Testing a Slingram system on resistive Zn-Pb targets in Paracatu prospects, Minas Gerais State, Brazil

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Abstract

Although systems based on the electromagnetic method were developed to detect conductive targets, we present a case in a Pb-Zn prospect in Paracatu mining district where it was possible to confirm (potentially mineralized) resistive pods due to their electrical resistivity contrast with the dolomitic and phyllite host rocks. The pods are elongated, with dimensions of about 100 m along strike, dipping 50 to 10 m, and 4 m wide. The pods consist mainly of quartz, sphalerite, disseminated pyrite and minor galena and marcasite. Measurements with portable conductivity meter proved the pods are electrically resistive. Initial interpretations based on pseudo-sections have guided a series of drill-holes that confirmed the pods. Later, inverse Occam models proved to map reasonably well the saprolite, main rocks and faults/pods, except where resistivity contrast was not high enough. Comparison of measured data with those obtained by plates and prism modelling were not successful, which indicate that the geologic structure is too complex to be represented by simple models. Establishing the repeatability of data by different sensor separations (100 m and 200 m) and sampling rate (2 m and 10 m) was important to confirm detection of target ore and depth of deeper conductive rocks.

Introduction

The Geological Survey of Brazil has begun a program to re-evaluate its prospect areas and new geophysical surveys have played a major role in this task. These surveys include, but are not limited to airborne and ground-based magnetics, gravity, radiometrics, resistivity and electromagnetic. Because electromagnetics has not been done for many years, the team had to gain experience and one strategy was to survey in known areas with drill-holes control.

In 2103, during a visit to Vazante-Paracatu district, one of the world´s largest zinc source, mining company, Votorantim Metais, was approved to survey the distinct's Ambrósia deposit (Figure 1). According to Votorantim geologists, an established mineralization models in Paracatu (e.g. Morro Agudo mine) are stratiform or massive due to hydrothermal mineralized fluid percolation

along the dolarenite. It was found that in Ambrósia area, the main control is tectonic, where promising grades are found in pods generated as extension gashes and brecciated zones due to a system of inverse faults. The system is a "positive flower" structure. Silica-rich hydrothermal fluids (containing Zn and Pb) have migrated from mineralized dolomite trough transtensional stress relief zones and have precipitated as amorphous silica, pyrite, sphalerite, subordinated galena and Fe-oxides to form the pods. These pods and breccias are oriented NNW-SSE, diping 70° to 90° to west or east, with dimensions of about 100 m along strike, 50 m in dip and 4 m thickness.

The study area is a hill where outcrops consist of rocks from Vazante Group of Meso/Neoproterozoic age. The mineralization is hosted in the Morro do Calcário dolomite/dolarenite which occurs in the central to western part of the hill, with thickness of 150 m or more. The base marker of the mineralization is the Mocambo Formation: a marl/carbonaceous phyllite/diamictite found at a depth of about 100 m, 20 m-thick, which is intercalated into the dolomite. To the east of the hill there is the thrust basal fault that puts the dolomite in lateral contact with the Garrote black phyllite/carbonaceous shale/slate. (Figures 3a,b).
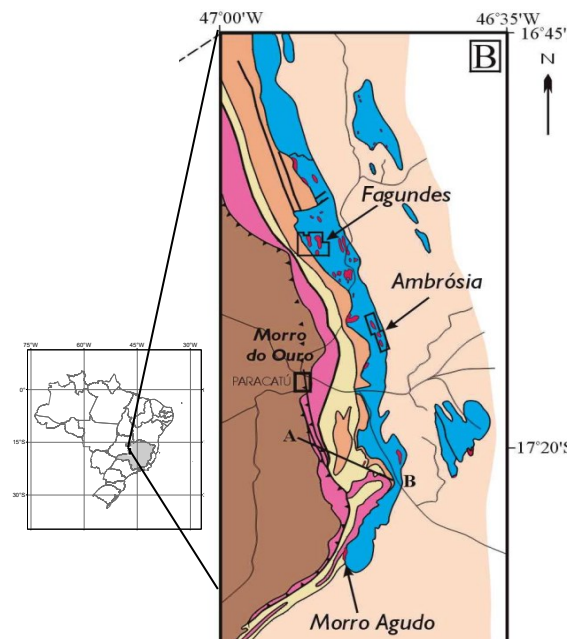

Figure 1 - Vazante-Paracatu mining district in Minas Gerais State, Brazil and the Zn-Pb prospects of Ambrósia and Morro Agudo. Litologies: Dolomite in blue; Garrote phyllite in light-yellow to East; all other litologies out of the

context of the study and not described in the text. (Modif. from CIA. Mineira de Metais, in Viviane et al., 2001).

