua, Mexico. Sierra Metals purchased the claims for the Bolívar Mine between 2003 and 2004, and has conducted mining activities at the Bolívar Mine since February 2005. Bolívar is a district-scale property considered prospective for new discoveries of precious metal and bulk-tonnage copper-skarn deposits.

Figure 8. Bolivar Mine location and local terrain conditions, Northwest Mexico.

The Bolivar Property is situated within the Piedras Verdes Mining District, which is within the major north-northwest trending Sierra Madre Precious Metals Belt extending across the states of Chihuahua, Durango and Sonora in northwestern Mexico. Late Cretaceous – Early Cenozoic sedimentary and volcanic rocks underlie the district (Lower Volcanic Series or "LVS").

Skarn-type Cu-Zn-Ag-Au mineralization in the Bolivar area is structurally controlled and forms mineralized zones that are close to structures. Mineralized zones occupy pre-existing fault structures and extensional openings formed during mineralization. The mineralized zones are dominated by calc-silicate minerals and variable quantities of quartz, calcite, and chlorite. Sphalerite and chalcopyrite are the predominant sulphides, commonly ranging from 5% to 30% (combined), with occasional massive sulphide zones. Sulphides occur within the carbonate rocks, which they replace, a common feature in skarn-type mineralization.

4.1.2. Exploration History

At Bolivar, small-scale mining was conducted during the Spanish Colonial days and then Minera Frisco conducted a mapping and exploratory drilling program from 1968 to 1970. Between 2003 and 2012, Dia Bras carried out an exploration program and the results have shown presence a polymetallic skarn mineralization within the Bolívar. In 2010 first deep survey was carried out with DCIP, however, the orientation of the lines focused on the eastern portion of the mine property. In 2014, underground drilling expanded the copper-gold-silver mineralization.

In 2017, the survey was re-oriented and MT was added for drill targeting in the immediate vicinity of the Bolivar mine. (Figure 9).

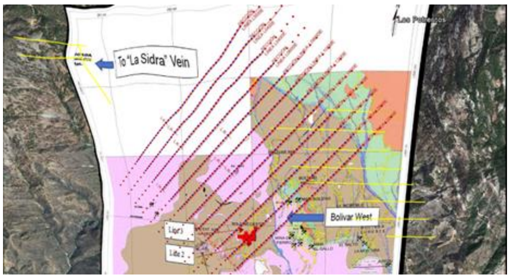

Figure 9. 2017 survey plan in red for DCIP&MT. 2010 survey in yellow lines. The Bolivar survey grid consisted of a total of 12 lines which were 26.5 km in length. Each line had a 100 m dipole spacing and was located 200 m from the line adjacent. The survey covered an area of approximately 2.4 km by 2.2 km.

The results of the survey were extremely useful for targetting. Figure 10.

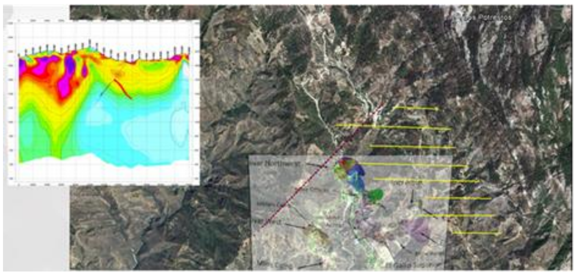

Figure 10. Line 1400 , with MT resistivity shown

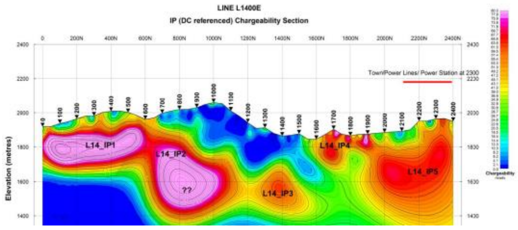

Figure 11. Line 1400 with chargeability shown.

Subsequent drilling over this region was very successful.

