REVISTA DE LA ESCUELA DE FÍSICA
UNIVERSIDAD NACIONAL AUTÓNOMA DE HONDURAS
Vol. 7, No. 2 • ISSNe: 2412-2564 • DOI: http://dx.doi.org/10.5377/ref.v7i2.9327

Detection of possible fault in steep hill of *Ecoparque El Espino, La Libertad*

Detección de posible falla en la empinada colina de *Ecoparque El Espino, La Libertad*

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Recibido: 21 de octubre de 2019 / Aceptado: 29 de noviembre de 2019

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Con el fin de investigar una posible falla en “Ecoparque el Espino”, una región dentro del complejo del volcán San Salvador, se realizó una tomografía de resistividad eléctrica utilizando una sola línea de exploración de electrodos en una matriz de Wenner. Se utilizó un inversor de software para producir secciones transversales bidimensionales de valores de resistividad a través de la línea de reconocimiento, mediante un método de optimización de mínimos cuadrados, con las respectivas correcciones topográficas. Los resultados muestran una distorsión de las líneas equipotenciales en una materia lineal en los primeros 20 metros del perfil, lo que indica que es muy probable que haya una falla con un ángulo de inclinación aparente de alrededor de 80 °.

In order to investigate a possible fault in “Ecoparque el Espino”, a region inside the San Salvador volcano complex, a electrical resistivity tomography was performed using a single survey line of electrodes in a Wenner array. A software inversor was used to produce a two-dimensional cross sections of resistivity values across the survey line, via a least-squares optimization method, with the respective topography corrections. The results show a distortion of equipotential lines in a linear matter in the first 20 meters of the profile, which indicates that a fault with an apparent dip angle around 80° is most likely present.

PALABRAS CLAVES

Detección de fallas, tomografía de resistividad eléctrica, matriz de Wenner, métodos de inversión, volcán San Salvador.

KEYWORDS

Fault detection, electrical resistivity tomography, Wenner array, inversion methods, San Salvador volcano.

PACS

93.85.Jk

I | INTRODUCCIÓN

THE detection of the possible fault was proposed with the aim of explaining anomalous concentrations of volcanic gases found on the delimitated zone of “Ecoparque El Espino, Cerro La Hoya”, located in La Libertad, El Salvador. Cerro La Hoya is a cinder cone; previous change of diffuse CO_2 has been detected in the zone (Perez et al., 2002), which indicates that the region presents a geological feature that allows the leakage of underground compressed gases, such as a geological fault. An alternative possibility is, that a thermal anomaly is bellow this zone, generating the gases that escape to surface by the porosity of adjacent rocks.

The profile of the volcanic land presents the following characteristics (Ferrés et al., 2013). The first layer is volcanic soil, normally it contains abundant organic material, implying abundant content of water on it, lowering the resistivity of the material. The stratum that is found bellow it is then volcanic ash and other pyroclast from previous eruptions. Deposits of hardened lava should be found in the regions with volcanic ash. The San Salvador volcano presents mostly hardened basalt and andesite lava (Ferrés et al., 2013).

Geo-electrical techniques, such as electrical resistivity tomography, are essentially concerned with the measurement of electrical resistivities of subsurface materials, which preferentially provides information on the different geological layers (Muchingami, Hlatywayo, Nel, & Chuma, 2012). Resistivity is related to various geological parameters such as the mineral and fluid content, porosity, and degree of water saturation (Muchingami et al., 2012). Hardened lava normally exhibits a much higher resistivity than the surrounding material for same thermodynamical conditions.

The methodology of the experiment revolves around performing a electrical resistivity tomography on the terrain where the concentration of gases indicates that a fault could be located, which means that the data consists on current and voltage drops across a survey line. The electrical resistivity tomography was performed using a linear Wenner array of electrodes to achieve a 2D resistivity profile, and from the contrast of resistivities determine possibly anomalies. The region where the topography was performed was inclined, which required topographical corrections in inversion. The experimental hypothesis is: "The gas emission on the delimited zone is caused by a fault that can be detected by electrical resistivity tomography taken across a survey line".

The results show that in the outermost level there is a material of relatively high conductivity (volcanic soil), and bellow there are two rock blocks of high resistivity, which are interpreted as deposits of andesitic hardened lava; and the region between the two presents a more conductive region, which is likely a deposit of volcanic ash. There is a clear distortion of equipotential lines, which is interpreted as a possible fault. Having calculated the relative dip angle of the inferred fault; the real dip angle was also calculated, to characterize this possible fault.

A direct geological exploration of the zone should be perform to confirm that the region actually presents it, and it is not some other geological feature with low resistivity.