Method

The frequency-domain electromagnetic method measures induced secondary magnetic field generated by conductive materials in Earth due to time-varying (primary) field transmitted from an EM system. As pointed out by Fitterman and Labson (2005) and previously by Ward (1967), electromagnetic induction is based on two physical observations: a) the flow of electrical current through conductors produces a magnetic field - Ampere's law; b) time varying magnetic fields induce current flow in media to which these magnetic fields are linked - Faraday's law. The electromagnetic response of a target is determined by the physical properties of the target and the subsurface and the survey parameters: the electromagnetic sources and sensors, and acquisition parameters: geometry, frequency, and measurement time. Three basic physical properties determine the behavior of electromagnetic energy in a material: the conductivity-σ, the dielectric permittivity-ε, and the magnetic permeability-μ. The conductivity (mS/m) or its reciprocal resistivity (Ω.m) is the most important in such methods.

The PROMIS-10 (IRIS-Instruments) is a portable Slingram system, consisting of a transmitter unit-Tx having power generator and coil, and a receiver sensor-Rx connected by a communication cable to Tx, with a monitor console located on top of Rx (Figure 2). It has capability to operate using ten frequencies in a range from 110 to 56,320 Hz, and, to change the Tx-Rx separation by using cable lengths from 20, 50, 100, 200 to 400 m, which also increase the depth of soundings. The in-phase-Ip and out-of-phase-Q components of the secondary magnetic field induced in the ground are measured as percentage of the primary field in three directions: Hz-vertical; Hx-horizontal along the profile; Hy-horizontal, orthogonal to the profile. The profile is carried out by measuring the components for a set of frequencies at each station, and by moving both the transmitter and the receiver to the next station. The reading is located at the half-distance between the sensors.

Figure 2: Details of the PROMIS-10 system: a) monitor and receiver-Rx; b) transmitting coil-Tx and batteries belt. Tx and Rx are connected by a reference cable.

Several soundings were acquired along line LT50S from WSW to ENE (Figures 3). The coil configuration was horizontal coplanar, which produces a vertical dipole magnetic field. The measurement frequencies were 440, 880, 3,520, 7,040 and 14,080 Hertz, with cable lengths of

100 m and 200 m. The Tx-Rx separations of 100 m (s100) had readings every 2 m and 10 m, while the 200 m separation (s200) had readings every 5 m. UTM coordinates were taken with a Garmin 60C-X GPS with horizontal and vertical resolutions of 10 m and 15 m, respectively. The depth of investigation is considered approximately equal to half of Tx and Rx distance, It is about 50 m for s100 and 100 m for s200.

The survey on Line LT50S begins with PROMIS configuration of s100 m/reading every 2 m until X-104 m, followed by configuration of s100/reading every 10 m. The profiles with s200 and s100 overlap, for stations X-150 m to X-180 m.

The cleaning of data eliminated spurious values due to system failure, low power injection to the transmitter, sudden movements which over-incline the Tx or Rx coils. The aim was to detect anomalies from three targets: Zn-Pb mineralized silica-pods within the dolomites; the contact between dolomite and the Mocambo marl; the fault contact between dolomite and basal Garrote Phyllite. So, we consider the contrast in resistivity rather than obtained absolute resistivity values.

Initial processing in 2013 used pseudo-sections of apparent resistivity to guide the locations of drill-holes that confirmed the pods. This year, one-dimensional inversion models based on smooth Occam technique were used to delineate main features. Occam models had 15 layers, 13.3 m thick and starting resistivity of 100 Ω.m each. Measured data were filtered with median and gaussian filter to eliminate high-frequency anomaly caused by small features and noise to enhance the broad features contrasts like dolomite and phyllite and the thrust fault. The cleaning of dataset was performed in EMSys® (IRIS Instruments, 2012). EMIGMA® (PetRos EiKon, 2014) software was used for Occam inversion. To help interpretation, geologic sections were provided by Votorantim Metais, one at the time of the survey in 2013, and an updated one (Figures 3a,b).

