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Tridimensional Inversion of DC Resistivity Data

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ABSTRACT

We have developed a new technique for tridimensional (3D) inversion of DC resistivity data like: dipole-dipole, Schlumberger, pole-dipole, Wenner or a mixture of these. The algorithm has been proved with synthetic data generated with another forward program and the results show that this is an efficient algorithm for recovering 3D structures in subsurface from resistivity data.

The Cerro Prieto region was prospected in 1977-79 with more than 400 long offset Schlumberger soundings. The geothermal area is at the center of a system of echelon faults that produce a slimming and possible rupture of the earth's crust. With the help of the resistivity data, we obtained a tridimensional resistivity image of the geothermal area and of the two principal faults that controls the regional tectonics. We assume that tridimensional inversion gives us a more accurate picture of the region than those bidimensional pictures obtained previously by two-dimensional inversion. We have discovered new features that are not shown in the previous geological models.

1. INTRODUCTION

Resistivity prospecting has been very important for the determination of the low-conductors associated with geothermal reservoirs. The complex tridimensional geology around the geothermal areas has favored the application of electrical methods such as direct current (DC) and magnetotellurics instead of seismic. Several techniques for interpreting resistivity data have been developed. The easier to use is by means of horizontal layers for the Schlumberger soundings. In the 1980s began the numerical modeling of bidimensional or elongated structures such as in Dey and Morrison (1979). At the end of the 1980's the first algorithms appears for inversion of resistivity data such as Cavazos-Garza and Gomez-Treviño (1989) for bidimensional structures with the approximation with circular bodies. Years after began the inversion of 2D structures using scattering theory such as Loke (1994). With scattering theory also began the 3D inversion methods such as Loke and Barker (1996) and Li and Oldenburg (2000).

In another approach, we used the nonlinear integral equation of Gomez-Treviño (1987) instead of scattering theory. The first bidimensional inversion with this equation was made by Pérez-Flores (1995) for 2D. Years after, joint bidimensional inversion with DC and shallow electromagnetics was done by Pérez-Flores at al. (2001). Now we are presenting an algorithm for full 3D structures with the option of joint inversion with shallow electromagnetics (SEM; Antonio-Carpio, 2003). For geothermal purposes SEM is not applicable. In the present work we show only the DC development and the application for the Cerro Prieto area.

2. DATA DESCRIPTION

Between 1977 and 1979, 411 long-offset Schlumberger soundings were taken in a region of 70x40 km with NW-SE direction, along the Cucapá and El Mayor sierras (Figure 1), and at the south of Mexicali (México) and Calexico (USA) cities. Every dot in figure 1 means the center of a Schlumberger sounding. The maximum distance of source electrodes was AB/2=5 km. Data were collected with equipment of Lawrence Berkeley Laboratory, but with participation of Comision Federal de Electricidad (CFE) technicians. All sounding electrodes were spread along a SW-NE direction. The centers of the soundings along lines in the SW-NE direction are as shown in figure 1. With those 411 soundings, 21 lines were covered. The bidimensional automatic interpretation of those lines are described in Charré-Meza (2000).

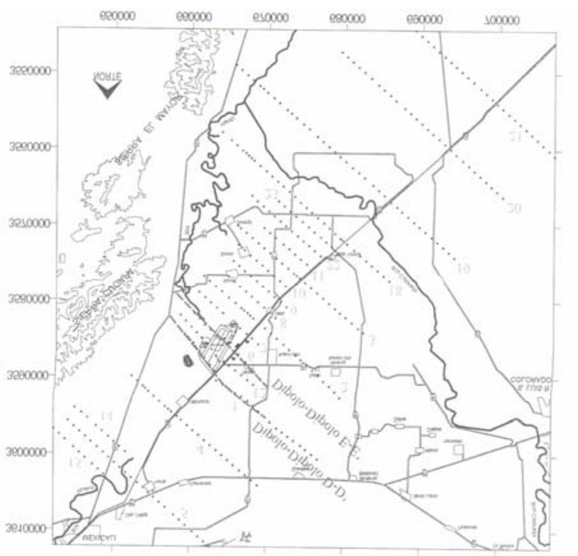

Figure 1. Location of the study area. Dots represent the center of the 411 Schlumberger soundings. It is also shown two dipole-dipole lines. Thick line is the Colorado river. Topography corresponds to the Cucapa and El Mayor sierras.

