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Geophysical Methods Implemented for Geological Structures Characterization in El Salvador

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ABSTRACT

One of the most difficult challenges in geothermal exploration is to identify the geological structures which contribute to confine and transport the geothermal resource. Within the exploration work in El Salvador geothermal fields, several geophysical methods have been implemented in order to characterize the more important local systems faults and obtained successful results. DC resistivity techniques such as Misse a la masse, Head on profile, dipole - dipole as well as electromagnetic method MT proved to be useful for this purpose. The integrated analysis of the results of these techniques with gravity anomalies and passive seismic data recorded at the geothermal fields have contributed to identify buried geological structures, which do not have evidence at the surface. Some case examples are presented in this work.

1. INTRODUCTION

Faults are important features in geothermal systems which contribute to confine as well as to transport the geothermal resource. Mapping them could become a very difficult task as they are sometimes physically visible because they are smoothened out by lava, affected by erosions, covered by vegetation or by scree, pumice, or other sediment and only visible in erosive channels, quarries, road cuts, or other exposures (Sewell et al,2015).

Identifying active faults is very important in a geothermal system, where permeability is mostly associated with the presence of these geological structures, and often leads to the drilling target either for production or reinjection wells.

There are high temperature geothermal systems, in a volcanic hosted environment, which are confined to fractures instead of permeable strata with good porosity and primary permeability.

A deep upflow may be located where vertical permeable conduits are created through otherwise impermeable formations by intrusive necks, a complex fault and stress geometry (Davatzes and Hickman, 2010)

Faults commonly create flow barriers within fields and many field edges are fault-controlled. For example, although extensional step-over zones associated with major strike-slip faults host several of the world's largest geothermal fields, the strike-slip faults themselves are more likely to be boundaries than conduits. Yet some of these faults both localize permeability near the fault and bound a permeable reservoir.

In El Salvador, all high temperature geothermal systems like Ahuachapán, San Vicente, Berlin and Chinameca are located on the northern flank of the active volcanic chain (Figure 1). Unfortunately in many cases, it is a hard task to identify the faults due to the fact that the surface evidence is covered by volcanic deposits. That's why it is important to use indirect exploration methods such as the geophysical techniques presented in this paper.

This document presents the most relevant cases using geophysical methods for identifying the main geological structures systems in the different geothermal areas of El Salvador.

2. DC RESISTIVITY METHODS

2.1 Mise a La Masse Method

Mise-a-la-Masse is a resistivity method where a DC current is injected into the ground using the well casing as an electrode; the other current electrode is set at theoretically "infinity," which means at least three times the depth of the well. The potential field caused by this signal at ground surface is measured by a roving dipole, set in radial lines usually separated at 45 degrees from each other and measured every 100 m, as shown in Figure 2.

In geothermal exploration, the Mise-a-La-Masse technique can be used to help define the ground fluids that flow into a well. It can also be useful for mapping faults and fractures.

This technique was widely used for the determination and characterization of geological structures in the Berlin geothermal field (BGF).