Results

Survey with s200 and readings every 5 m

The goal of this survey was to detect 1) the contact between dolomite and Mocambo marl, expected to be at 100 m depth, and 2) the fault contact between dolomite and basal Garrote Phyllite. The resistivity model produced by Occam inversion (Figure 4a) depicts a resistive top layer associated to the dolarenite formation,which is thicker west of station X-160 m, which abruptly turns less resistive to east. Comparison with the geologic section of Figures 3a,b suggests that conductive unit (a stripe with resistivity < 50 Ω.m) detected under the resistive domain, is probably Mocambo marl. For this short survey segment, the Occam model indicates that the limit of investigation is about 113 m depth.

Surveys with s100 and readings every 2 m

This profile extends from X-50 m until position X-104 m. The purpose of the shorter cable and closely spaced

measurements was to increase lateral resolution needed for the silica-pod targets, expected to be about 4 m thick. This configuration may investigate ore bodies until 50 m depth and possibly until the contact with Mocambo Marl. Apparent resistivity section (Figures 5a), shows elongated resistive anomalies in a less resistive environment. The configuration of these anomalies indicates probable dip to west, similar to the geologic section. Such anomalies were found to be silica pods inside dolomite, as it was seen in nearby outcrops. Resistivity section from Occam inversion (Figure 5b) confirms large resistivity contrast between stations 80 and 90 and suggests faults and pods (> 1200 Ω.m), as well as map the dolomite-derived saprolite with cavities (400 to 800 Ω.m), the resistive dolomite unit (200 to 450 Ω.m) and the conductive Mocambo marls/carbonaceous phyllite (> 16 Ω.m).

Surveys with s100 and readings every 10 m

The goal of this longer profile (from X-100 m to X-360 m), was to confirm the detection of ore bodies found with the 2 m–spaced survey, and to investigate the contact with the Garrote Phyllite, located at about X-200 m. The apparent resistivity pseudo-section (Figure 6a) shows several small very resistive anomalies below stations X-120 m, X-200 m, X-330 m and few minor ones above less resistive host-rock. These anomalies tend to go deeper and are suggestive of silica-pods already found in drill-holes or outcropping. To the east of station X-200, a deeper zone of lower resistivity might be related to the Garrote Phyllite. Occam inversion (Figures 6b) produced a resistivity model, where the surface resistive (400 to 700 Ω.m) zone, of varying thickness of up to 40 m, correlates with saprolites derived from dolomites; Morro do Calcário dolomite (200 to 400 Ω.m); very resistive and discrete verticalized faults and silica pods (> 1000 Ω.m); and the conductive (~5 Ω.m) Mocambo marl/phyllite. To East of position X-200 m, the Garrote phyllite is not well detected. Here an upper resistive layer is about 150 Ω.m, with more resistive discrete zones and a lower conductive layer, which may represent variations within Garrote Formation below 60 m depth.

The datasets of the two surveys s100m were merged and median low-pass and Gaussian filters were applied. Occam inversions were performed on quadrature data. Figure 7 presents the results on the gaussian filtered data. Four well-defined geophysical units are compared with geologic sections provided by Votorantim Metais:

- L1 outcropping: resistive range of about 500 Ω.m to 8000 Ω.m, interpreted as saprolite with cavities derived from dolomites/dolarenite with thickness about 30 m;
- L2: medium resistivity (200 Ω.m to 550 Ω.m), usually in between 30 m to 65 m deep, interpreted as dolomites/dolarenite with less silica-pods;
- L3: conductive geophysical marker (1 Omh.m to 5 Ω.m) associated with Mocambo phyllite;
- F: Discrete high-angle very resistive markers; probably faults or shear zones rich in silica at the surface or with top at least 45 m-depth. That is clear where the two surveys s100 have stations overlapped (X-102 to X-106), repeated passes give similar values, with differences

about 10% for frequencies 880 Hz, 3520 Hz and 14080 Hz and, 15% for frequency 7040 Hz. Also the pattern of both surveys define an ascent curve around station X-100 m. (Figures 5b; 6b).

The depth of investigation is about 70 m to 120 m, below that uncertainty is high and the method is not sensitive to resistivity variations. These models show that the Garrote black phyllite could not be resolved, and we present some plausible reasons:

a) At depth, next to the basal fault at X-200, the models could not resolve the contrast between Mocambo marl/carbonaceous phyllite and Garrote black phyllite, indicating they might have similar resistivity;
b) The top 60 m-thick saprolite over the Garrote phyllite has slightly less resistivity than the dolomite/dolarenite, yielding an apparently continuity of dolomite in the model image;
c) The sensors did not surveyed over the black phyllite outcrops, since the receiver-Rx stopped at station X-230 m.