The interest on detecting a fault in volcanic terrain is motivated by the fact that knowing where a region susceptible for the emanation of volcanic fluids (such as radon gases and lava), can be useful for monitoring the volcanic activity, as well been a factor to consider when planing risks prevention on surrounding areas.

Endpoints	X coordinate (m)	Y coordinate (m)
First	0254701±2	1516271± 4
Last	0254521±1	1516333± 2

Table 1: UTM coordinates for the end points of the survey line, in UTM zone number 16P. Uncertainty in the table follows from the standard deviation of five measurements of each coordinate with a GPS.

Figure 1: Region of study from Central America view. The study area of 'Ecoparque El espino' has a straight line of $189.1m \pm 0.5m$*, and the coordinates for the end points of our survey are presented in table 1.*

II | THE STUDY AREA

The study area is a steep hill terrain inside *Ecoparque El Espino*, located in "Cerro la Hoya, Volcán de San Salvador, El Salvador". The location of this complex is shown the figure 1. The coordinates shown in table 1 are the same UTM coordinates of the first and last electrodes in the survey line.

III | METHODOLOGY

1 | Instruments

The experimental setup for resistivity survey consisted on two 100 m wires connected to electrodes in earth, which are used to inject current and to measure voltage. The information is transferred to the main device for the survey, which is a signal averaging system.

The function of the *signal averaging system* (SAS) is that its discrimination circuity and programming separates voltages, self potentials, and noise from the incoming signal. The ratio between voltage and current is calculated by this program, and using the geometry data, apparent resistivity is then calculated.

The switching unit serves to select which electrodes are used to measure voltage or to inject current, because the device can use the electrodes in different, which in the experiment consisted on a Wenner array.

2 cable rolls of 100 m of length each were plugged to the switching unit. To the cable rolls, a system of 41 electrodes were connected so the system could make the measurements.

Additional to these basic equipment for resistivity, the geographical location for this project was specified via a GPS for obtaining the UTM coordinates and the height relative to the elliptical earth model. A compass was used to indicate the angle respect with north of where the geological fault is inferred to be.

2 | Procedure

The direction of the inferred strike was registered using a compass to indicate the angle respect to the north of the intuited geological feature. When the localization for placing the SAS and switching unit was selected, it was specified using UTM coordinates given by a GPS device, and the respective coordinates of these points were measured 5 times each one. The terrain presented many coffee plantations that were assembled in a regular matter. This fact was used for extending the survey line, so that, on surface, the array was as lineal as possible.

The Wenner array was selected for placing a total of 41 electrodes, with a separation of 5 meters between each other. The 21-nth electrode was used as a connection between the wire lines. The source of the current (a battery) and the rest of equipment directing the current to the different electrodes was placed near to the 21-nth electrode.

The Wenner array is the most commonly used technique for soil resistivity measurements, and it has a sharp vertical resolution and high signal-to-noise ratio, making it appropriate for fault investigation (Monahan, 2013).

In the integrated software of the SAS, we selected a Wenner_L and Wenner_S protocols for testing electric contact of the electrodes with the medium. This is done by the SAS by injecting small and large current respectively and measuring the voltage. After this test, the actual measurement of electrical resistivity was performed. The measures of current and voltage for each series were used by the SAS to calculate the apparent resistivity (Herman, 2001) and the values were saved for their latter inversion.

As for the inversion, a least squares optimization inversion was selected for data fitting. This permitted a smoothness constrain on the generating image (Loke, 2003). Our criterion to analyze if a fault is present in the tomography, follows from considering the region with aligned peak-like distortions of the resistivity isocurves, to trace a line representing the inferred fault (Monahan, 2013). The larger conductivity that faults present, relative to the surrounding meteorized rock, allows a greater bending in the equipotential lines away from it.

Since the terrain was not flat, **topographical corrections** were incorporated before making the inversion of resistivities (Loke, 2003). The corrections simply consist on entering the coordinate of each point of the electrodes in a Wenner array, and the resistivity for each measurement. The surface measurements were incorporated to the software instead of a x coordinate, whereas the y coordinate is obtained by making GPS measurements of height respect to theelliptical earth model *for each electrode*.

