

# Comparison of 3D conductivity imaging from multiple EM surveys

## Douglas Oldenburg

Geophysical Inversion facility  
University of British Columbia  
6339 Stores Road,  
Vancouver, Canada  
doug@eos.ubc.ca

## Robert Eso

Geophysical Inversion facility  
University of British Columbia  
6339 Stores Road,  
Vancouver, Canada  
reso@eos.ubc.ca

## Scott Napier

Mira Geoscience  
409 Granville Street,  
Suite 512 B,  
Vancouver, Canada  
scottn@mirageoscience.com

## Nigel Phillips

Mira Geoscience  
409 Granville Street,  
Suite 512 B,  
Vancouver, Canada  
phillipsn@mirageoscience.com

## SUMMARY

It is now possible to invert frequency and time domain data to recover 3D conductivity models. The San Nicolás deposit makes an ideal test site because much is known about the deposit and also many different types of survey data have been collected there. In particular DC resistivity, 3D controlled source frequency domain data, and UTEM data have been acquired. We have inverted each of these data sets. In this talk we describe the data sets and the methodologies for inversion and compare the resultant models. The DC resistivity data were not able to see the deposit because of the conductive overburden, but both the frequency and time domain inversions produced a good image of the primary mineralized zone.

**Key words:** DC resistivity, electromagnetics, inversion, case history, UTEM, CSAMT

## INTRODUCTION

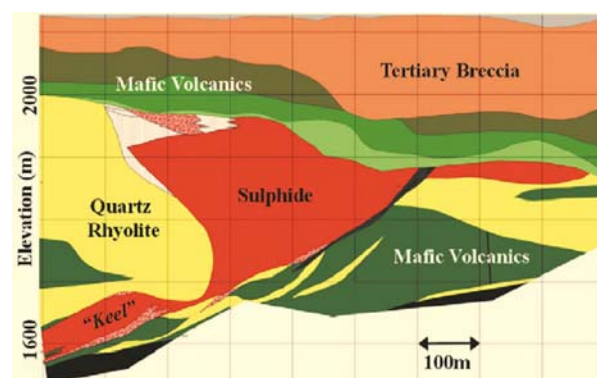
Advances in forward modelling and inversion coupled with the increase in computing power over the last decade have made the 3D interpretation of electromagnetic measurements a feasibility for geophysicists. The 3D inversion of DC resistivity has been available for over a decade and 3D inversions of electromagnetics measurements are moving from the research arena to being applied on field data sets by practicing geophysicists.

The San Nicolás deposit is a relatively well explored massive sulphide deposit in central Mexico. The deposit has been host to several geophysical surveys including gravity, magnetics, DC, IP, airborne TEM, airborne FEM, UTEM and CSEM. The deposit has also been extensively drilled. The abundance of data, coupled with 3D inversion methodologies, allows us to generate numerous 3D physical property models for the deposit, and compare the inversion results with lithological knowledge of the deposit derived through drilling.

Here we will concentrate on the geophysical surveys that are sensitive in variations of the electrical conductivity and can be inverted in 3D, namely DC resistivity, UTEM and CSEM. We first outline the physical characteristics of the San Nicolás deposit and discuss details of the geophysical surveys and interpretation techniques. Conductivity models from the various surveys are computed and compared. We conclude with remarks about the resolving power of the experiments and survey design.

## THE SAN NICOLÁS DEPOSIT

San Nicolás is a Cu-Zn massive sulphide deposit located in central Mexico in the state of Zacatecas. The deposit is a continuous but geometrically complex body of sulphides which is covered by 175-250 meters of variable composition overburden. Although unmined, the deposit is known to contain ore-grade copper and zinc, with some associated gold and silver. The local geology is also complex and contains numerous sedimentary and volcanic units. The deposit has also been thoroughly drilled and, as a result, the geology and physical properties of the deposit are reasonably well understood. A geologic cross section over the main deposit is shown in Figure 1. Table 1 provides a summary of typical values of the various physical properties of the deposit and its hosts.