3. GEOLOGICAL BACKGROUND

Cerro Prieto region is located 40 km south of the USA (Calexico) and in the land area of the northern side of the Gulf of California, very close to the Colorado river outlet. Tectonically, the Gulf was opened in the Miocene, beginning from the south and propagating to the northwest. Presently, Baja California peninsula belongs to the Pacific plate and the rest of Mexico to the North American plate. The border between both plates constitutes the San Andreas Faults system. From the south of Baja peninsula this border takes other names. The border constitutes a strike-slip fault.

At the south of Gulf of California are pull-apart basins very well defined. However, at the northern side (younger aperture), specifically in the Cerro Prieto area, we have a not very well defined pull-apart basin. Because of the very thick sediment layer, it is difficult for geologists and geophysicists to infer how thin is the earth crust below (Elders et al., 1972). Some believe that a magmatic chamber is intruding through the earth crust, producing the high geothermal gradients observed (Goldstein et al., 1984). Cerro Prieto is at the center of echelon faults. These very big faults are the Cerro Prieto fault at the southwest and Imperial fault at the northeast. Both belong to the San Andreas fault system. This is a seismic active area. Because of the soft consistency of the soil, the trace of the faults are hard to follow and in some places it is completely buried. Earthquakes epicenters give a good evidence of the movement of these two faults, but they define a wide active area. The interpretation of the resistivity data defines a narrower trace of the faults. We believe that resistivity interpretation can better define the geometry of these two faults and from other important features.

4. GEOPHYSICAL METHOD

There are two main approaches for doing resistivity inversion by mean of integral equation. One uses scattering theory and then does the approximation for low resistivity contrast (Hohmann, 1975; Loke and Barker, 1996; Li and Oldenburg, 1992). The other approach is by means of a nonlinear integral equation (Gomez-Treviño, 1987), and then a low-resistivity contrast approximation (Cavazos-Garza and Gomez-Treviño, 1989; Pérez-Flores, 2001). By scattering equation, it is possible to estimate the deviation of the resistivity with respect a constant resistivity subsurface $\delta\rho$ and the data are the deviations of the apparent resistivity with respect to a constant resistivity $\delta\rho_a$.

$$\delta\rho_a = \int_v K(r, r_i)\delta\rho(r)\ dv \qquad (1)$$

The nonlinear integral equation relates directly the apparent resistivity measured ρ_a with the true resistivity ρ in the subsurface through a weighting function G ..

$$\rho_a = \int_v G(r, r_i)\rho(r)\ dv \qquad (2)$$

We have the advantage that we do not need to define any constant initial subsurface model and therefore the estimated resistivities are not subject to be very close to that constant model. By equation (2) the apparent resistivity takes the meaning of an average resistivity of all the resistivities multiplied by their respective weight. Numerically it is very efficient because that integral is very well evaluated when unity. *G* and *K* represent the product of the Green function and the electric field. In *K*, the Green function is evaluated for a half space and the electric field must be approximated for the same half-space. In case of *G*, the Green and the electric field are evaluated in an inhomogeneous half-space and the approximation must be directly over *G* in order to keep the Frêchet derivative as defined by Gomez-Treviño (1987). Details of the method for 2D inversion can be found in Pérez-Flores et al. (2001).

Many observations of apparent resistivity over the same unknown subsurface define a linear system of equation.

$$\mathbf{Y} = \mathbf{A}\mathbf{X} \qquad (3)$$

Where **Y** represents the observations, **A** the weighting function and **X** the true resistivities to be determined over a tridimensional subsurface. The observation can be obtained from dipole-dipole, Schlumberger or others arrays. Arrays can be constituted by more than four electrodes or less.

The system of equations (3) is solved by mean of quadratic programming, imposing equality and inequality constraints over the unknown resistivities. This is very useful when we have *a priory* geological or geophysical information of the tridimensional subsurface.

5. RESULTS

We did 3D inversion over dipole-dipole of synthetic data from a constant half-space scattered by a conductor and by a shallower resistive 3D body. Synthetic data were contaminated with 5% Gaussean error. Figure 2 shows with shadows the regular bodies and their bidimensional projections. The solid surfaces represents the 3D bodies recovered. We can see that the fit is very good.