- 12 drill holes have been executed in the area where a Titan 24 program identified geophysical anomalies
- Drilling identified a new wide high-grade copper structure which extends the continuity of the Bolivar Northwest structure by an additional 400 meters
- Average grade of intercepts is 1.37% copper with an average true width of 8.1 meters

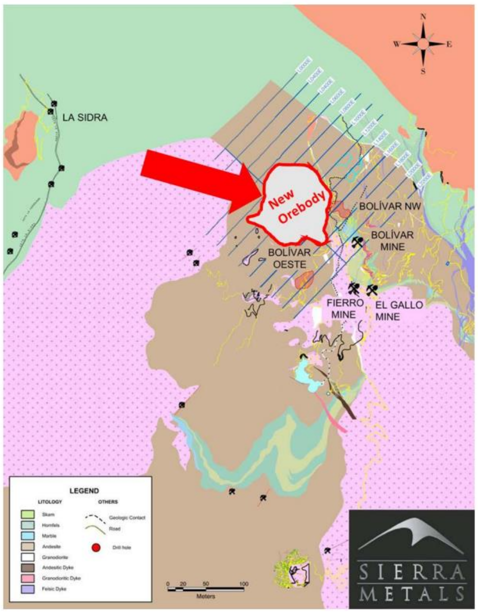

Figure 12. New extension of Bolivar NW Orebody.

Alonso Lujan, Vice President of Exploration, stated: "The areas tested in the Titan 24 survey demonstrated an excellent relationship between chargeability and the structures. Based on those results, the Company continued to test these areas with drilling programs. This has resulted in the definition of a new structure which demonstrates the continuity of previously defined wide, high-grade, copper structures. The Company plans to drill an additional six to seven holes, approximately 2,500 meters, within this area in 2019. Depending on success further holes and drilling could be added. Further to the success at the West Extension, the potential for further extensions to the North of this zone remains open."

These large scale data sets, typically collected over 3 - 4 weeks, provide companies with an active repository for continued and ongoing exploration. The survey, acquired in 2017, provided over 50 areas of interest and targets.

Considerations for exploring in brownfields must be recognized. This includes detailing cultural issues and careful planning and coordination with minesite personell. High levels of safety standards and protocals must be in place and recognised.

4.2. 3D Imaging at Santa Ceclia, Copper Porphyry

The Santa Cecilia Porphyry Copper-Gold deposit is located in Chile's Third Region in the high Western Cordillera at an elevation of 4400 m ASL, and lies within the well-known Copper-Gold-Silver Maricunga Belt [1]. Following a helicopter-borne reconnaissance survey done by Mario Hernandez and David Thomson over the Santa Cecilia project area in 1983 a merit to further explore this area was justified. Anglo American Chile (AAC) conducted an aggressive exploration program including geochemical sampling and diamond drilling, and from shallow holes they intercepted low grade Cu-Au-Ag mineralization, but dropped the option in 1990 [2].

Mining exploration within the property resumed in 2009, when a ground magnetic survey conducted by Quantec Geoscience precisely delineated the peripheral alteration zone as a magnetic low-gradient area. Later, a CSAMT survey mapped a strong conductor centered on the main alteration zone, confirming the Au and Cu geochemical anomalies obtained from an MMI survey conducted at the same time. Drill testing of the CSAMT conductor and the MMI anomalies confirmed the presence of continuous Cu, Au and Mo mineralization over 1000m.

To further delineate and map the alteration and extendt of the discovery, a deep comprehensive 3D survey was carried out over Santa Cecilia in 2012. In this case a broad area was covered (3km x 7km) using 150m dipoles for the IP survey and 300m centres for the MT survey. The survey used 50 Data loggers, 300 receiver dipoles and 559 current injections. The survey took 4 weeks to complete at a cost of $400,000.00 US. Resistivity and chargeability models are shown in Figure 13. The DCIP data has been inverted using UBC 3D DCIP inversion code.

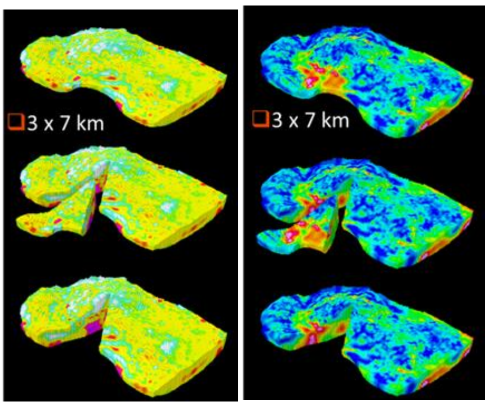

Figure 13 *Santa Cecilia ORION3D survey results. DC resistivity left, Chargeability right.*