**Figure 1. Geological cross-section of the San Nicolás deposit showing the main massive sulphide body and surrounding host rock geology**

The sulphide deposit presents a conductivity contrast with most of the geologic units in the area. However some of the overburden, the tertiary volcanic breccia, has a conductivity in the range of that found in the sulphide. This conductive overburden will act to shield the deposit from electromagnetic exploration methods. The relatively deep deposit and the presence of conductive overburden make imaging the San Nicolás deposit a challenge for electromagnetic geophysics.

The extensive drilling and interpreted geologic sections has resulted in a 3D rock model. Physical property measurements and geological interpretation have been used to create a 3D conductivity model of the deposit.

Unit	Density (g/cc)	Susceptibility (S.I. $\times 10^{-3}$ )	Resistivity (ohm-m)	Chargeability (msec)
Qal	2	0-10	50	5
Tv	2.3	0-5(20)	20-30	10-30
Mst./Lst.	2.4	0	150	20-40
Mafic Vol.	2.7	0-5	80	30-50
Mafic/Int Vol.	2.7	0-5	80	30-50
Sulphide	3.5	10	20	200
Qtz. Rhyolite	2.4	0-10	100	10-20
Graphitic Mst.	2.4	0-5	100+	30-70

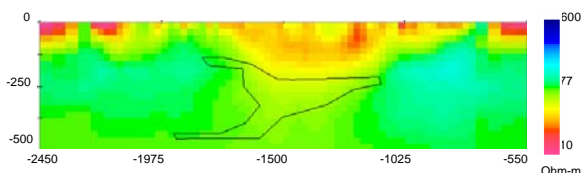
**Table 1. Physical property information obtained through analysis of core samples**

The combination of a 3D geologic model, quantitative petrophysical information and a suite of geophysical surveys over the deposit create a valuable benchmarking environment in which to test and compare the resolving capabilities of different geophysical techniques.

### DC/IP MEASUREMENTS

Gradient and real-section arrays of DC resistivity (DC) and induced polarization (IP) data were collected over the deposit. In the gradient array, the transmitter electrodes were 900 meters apart. The potentials were measured using a dipole spacing of 20 meters in lines co-linear with the transmitter. The line spacing was 100 meters.

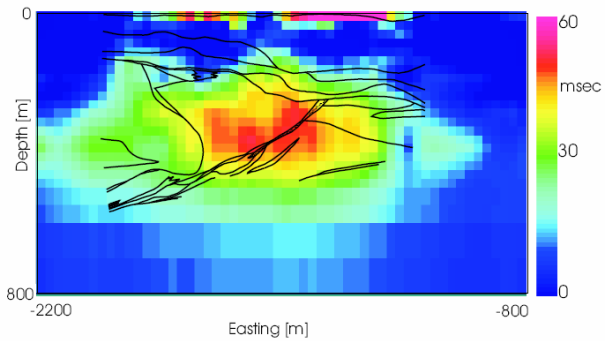
The real-section data were collected in a similar manner, with potentials measured using 25 meter dipoles. In this case however, the transmitters were successively reduced to obtain the "real section" data. The gradient array and real-section data were simultaneously inverted in 3D using the algorithm of Li and Oldenburg (2000). The resulting combined dataset contains 9 lines and 1182 individual measurements.



**Figure 2: DC Resistivity inversion of gradient and real-section measurements**

The DC resistivity inversion is shown in Figure 2. An outline of the main massive sulphide conductor is superposed on the image. The resistivity data are only resolving the surface conductor, and it is likely that the conductive tertiary overburden is preventing currents from penetrating into the deposit. The conductivity values corresponding to the overburden recovered from the 3D DC resistivity inversion are between 10 and 40 Ohm-m. This agrees with the overburden conductivity derived through sample analysis in Table 1.

The IP measurements (related to the imaginary part of the electrical conductivity) were also inverted in 3D and a 3D chargeability model is shown in Figure 3. There is highly chargeable material in the vicinity of the massive sulphide deposit.



**Figure 3: IP inversion of gradient-array and real-section IP measurements**

The thin layer of highly chargeable material at the surface may in part be real but some of the structure is likely due to an electrode-artefact, arising from model cells located in close proximity to measurement locations.