The use of a portable conductivity meter MPP-EM2S+ (GDD Instrum) confirmed that core sample from Ambrosia´s ore and other occurrences are not electrically conductive and it has magnetic susceptibility less than 10^{-3} SI. The portable X-Ray Fluorescence accounted for Ambrosia deposit a maximum Zn grade of 49.87 %; and mean Zn of 19.65 %.

Conclusions

CPRM´s geophysical team achieved the goal to test the PROMIS-10 system as tool in mineral prospection and to increase the technical expertise. Although the system has been designed to detect conductive targets as presumed by the electromagnetic method, there is a chance to use it in a resistive environment when a good geologic knowledge is combined with proper survey configuration, as presented in this work. Establishing the repeatability of data with different cable separations (100 m and 200 m) and sampling rate of 2 m and 10 m was important to detect discrete and resistive targets and to confirm deep conductive rocks. The best data were at the frequencies of 3520 Hz, 7040 Hz and 14080 Hz.

Drilled targets confirmed the resistive bodies identified in the surveys. New drillings and updated geologic section confirmed that identified targets from positions X-60 m to X-150 m are indeed mineralized pods; however, their grades of zinc and lead were below the economic cut-off, so far. Nevertheless, the northern segment of the hill has been approved for mining. Where the resistivity contrast between similar rocks was small, the differentiation between them was not possible, as theoretically expected. The use of forward models using plate or prism models will be the next step of this study. Although models were not satisfactory to depict framework complexity, we suppose the main lithologies can mapped.

Acknowledgments

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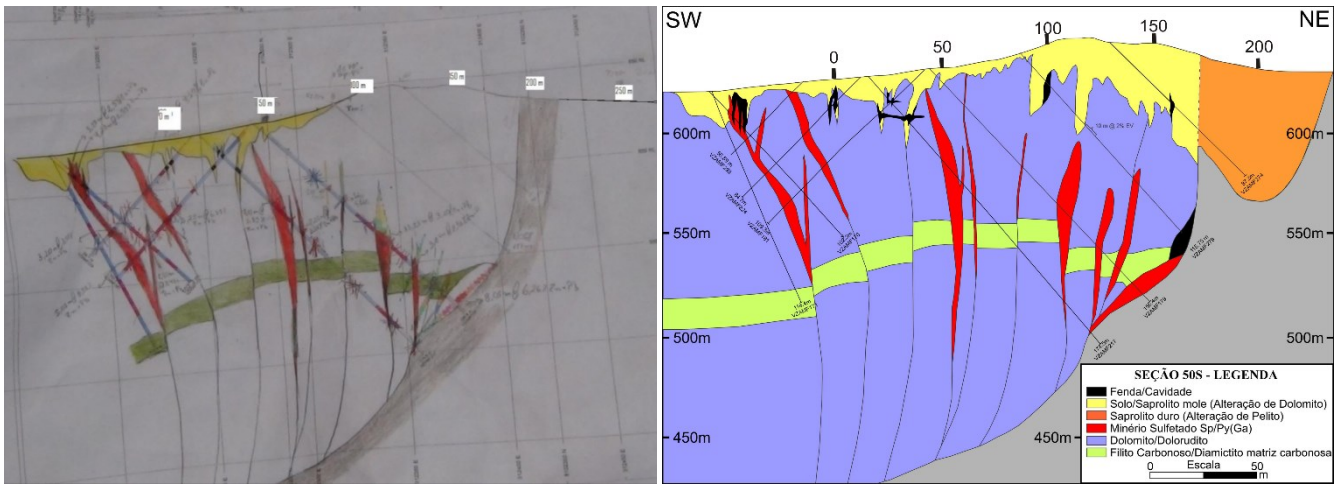