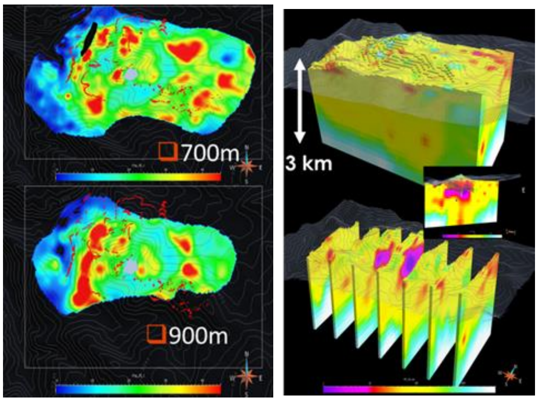

Figure 14 *(left)Chargeability slices at 700 and 900 meters depth.(right) 3D MT Inversion model shown at right to a depth of 3 km.*

The results have provided an accurate delineation of deep seated alteration zones that host the mineralization. The 3D DCIP results gave a detailed insight of the area to a depth of approximately 1000m, and the MT results suggest a significant extension of the deep alteration zone laterally and vertically. The down-dip extension was estimated as over 2km.

4.3. Charcas 3D Exploration

4.3.1. General Geology Charcas District

The mining district of Charcas is located in the NE part of the physiographic province of Mesa Central, near the western boundary of the Sierras Bajas subprovince of the Sierra Madre Oriental. (Raiz, E. 1964). In general, the area is characterized by the presence of small elongated hills that vary to rounded with form where marine rocks from the Triassic to the Upper Cretaceous emerge, which are intrusive by plutonic bodies of the tertiary. (Figure 15).

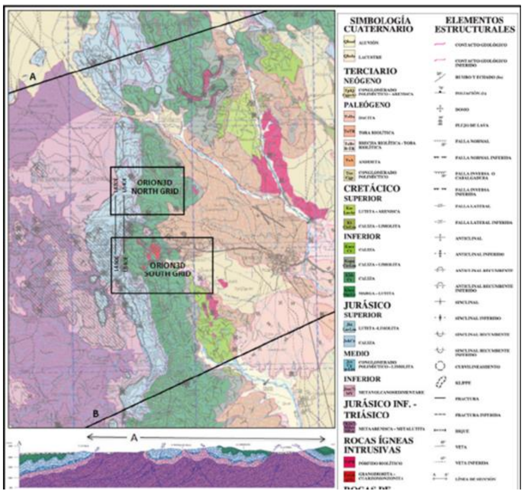

Figure 15. Regional Geology Charcas District, Mexico.

The oldest rocks that make up the basement are represented by the Zacatecas Formation of the middle and upper Triassic, which is why this formation is also known as Triassic of Zacatecas and corresponds to a rhythmic alternation of shales, siltstones and sandstone that underwent metamorphism. Figure 16 low grade and appears in dark gray to greenish, considered a flysh type sequence. Mc Gehee (1976)

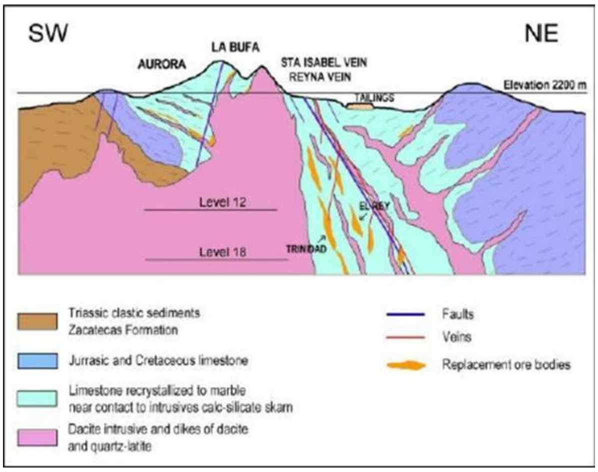

Figure 16. Cross section at Charcas, Mexico

4.3.2. Recent Exploration utilising 3D Deep Earth Imaging

In the exploration of the Charcas project several geophysical methods have been applied; mainly aerial magnetometry in 2009 and terrestrial magnetometry in 2007. Geoelectric studies (IP and Resistivity) were carried out in the years 2001 and 2006. These methods served to detect and delimit the development of the different zones of alteration, as well as to detect and delimit zones related to mineralization up to about 250 m deep in areas such as Santa Rosa, La Blanca, Manganeso, South Falla Norte, Plomosas, Las Eulalias and Las Palmas.

The results of the drilling and the progress of the exploration showed some ambiguity between the geophysical and the geological model; on the other hand the perforations revealed that the mineralizations are located at great depth. Taking into account the depth of the site and the high risks of planning deep drilling, a study with ORION 3D technology was requested, which could potentially allow the detection of new mineral bodies in the vicinity of the mine.