### ELECTROMAGNETIC MEASUREMENTS

Ground based frequency and time domain electromagnetic measurements were collected over the San Nicolás deposit. Typically, electromagnetic measurements have been interpreted using reduced dimensionality (i.e. 1D or 2D models), or by parametric models (i.e. spheres, plates, or other geometric primitives). Here a full 3D forward modelling and inversion scheme is used to interpret the San Nicolás measurements.

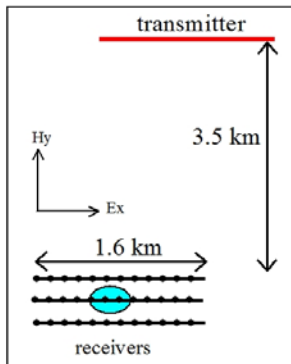
Maxwell's equations are discretized using a finite-volume formulation on a staggered grid using a potential formulation described in Haber and Ashcer (2001). The resulting sparse linear system of equations is solved using conjugate-gradient methods. In the time domain, Maxwell's equations are discretized in both time and space and the initial conditions are propagated through time using a backwards differentiation formula. The inversion algorithm uses a Gauss-Newton approach to minimize an objective function that measures both the size and complexity of the resulting conductivity. The inversion methodology for frequency and time domain data are described in papers Haber *et al.* (2004) and (2007).

A challenging aspect of interpreting electromagnetic measurements in 3D arises from the large domain that must be discretized in order to form an accurate forward model that honours the prescribed boundary conditions. In the time domain, the discretization must be sufficiently fine such that fields are accurately modelled at early times and very small diffusion distances, but must contain a very large volume such that the fields do not interact with the boundary at late times. A similar situation is faced in the frequency domain.

The net result is that the numeric mesh must contain a large number of cells far away from the region of interest. A corrective-source technique is used in both the time and frequency domain modelling to greatly reduce the region of interest while maintaining an accurate forward model.

**Frequency domain EM measurements**

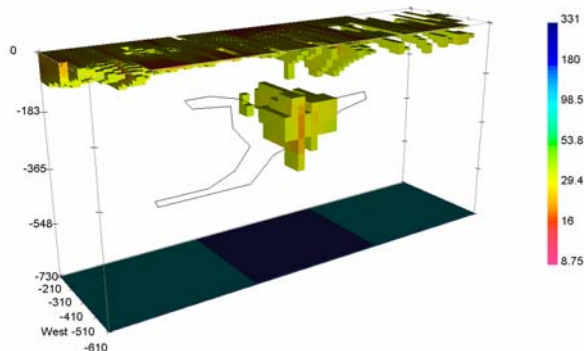
Conventional controlled source audio magnetotelluric (CSAMT) measurements were made over the San Nicolás deposit with the survey geometry shown in Figure 4. In this acquisition scheme, measurements are collected from a transmitter positioned sufficiently far from the area of interest that the incident waves are planar. Three survey lines 1.5 kilometers in length were collected over the deposit. The data collected is the electric field parallel to the transmitter (Ex) and the magnetic field perpendicular to the transmitter (Hy).



**Figure 4. CSEM survey over the San Nicolás deposit**

These measurements are treated as the amplitude and phase of the ratio of electric to magnetic fields,  $Z = Ex/Hy$ , referred to as scalar impedances. Each line contains 60 stations, spaced 25m apart, with lines separated by 200 m. Measurements were made using a single grounded transmitter, 1.6 kilometers in length, located 3.5 kilometers from the receivers. A total of 15 frequencies between 0.5 and 8192 Hz were collected.

Although the data was collected in a CSAMT configuration, several of the frequencies are in the near-field and transition zone. Since the 3D modeling used calculates the fields due to the grounded wire, and does not use a plane-wave assumption, we refer to the measurements as being controlled source electromagnetics (CSEM) measurements.