Figure 1: Location of the El Salvador high temperature geothermal fields

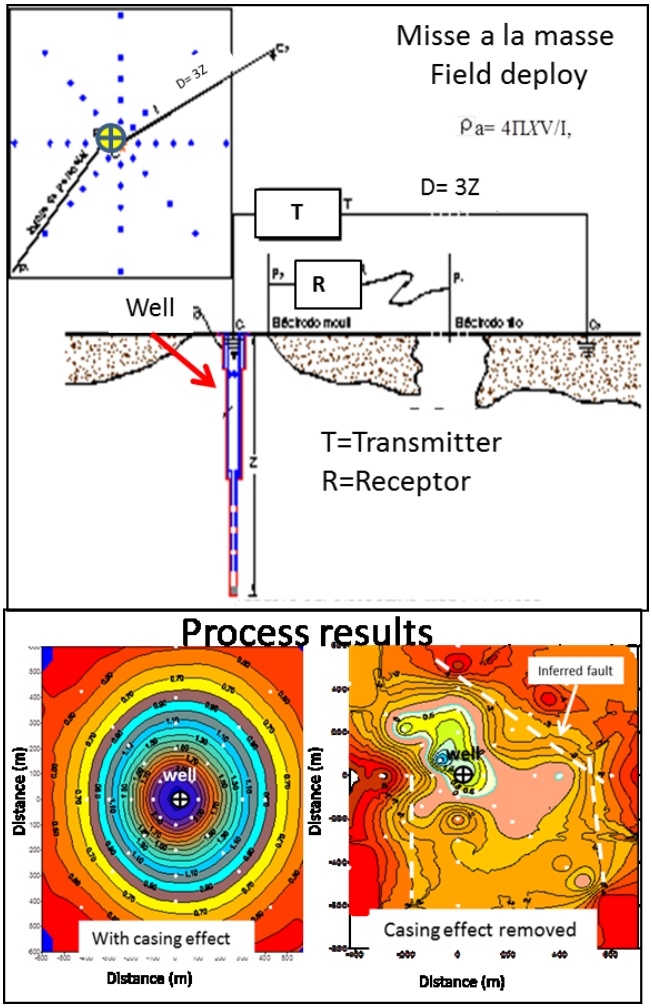


Figure 2: Mise a la Masse array and resulting graphs with and without casing effect

The well casing effect produces a kind of concentric ring which is removed by using the Misanaly software as illustrated in Figure 2.

This method was implemented, with successful results, in most of the geothermal wells of Berlin and Ahuachapán geothermal fields of El Salvador. These results were used for defining new drilling targets for directional wells.

An example of the Mise a la Masse resistivity map of Berlin geothermal field (BGF) is shown in Figure 3. The lateral resistivity discontinuities as well as the strong gradient curves observed in the residual resistivity anomaly map are correlated to the presence of possible permeable fractures. The resistive layer is shown in blue and the conductive in red, the transition between them (area of interest) in pink. The inferred faults are shown by green dotted line. The results of new directional wells confirmed some of these inferred faults.

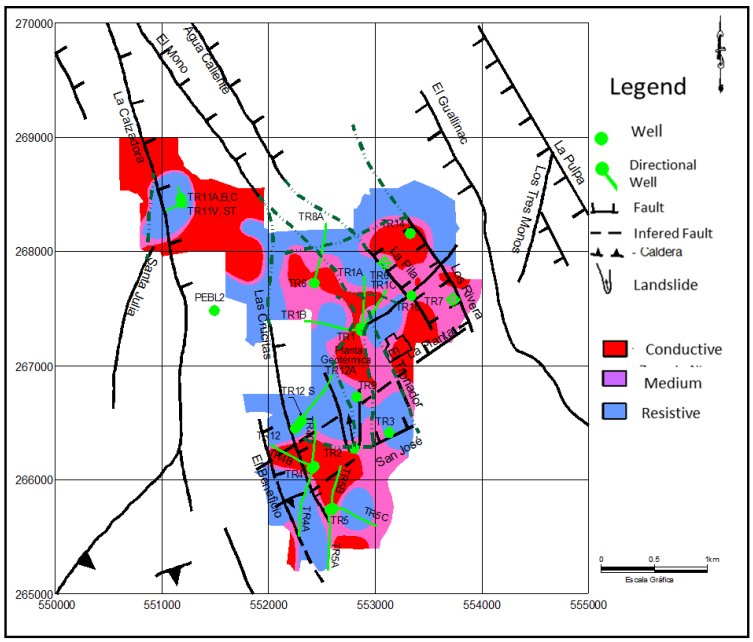


Figure 3. Mise a la masse resistivity map of Berlin Geothermal Field

A new precise seismic method known as “Double difference re-location” technique (Waldhauser and Ellsworth, 2000) uses differential travel times of body waves to improve the hypocenter location for accurate epicenter location. This method was implemented by Grzegorz Kwiatek and was used in Berlin geothermal field. The precise epicenter localization correlates well with the electric resistivity discontinuity, suggesting the possible existence of a permeable geological structure as shown in Figure 4.