The purpose of the survey was multifold. One important aspect was to characterise the known minerisation in the area of the mine. This is idealy done right at the time of discovery, where a complete survey can be done around an initial discovery to help test the overall size and shape of an orebody, to provide condemnation imaging and to potentially guide resource drilling. In this case, the mine and development was already in place, so that it meant that the survey would have challenges due to electrical noise and culture. However, sophisticated processing and oversampling allows systems like these to provide good quality images in most noisy environments.

The distribution of receivers throughout the entire study area allows obtaining data in all directions simultaneously. Figure 17. The omnidirectional data collection eliminates any bias depending on the direction in which the study is conducted.

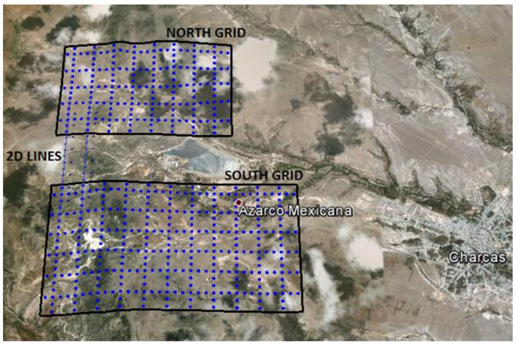

Figure 17 shows the design of the ORION 3D study for the Charcas project. This design made it possible to obtain IP data and DC resistivity up to 1 km depth and up to 3 km of MT resistivity.

The DCIP-MT study on the Charcas Project was completed using three blocks of Orion 3D, covering an area of 2.9 km x 1.8 km to the north and 4.0 km x 2.2 km to the south. The study was carried out in a P-DP configuration with 120m dipoles and with current injection points distributed at nominal distances of 120m to 180m following a pattern of optimizing data coverage.

The inversion models of DC resistivity, MT resistivity and IP chargeability for the North block are presented as Geosoft voxel volumes in Figures 18,19 and 20.

The results from the Northern Block are discussed here.

In the resistivity model (figure 17) the main contacts and fault zones are highlighted, which have conductive signatures. A prominent NW-SE fault zone is evident in the resistivity model from the presence of a low resistivity anomaly extending from the SE boundary to the NW side of the study grid. This conductivity anomaly coincides with the so-called Charcas-Plomosa fault zone. Numerous conductive anomalies have been detected, which represent a highly deformed tectonic framework associated with the Laramide orogeny and late intrusive regime. At the 1800m elevation, the distribution of resistivities shows a sub-horizontal conductive zone with related chargeabilities; this characteristic could indicate the presence of mantle-like bodies, where alterations parallel to the stratification planes occur. (Figure 18)

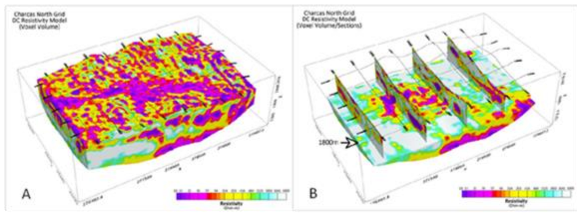

Figure 18. Resistivity model North Block, left. Level plan in resistivity model shown at 1200m

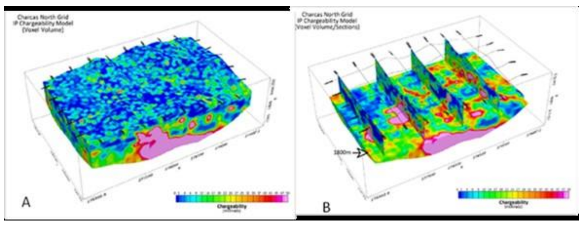

Figure 19 Chargeability model, North Block (left)

The resistivity data MT (Figure 20) shows the conductivity anomaly that represents the main NW-SE fault zone, similar to that observed in the DC resistivity maps. This model is used to map the roots of the system and the presence of a large conductor in the eastern area of the project is evident (Figure 20 B).

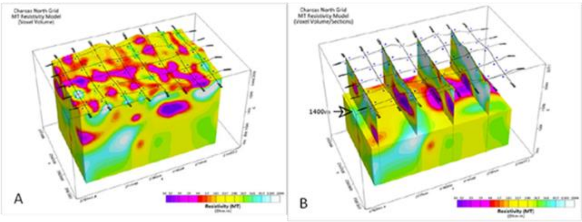

Figure 20 North Block. A- 3D inversion resistivity MT. B-Plan at 1400m elevation with selected cross sections NS.