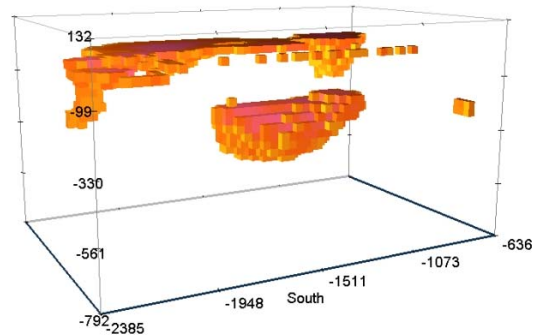


**Figure 5. 1D CSEM inversions stitched to create a 3D volume. Iso-surface cut-off of 34 Ohm-m**

A 1D CSEM interpretation using all available frequencies and which incorporated the transmitter geometry was performed using the method described in Routh and Oldenburg (1999). The resulting conductivity model was able to image the sulphide conductor at depth (Phillips *et al.*, 2001), and is in

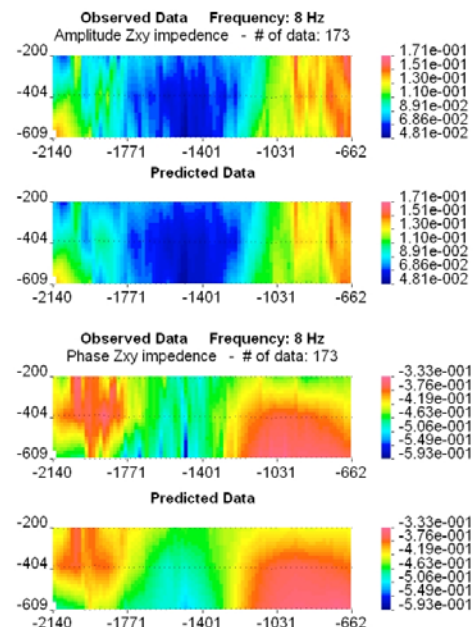
agreement with the known lithological interpretation. The 1D interpretation can be seen in Figure 5.

The CSEM data were inverted in 3D. Although fifteen frequencies were collected, for computational expediency only four frequencies were selected for inversion: 0.5, 8, 64 and 256 Hz. These frequencies were chosen because they cover a relatively wide range of skin depths, but are still sensitive to variations in conductivity on the scale of the mesh discretization and depth of the San Nicolás deposit.



**Figure 6. 3D CSEM conductivity model displayed as an iso-surface using a cut-off of 20 Ohm-m**

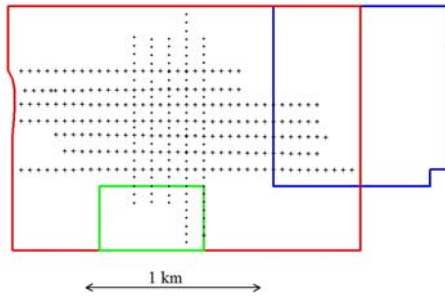
An iso-surface of the resulting 3D conductivity model is shown in Figure 6. The observed and predicted amplitude and phase data at a frequency of 8 Hz is shown in Figure 7, showing the high-level of agreement between the collected field data and the data predicted by the 3D conductivity model. The resulting inversion model images both the conductive overburden, and the massive sulphide body.



**Figure 7. Observed and predicted amplitude and phase of scalar impedance data at 8 Hz**

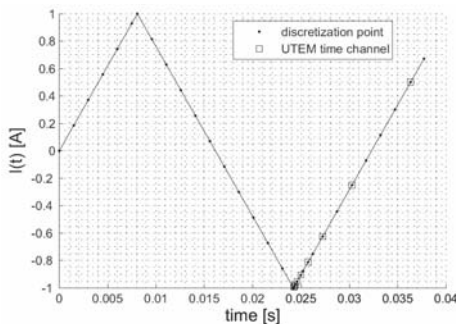
**Time domain EM measurements**

A UTEM time-domain survey was carried out over the San Nicolás deposit. The survey used three large ground based transmitting loops, with receivers both inside and outside the loops. The survey configuration showing the location of 3 transmitting loops and receiver locations is provided in Figure 8.