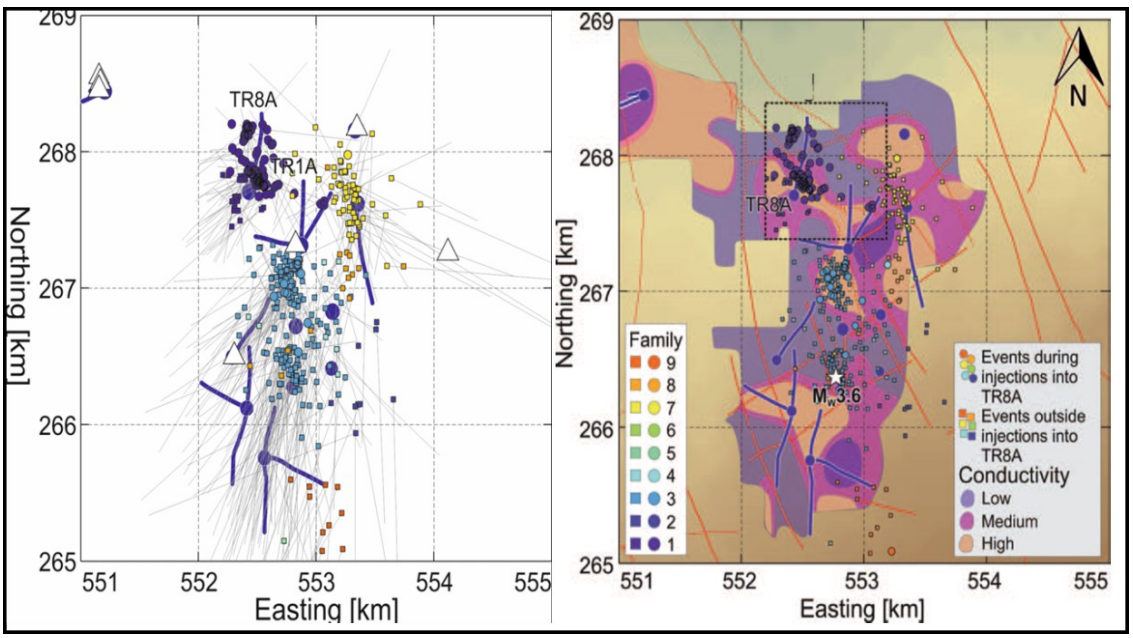


Figure 4: Correlation of local epicenter map of seismicity and Mise a la Masse resistivity map (taken and modified from Grzegorz Kwiatek et al, 2013)

2.2 Dipole Dipole Resistity Method

The Dipole - dipole surveys are conducted with the electrodes set in a linear array as illustrated in Figure 5. The first pole is used for injecting the current, while the other poles are used for measuring the induced potential.

The 2D DC-resistivity profile data are inverted to create a model of resistivity along a section of the subsurface that can be used to detect and define individual fracture zones. A good lateral resistivity resolution is provided by this method and electrical discontinuity is well defined, as shown in Figure 5.

One of advantages of this technique is the good resolution defining lateral resistivity contrast. It was implemented in the Ahuachapán geothermal field with good results, where it defined geological structures shown in Figure 5.