The survey image was not made entirely perpendicular to the inferred strike line, which means that a dip angle would not be found from the inversion image; but there is a way of calculating it, although it should be taken just as a reference value. Let the strike have an x direction, the dip has a projection on

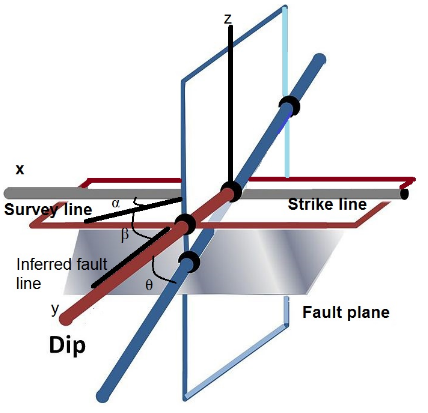

Figure 2: Dip and strike represented by coordinates, α *indicates the angle between the survey line and the strike,* β *the angle between the surface and the fault line seen in the tomography, and theta is the dip angle.*

the surface, in the y direction. The fault line can be specified as in figure 2. A unit vector on the fault line would be found by using spherical coordinates, as:

$$\begin{aligned}\hat{\mathbf{r}} &= \left[\sin\left(\beta+\frac{\pi}{2}\right)\cos\alpha, \sin\left(\beta+\frac{\pi}{2}\right)\sin\alpha, \cos\left(\beta+\frac{\pi}{2}\right)\right] \\ &= \cos\beta\cos\alpha\hat{\mathbf{x}} + \cos\beta\sin\alpha\hat{\mathbf{y}} - \sin\beta\hat{\mathbf{z}}. \end{aligned} \tag{1}$$

The angle between the two planes is simply the angle between the normal vectors to these planes. The dip angle; the angle formed from the surface plane spanned by $\hat{\mathbf{x}}$, $\hat{\mathbf{y}}$ and the fault plane spanned by $\hat{\mathbf{r}}$ and $\hat{\mathbf{x}}$; can be calculated from as:

$$\cos\theta = \hat{\mathbf{n}}_1 \cdot \hat{\mathbf{n}}_2 \tag{2}$$

where $\hat{\mathbf{n}}_1$ is the unitary normal vector to the fault plane, and $\hat{\mathbf{n}}_1$ the unitary normal vector to the surface. In this case $\hat{\mathbf{n}}_1 = (\hat{\mathbf{x}} \times \hat{\mathbf{r}})/|\hat{\mathbf{x}} \times \hat{\mathbf{r}}|$ and $\hat{\mathbf{n}}_2 = \hat{\mathbf{x}} \times \hat{\mathbf{x}} = \hat{\mathbf{z}}$. The result from evaluating (2) is:

$$\cos\theta = \frac{\cos\beta\sin\alpha}{\sqrt{\cos^2\beta\sin^2\alpha + \sin^2\beta}}. \tag{3}$$

IV | RESULTS

The apparent strike line was determined to be N36°W. The mean value of the survey line end points are those shown in table 1. From it the direction of the survey line was calculated to be N73°W.

By using the inversion of the apparent resistivity with topography corrections, the 2D profile was generated, as it is presented in figure 3, with a line representing the inferred fault. The angle between the fault and the horizontal was calculated with a software, with the result being 74.7°.

From (3) the apparent dip angle was calculated to be 81°. Since the strike line is only apparent, and the inferred fault line is likely altered by the numbers of iterations in the inversion, this dip angle value should not be interpreted an accurate value, but only a reference for future surveys.

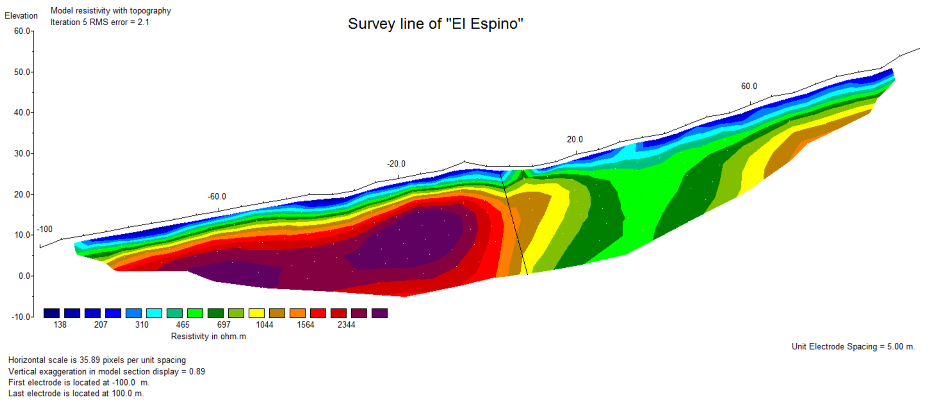

Figure 3: Resistivity profile across the survey line after topography corrections and 5 iterations in the inversion program, for a RMS error of 2.1%. The black line represents the inferred fault. The resistivity values are shown in a logarithmic scale.

V | DISCUSSION

The resistivity profile of figure 3 shows some important geological features. The topography correction in the survey was made by considering the relative elevation of the electrodes and it is therefore just an approximation. The survey line was not perfectly aligned, the elevations were subject to the uncertainty of ±3m of the GPS and do not give a precise fitting of the material that is between the electrodes.