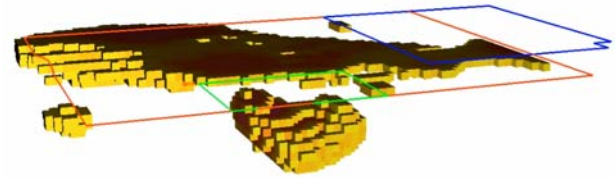
**Figure 8: UTEM survey geometry at San Nicolás**

UTEM measurements are collected from a continuous on-time loop transmitting source using a sawtooth waveform. Data are collected from a horizontal coil, measuring dBz/dt. The UTEM waveform was discretized using 38 time-steps, with both the discretization and measurement locations shown in Figure 9. As discussed in Napier *et al.* (2006), it was necessary to model 1 ¼ cycles of the waveform to reach equilibrium prior to measuring the fields for the inversion.



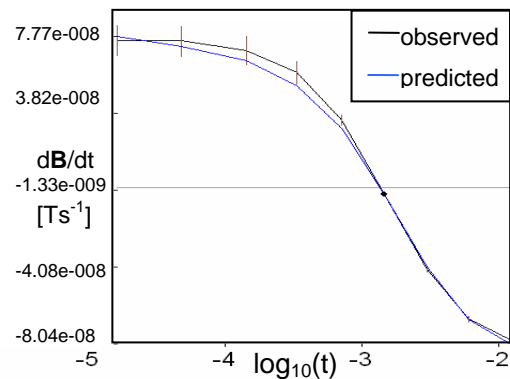
**Figure 9. UTEM sawtooth waveform**

Data collected from the three separate transmitters were simultaneously inverted over the San Nicolás deposit. A sensitivity based weighting scheme was used to suppress artefacts associated with the high sensitivity to model cells near the transmitter loops. An additional constraint was placed in the inverse problem through the use of *a-priori* geological information about the conductive overburden layer over San Nicolás deposit. This was accomplished by using a model which contained a 90 meter thick conductive overburden layer in the inversion. The resulting 3D conductivity image is shown in Figure 10. The UTEM conductivity model recovers both the surface conductive layer and the massive sulphide body at depth.



**Figure 10. 3D UTEM conductivity model displayed as an iso-surface using a cut-off of 20 Ohm-m. Geometry of the three surface transmitting loops is shown for reference.**

An example of a sounding curve collected above the deposit is provided in Figure 11. It shows the good agreement between the observed UTEM measurements and those predicted from the 3D conductivity model.

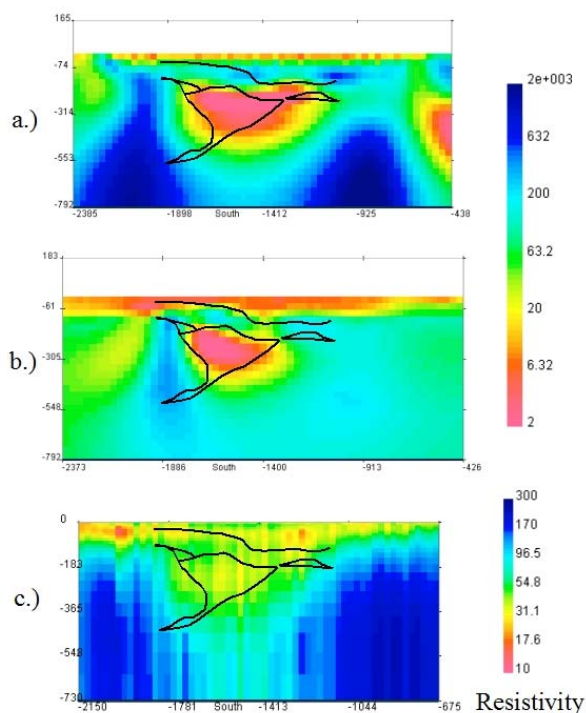


**Figure 11. Observed and predicted UTEM sounding**

**COMPARISON OF CONDUCTIVITY MODELS**

A cross-section view of the 3D UTEM, 3D CSEM, and stitched 1D CSEM conductivity models is shown in Figure 12. We note that both the 3D UTEM and 3D CSEM model are displayed using the same color scales, demonstrating the high-degree of similarity between these two conductivity models. This highlights the importance of interpreting electromagnetic measurements in three dimensions, and has been seen in 3D EM interpretation over other deposits (Oldenburg *et al.* 2004).