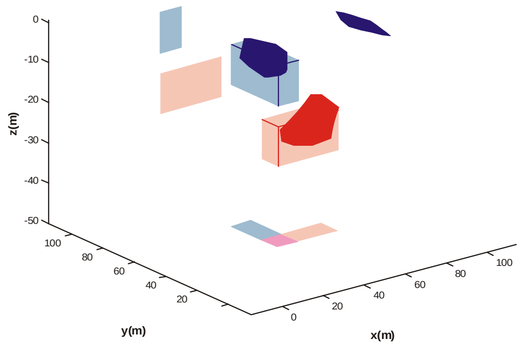

Figure 2. Recovery of a conductor (red) and a resistive (blue) bodies, using data contaminated with 5% gaussean error.

In case of the Cerro Prieto data we first did a bidimensional interpretation of every Schlumberger line (Figure 3). We obtained many bidimensional resistivity images. These images show a very constant presence of linear trends in the subsurface. These trends correlate very well with the expected position of the Imperial and Cerro Prieto faults. In order to have a more accurate geological picture, we decided to do tridimensional inversion of the same data. The problem was very unstable numerically, because the number of unknowns increased too much. We stabilized by applying the spatial derivatives of the estimated resistivity and at the same time reducing the roughness of the tridimensional models obtained.

The resistivity estimation for surface correlates very well with the irrigation of fresh water from the Colorado river, giving high resistivities, and low-resistives close to the geothermal production area and at the south. These conductors can be explained by the salty sediments over the surface that come from historical floods of the Gulf of California into land.

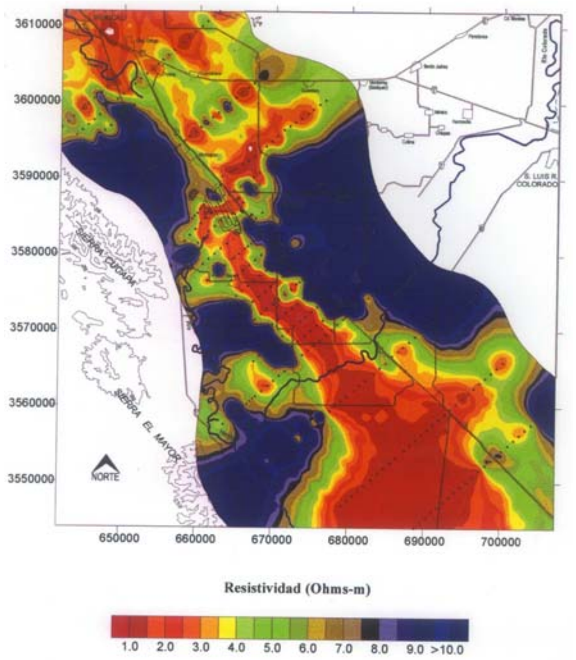

Figure 3. Horizontal slice of the tridimensional resistivity model obtained at 1200 m depth. Red correspond to conductors and blue to resistives. Three linear trends seems to be present, two of them correspond to Cerro Prieto and Imperial faults.

The 1200 m horizontal resistivity slice of the 3D model obtained shows linear trends at the southwest that may corresponds with the presence of the Cerro Prieto fault and at the northeast with Imperial fault (figure 2). These are the known geological features, but their geometrical position is not well defined by the distribution of seismic epicenters and better defined by the resistivity interpretation. In figure 2 is also shown another trend at the northeast, between the two main faults. This trend may correspond to an unmapped fault. The presence of this fault is difficult to justify tectonically. There are no seismic epicenters mapped close to it. This leads us to think that correspond to a fault that was active in the past.

6.CONCLUSIONS

The inversion technique developed is very stable and gives a model without unnecessary roughness and we are able to put as many constraints as we need in order to get a geophysical model with more geological meaning.

Tridimensional inversion of the 411 Schlumberger soundings gave a better geological image than that obtained by the previous bidimensional images.

Cerro Prieto and Imperial faults are better defined than when using seismic epicenters. Another unmapped fault seems to be present.

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