Figure 3 - Geologic section of Ambrósia prospect along line LT50S provided by the mining company: a) original section at the time of the survey in 2013; b) updated section. Coordinates of survey profile LT50S stations are marked above the topography. Mineralized pods in red, dolomite in purple, Mocambo Marl in green, Garrote Phyllite in grey/brown and its saprolite in orange, faults in black traces, soil from dolomite in yellow. Drill-holes projections with mineralized segments in red. No vertical exaggeration.
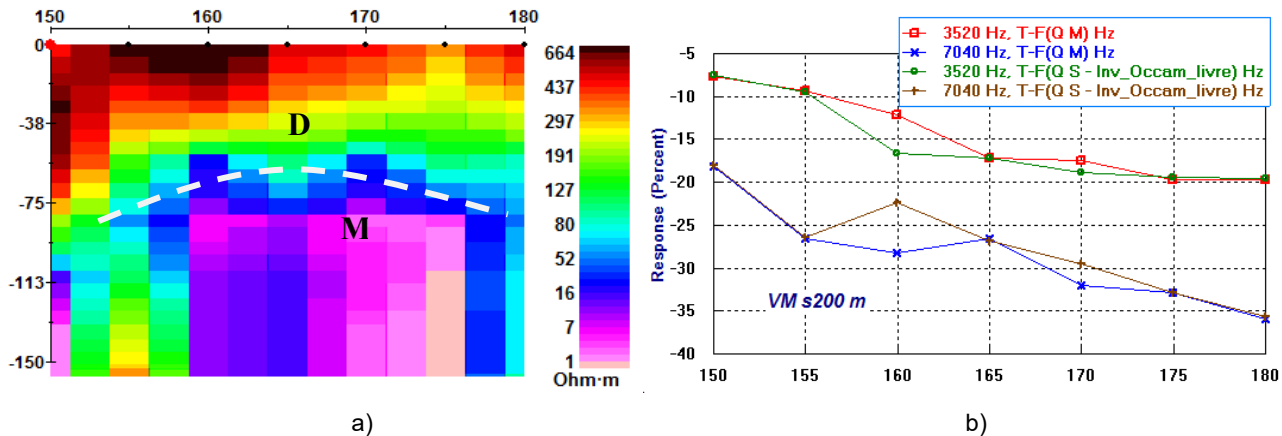

Figure 4 - Survey with Tx-Rx s200 m: a) resistivity section calculated from Occam inversion with quadrature-Op data; b) Values of measured and calculated data for intermediate frequencies. White trace marks the interpreted contact between the resistive dolarenite-D and the less resistive Mocambo marl-M.

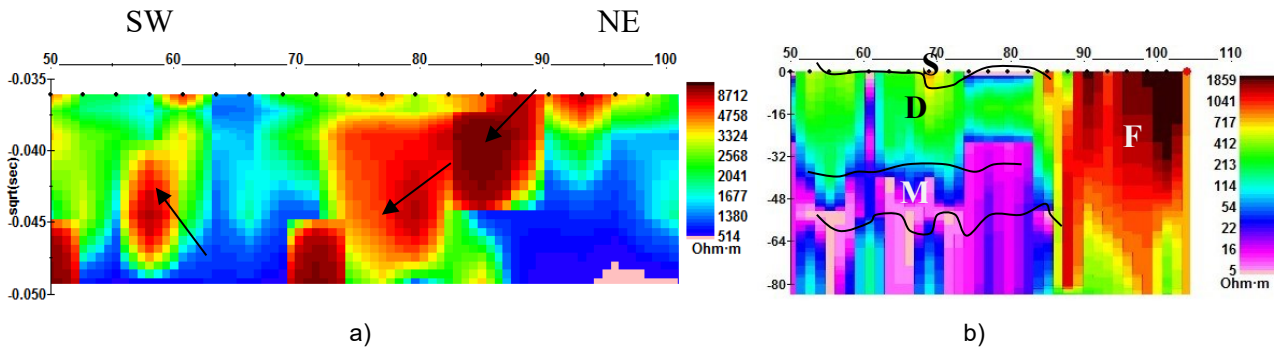a)   b)

Figure 5 - Survey with Tx-Rx s100 m/readings every 2 m: a) apparent resistivity pseudo-section calculated with quadrature-Op data. Anomalies (shown by arrows) depicts higher resistivity zones considered to be mineralized silica pods, with probable dip to west. Y-axis is the square root of the period of the each acquisition frequency; b) resistivity section from an Occam inversion. Fault/silica pod-F, Mocambo marl-M, dolomite-D and saprolite-S. The higher resistivity under stations X-90 to X104 m is due to combination of thicker saprolite, metric caves, and silica pods.