Upon closer inspection of the cross-sections presented in Figure 12, we note that the 1D CSEM model, although delineating the overburden and deposit, does not exhibit as sharp of features, nor does it extract the resistive layer between the massive sulphide and conductive overburden. Additionally, the 1D model does not exhibit the range of physical properties as seen in the 3D modelling results. However, this is not entirely unexpected based on the assumption of a 1D layered Earth.



**Figure 12: Conductivity models of San Nicolás. a.) 3D CSEM b.) 3D time domain c.) 1D CSEM**

The 3D UTEM model, when compared to the 3D CSEM model, shows a higher level of detail in the conductive overburden, which is most likely attributed to the incorporation of *a-priori* information into the reference model. Additionally, the 3D UTEM model does appear to have a tighter control on the bounds of the massive sulphide body when compared to the 3D CSEM model. This is likely attributable to the added value of incorporating multiple transmitters and a smaller receiver spacing in terms of the resolving power of the inversion.

## CONCLUSION

The vast amount of geological information available over the San Nicolás massive sulphide deposit makes it an ideal geological scenario for testing and benchmarking of geophysical inversion algorithms. Here we have compared several electrical conductivity models over the deposit obtained from DC resistivity, CSEM and UTEM experiments. It was found that the DC resistivity lacked the ability to image below the conductive overburden, while the frequency and time domain EM methods had much better success at imaging both the conductive overburden and the massive sulphide deposit. Although the 3D EM methods were able to define the massive sulphide body, neither the CSEM, UTEM or DC/IP was able to detect the “keel” of the deposit shown in Figure 1. In actuality, the keel has a small volume and its detection and delineation were based solely on drilling results.

The ability for the IP inversion to image the massive sulphide deposit, while the DC results are only imaging the overburden, may seem counter intuitive. However, as IP is measured in the off-time, it is able to detect the small secondary field associated with charge build-up on the massive sulphide due to small currents penetrating the overburden.

With the increasing use of 3D interpretation by geoscientists, the ability to effectively view and manipulate 3D spatial information becomes increasingly important. To this end, we have created a composite 3D image in Figure 13. This figure shows the 3D DC resistivity, 3D UTEM and 3D CSEM models displayed as 3D volumes on top of the geological cross-section. Having the ability to quickly and accurately assess the geological and spatial relationships between the transmitters, receivers, physical property and geology is invaluable when interrogating complicated 3D geological data.

## REFERENCES

- Haber, E. and Ascher, U., 2001, Fast finite volume simulation of 3D electromagnetic problems with highly discontinuous coefficients: *SIAM Journal of Scientific Computing*, 22, 1943-1961.
- Haber, E., Ascher, U. and Oldenburg, D., 2004, Inversion of 3D electromagnetic data in frequency and time using an inexact all-at-once approach: *Geophysics*, 69, 1216-1228.
- Haber, E. and Oldenburg, D. and Shekhtman, R., (2007), Inversion of 3D time domain electromagnetic data: *Geophysical Journal International* (in press).
- Li Y. and Oldenburg D., 2000, 3D inversion of induced polarization data: *Geophysics*, 65, 1931-1945.
- Napier, S., Oldenburg, D., Haber, E., & Shekhtman, R., 2006, 3D inversion of time domain data with application to San Nicolás: *SEG Technical Program Expanded Abstracts*, 1303-1307.
- Oldenburg, D., Shekhtman, R., Eso, R., Farquharson, C.G., Eaton, P., Anderson, B., Bolin, B. 2004, Closing the gap between research and practice in EM data interpretation: *SEG Technical Program Expanded Abstracts*, 1179-1182.
- Phillips, N., Oldenburg, D., Chen, J., Li, Y and Routh, P, 2001: Cost effectiveness of geophysical inversions in mineral exploration: *Applications at San Nicolás, The Leading Edge* Volume 20, Issue 12, 1351-1360.
- Routh, P. and Oldenburg, D., 1999, Inversion of controlled source audio magnetotelluric data for a horizontally layered earth: *Geophysics* 64, 1689-1697.