Overall, this exploration approach provides both short term specific targets for immediate follow-up plus additional deep terrain information that can assist with the overall geological conceptual models that exist. At Charcas , a summary of the survey included;

- Reliable deep and high resolution data obtained in extremely noisy Charcas mine environment
- Good correlation between geophysical data obtained and available drill information
- Main geological and structural features located and delimited at distance of 2 km around mine
- 76 new drill targets identified by survey

Large scale exploration data volumes can provide a repository for knowledge that can be interogated for years. Typical costs are in the $400,000.00 dollar range for such imaging, which although significant, is very little compared to drilling budgets that can range in the 10’s of millions of dollars and are still drilled on very little hard data.

5 Conclusions

With deposits being found deeper and deeper, the industry has been struggling to match the pace of discoveries in the recent past. Geophysics, as a tool is one of the only ways to cost effectively provide key physical rock property information about the subsurface to great depths. Inevitable ambiguities of what exactly the surveys are sensing remain a challenge but can be assesssed though planned and cost effective drilling.

Today, new emerging technologies coupled with existing methods of imaging are providing explorers with new models and images of the subsurface that help focus drilling efforts. Overall, users of the technology are seeing huge benefits with more effective and successful exploration. Vast regions on the km scale can now be pre-emptively imaged prior to intensive drill programs thereby saving time and money. When used in the right districts and on the right prospects discovery rates should rise.

The Santa Ceclia study shows the power and place of these technologies right at the initial discovery stage; a. to map out further drilling b. to guide potential resource drilling. These technologies also have a place prior or during feasibility to provide effective ground condemnation, planning for tailings and additional imaging for further exploration, once the mine is going.

We can now collect large km scale multi-parameter data cubes of 4 or 5 parameters in as little time as a month. The industry can now thoroughly interrogate the data volumes for probabilistic occurrences prior to any drilling. Other advances in technology such as machine learning are well suited to deal with large data volumes and promise to advance the industry even further in the coming years.

Thanks

The author wishes to acknowledge Sierra Metals, Grupo Mexico and Minera Santa Ceceliafor help and use of the data examples. I wish to also acknowledge the vast array of people that are involved in the data acquisition and processing portions of these surveys. They have contributed significantly over the last 19 years to continuously improve survey logistics, QA/QC, processing routines and suggestions, all of which have contributed greatly to the overall accuracy and quality of the information. In many cases the field people do not get to appreciate the excitement of the follow-up drilling. These people are all an essential part of our exploration industry.

References [last names in lower case]

Sharpe, R.[1], Gordon, R.[1], Zhurba, A. [1], Data, E. [1], 2018. A decade of technological advances in distributed IP & Resistivity. Why it was needed. What was achieved.

Gordon R, 2006, New technology approach needed for mining industry. First Break, Vol 24, July 2006.

Goldie M, 2007, A comparison between conventional and distributed acquisition induced polarization surveys for gold exploration in Nevada: The Leading Edge PP 180-183

Kingman J, 1994, Digital signal processing approaches to interpreting induced polarization data: John S. Sumner memorial international workshop on IP in mining and the Environment, Tucson AZ

Thomson D, 2010: Santa Cecilia Project – geology, Geophysics and Geochemistry 1985 to 1990 and 2010. Report for Minera Santa Cecilia.

McGehee, R.V., 1976, The Metamorphic Rocks of La Pimienta Stream, Zacatecas, Zac .: Boletín de la Sociedad Geológica Mexicana, 37 (1), 1-10.

Raisz, E., 1964, Landforms of Mexico, Geography branch of the Naval Research office, second edition, Cambridge, Mass. Plano de Provincias Fisiográficas.

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Leduar has 15 years of experience in exploration on Geothermal, Mining and Oil Industry, working in a wide variety of geologic and exploration environments. His main expertise is designing and developing exploration programs, from area selection to target definition and field evaluation, based on innovative concepts and ideas. He also has broad experience in interpretation of geophysical data as it relates to geology. As the Senior geologist for Quantec he has have been involved with many projects across the Americas, achieving excellent results in several exploration surveys. He has worked in several countries of America including Argentina, Chile, Brasil, Bolivia, Cuba, Colombia, Peru, and Mexico.