The upper stratum showed the lowest resistivity in the profile, this was expected because of the exposure of soil to humidity and the abundance of organic material in the upper region where the survey line was placed. This region is therefore interpreted simply as hydrated volcanic soil and organic material. It can be observed that there is also a region in the upper stratum that presents more resistivity, but this is placed according to the topography of the image, in the region where the road was constructed, it is nothing significant.

The green zone represents a relatively low resistivity, it could be a material under the presence of stream, increasing its conductivity. This is interpreted as a predominately volcanic ash affected by the emission of stream, which would be a source of the CO_2 concentrations in this zone. It could be an indicator of a thermal anomaly further bellow the structure, and a region of interest for future studies of the geochemical processes occurring in El Espino.

The purple region characterizes a much higher resistivity material, which is interpreted as hardened lava, with high presence of andesite and basalt. The existence of this type of lava was found in nearby locations to the survey region, been in the surface by erosion. In the profile, this lava is at 10 meter of depth, which seems possible since other hardened lava was found exposed in surface. It is possible that below the green region another zone with larger resistivity is present, such as hardened lava, but it could also be the effect of the inversion method, so a larger tomography in this region should be performed.

The possible fault in the figure 3 was delimited from considering the region with aligned peak-like distortions of the resistivity isocurves (Monahan, 2013), to trace a line representing the inferred fault.

This analysis of the image is not sufficient to affirm the existence of a fault. The fault could be older than the hardened lava, since explosions of Cerro La Hoya had happened around 1000 years ago (Major, Schilling, Sofield, Escobar, & Pullinger, 2001), which means that the lava could be concealing part of the fault. It could also be a feature of the image reconstruction method or of the deposition of strata in the zone. Other techniques such as a 3D resistivity profile or a direct geological exploration could be performed to confirm this fact.

The dip angle that appeared on the tomography is just an apparent angle because the 2D profile is not adequate for it. The dip angle is the angle that the fault plane forms in the surface level, which required the correction given by (3) based on an the inferred strike direction, to calculate the proper dip angle, of around 80°. This angle would indicate that the crustal blocks would have moved sideways past each other, in a nearly-vertical matter, as a *strike-slip* type of fault (TARBUCK & LUTGENS, 1998). Nonetheless, this calculation is subject to many systematic and human errors, so it should not be considered as an accurate calculation, but more as a reference value.

VI | CONCLUSIONS

Most likely the study region has the presence of lava in a 10m depth, because of the appearance of highly resistive materials in the tomography. The presence of andesite-basalt lavas on the region supports this fact.

In the region between possible lavas, a much smaller resistivity was found in the tomography. This is inferred to be a material, such as volcanic ash which is abundant on the region, under the presence of stream, which would be the possible source of the gas concentrations in the region and be caused by a thermal anomaly. Further research, such as electrical vertical sounding, should be performed to confirm how the resistivities bellow change and detect the possible thermal anomaly. In the profile the alignment of distortion of an equipotential line was interpreted to be a fault based on conductivity considerations. Our study is limited by the reconstruction method, alteration of the equipotential lines by other materials. Therefore other studies less susceptible to these limitations should be performed in the region where we delimited the existence of the possible fault, to test our results and predictions.

Also an approximation to the dip angle of the inferred fault was calculated, but only as a reference value, that indicates that it would be near normal respect to surface. This would suggest that the fault could be a strike-slip type. This fact could be used in a direct geological exploration to confirm that the fault is there and give a better estimate to the dip angle.

VII | RECOMMENDATIONS

The main recommendation is that a 3D profile should be generated and a direct geological exploration for detecting the fault in a future study. The 2D profile generated a series of distortions representing a more conducting line around the materials, representing a fault. However, it could also be a feature of the image reconstruction method or of the deposition of strata in the zone. A 3D model would show a plane of low resistivity, in case a fault plane existed, so it should also be performed. This would imply making survey lines parallel to others, using the same array of electrodes, for creating individual 2D profiles and use a reconstruction method to connect the planes.

For measuring the correct dip angle, a 3D profile would be convenient, which can be performed using several linear arrays, parallel between each other. The topography correction is necessary for generating the profile because is more real in the area of measurement, but the fault might not be a single one, instead doing more profiles in the area might lead to a fault map of the zone.

To test if a thermal anomaly actually occurs bellow the green region of figure 3, a vertical electrical sounding should be performed, or other methods, to study the properties of the materials as the depth of exploration is increased.

ACKNOWLEDGEMENTS

We are grateful to for the assistance of Josue Quintanilla, Alexis Ándres, Diego Martínez in performing the survey. We also thank Nelson Cedillos for useful discussions and for planing the field exploration which led to this publication.

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