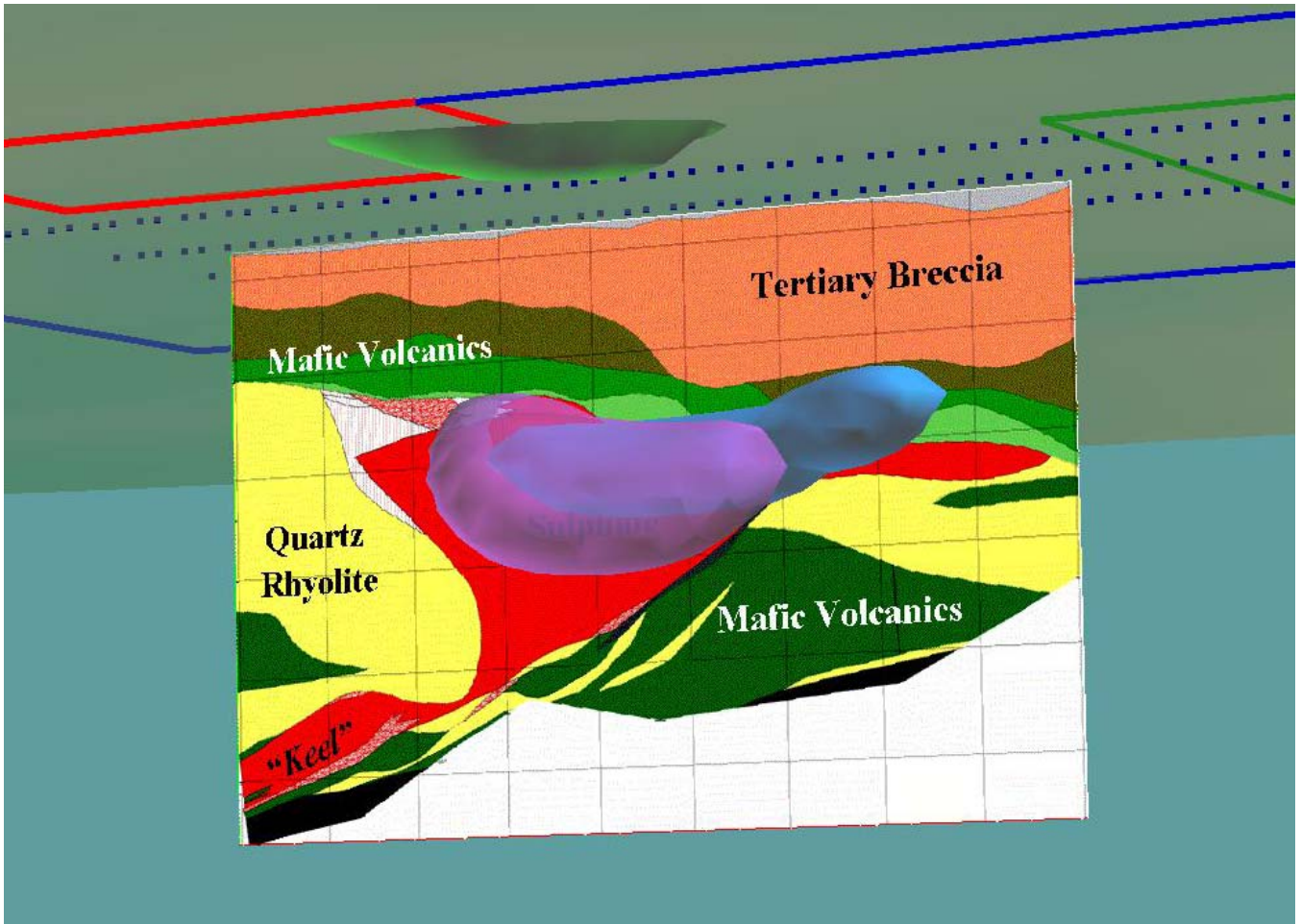


Figure 13: A composite 3D Visualization of the 3D conductivity models over the San Nicolas deposit with geologic cross section. Displayed are the 3D UTEM model (purple), 3D CSEM model (blue), and 3D DC resistivity model (green). Surface transmitting loops of the UTEM survey, and receiver locations of the CSEM measurements are shown for reference.