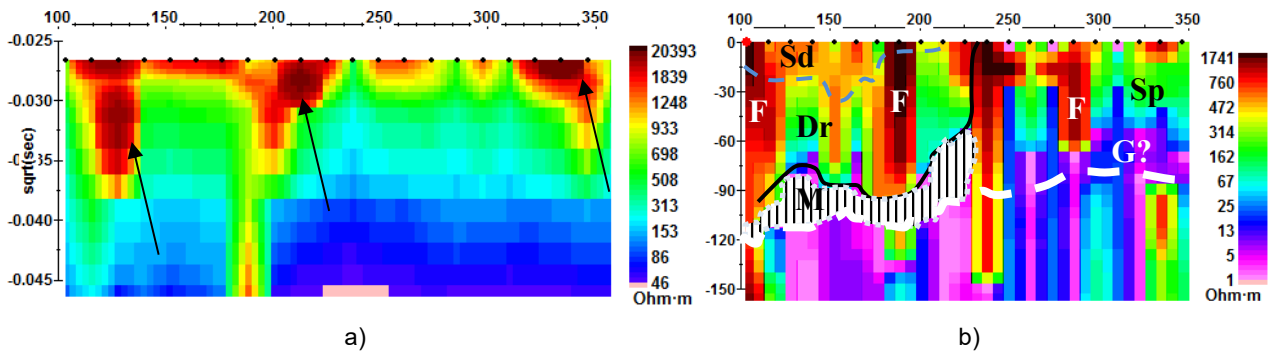a)   b)

Figure 6 - Survey with Tx-Rx s100 m/readings every 10 m: a) apparent resistivity pseudo-section calculated with In-phase data. Anomalies of higher resistivity (shown by arrows) are considered mineralized silica pods. Y-axis is the square root of the period of the each acquisition frequency; b) resistivity section calculated from Occam inversion. Resistive domains up to 30 m depth are related to dolomite-derived saprolite and cavities-Sd, black trace limits dolomite-D over the Mocambo Marl-M (hatched layer), phyllite-derived saprolite (Sp), faults and pods-F. Thicker white trace marks the reasonable depth of investigation for the model.

a)   b)
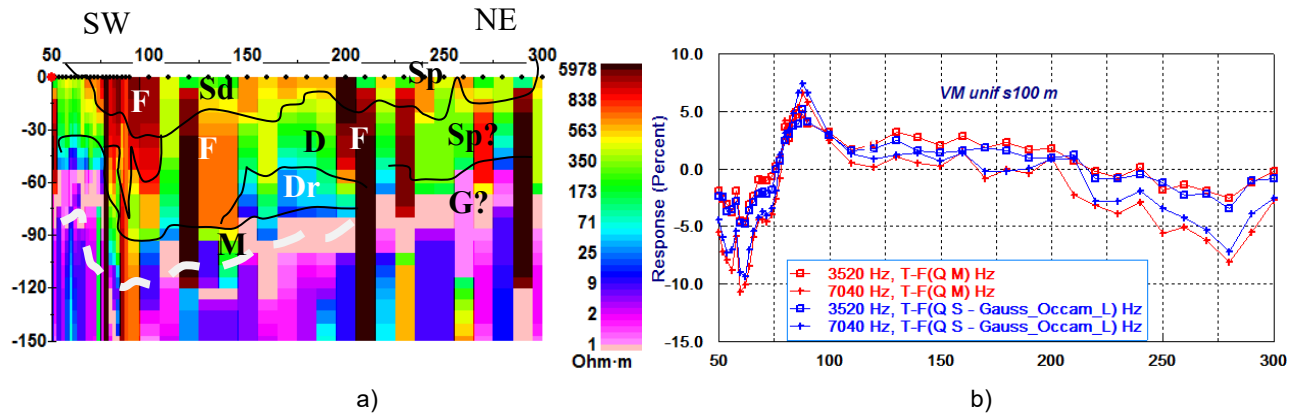
Figure 7 – Merged s100 surveys: a) resistivity section from 1-D occam models applied to gaussian-filtered data. Geophysical units related to known lithologies are: resistive dolomite-derived saprolite-Sd on top (500 to 800 Ω.m); resistive dolomite-D (200 to 550 Ω.m); conductive (about 1 Ω.m) Mocambo marls/carbonaceous phyllite-M; very resistive (> 840 Ω.m) verticalized faults and silica pods-F. Dubious correlations with rocks appear as: low resistive dolorudite-Dr (25 Ω.m); Garrote black phyllite-G? (> 9 Ω.m); phyllite-derived saprolite-Sp (560 to 700 Ω.m). Thicker white trace marks the reasonable depth of investigation for the model; b) Comparative response of measured data and calculated Occam inverse model on gaussian filtered data.