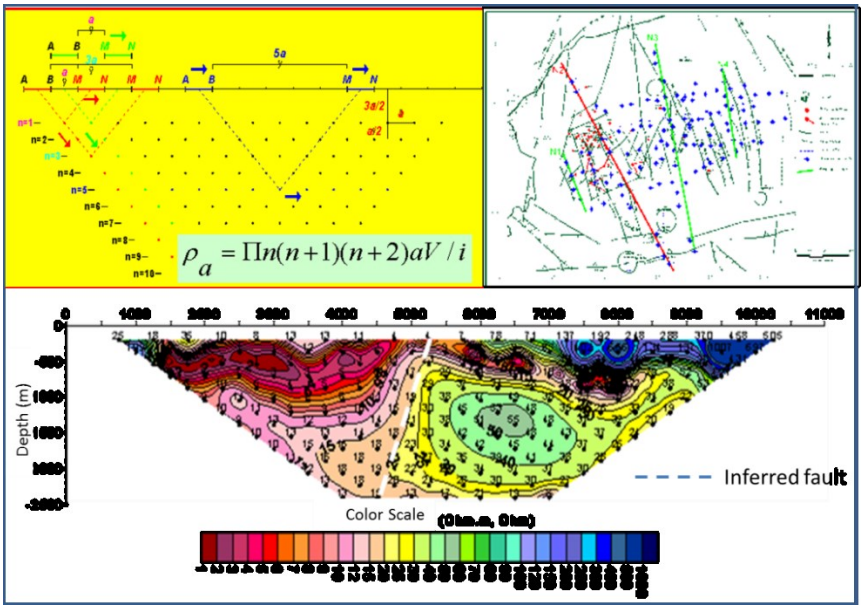


Figure 5: Dipole dipole array and profile results from Ahuachapán geothermal field

2.3 Head-on profile method

Head-on resistivity is a modified Schlumberger (VES) technique designed to detect narrow conductive zones in a resistive background. The method uses a half-Schlumberger electrode layout, where the other electrode is removed to infinity (Figure 6). The penetration is restricted to the shallow surface layer. The advantage of this method, in fault detection and location, is the resolution of the vertical conductive subsurface contrasts, typically associated with faults.

This technique was widely used in Berlin Geothermal Field and was very useful in identifying geological structures, which do not have surface evidence as shown in Figure 6, where the head on profile is shown in red line and inferred fault trace in pink colour.

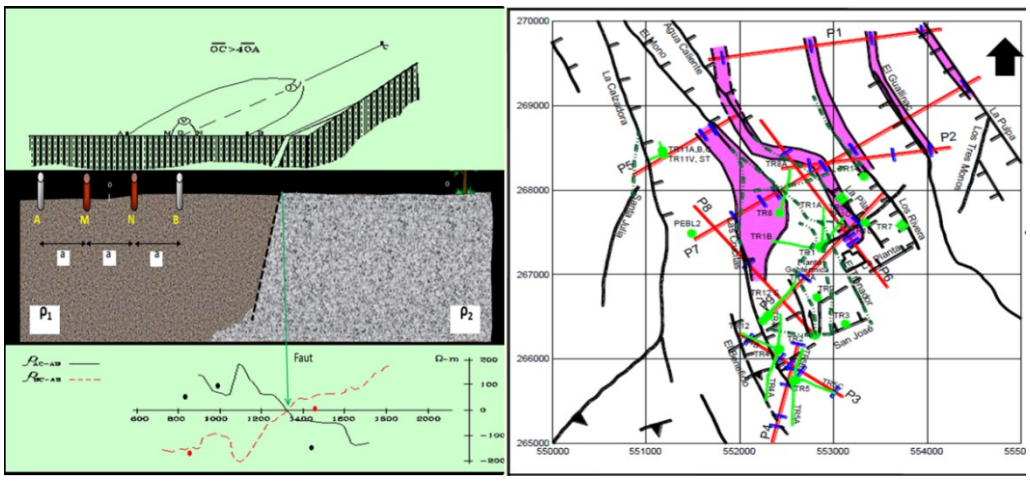


Figure 6: Head on profile array (modified from Flovenz, 1985) and Head on inferred faults of Berlín geothermal field

3. MAGNETOTELLURIC METHOD

The Magnetotelluric method results in Berlin geothermal field (BGF) has been useful to infer geological structures based on the interpretation of lateral resistivity discontinuity.

A resistivity discontinuity is a structure that exhibits a large lateral change in resistivity and/or apparent resistivity. These electrical features are usually distributed along faults systems and their associated fracture systems. In general, geothermal fluid is trapped in and around the fault/fracture system. The geothermal fluid moving along these preferential high permeability routes of high temperature can alter the matrix rocks. Thus, detecting the resistivity discontinuities is important in studying the geothermal structures in the survey area (WestJec, 2001).

A total of seven discontinuity structures were inferred from a MT resistivity map in Berlin geothermal field, some of them are shown in Figure 7. This information was useful in defining drilling targets with successful results.

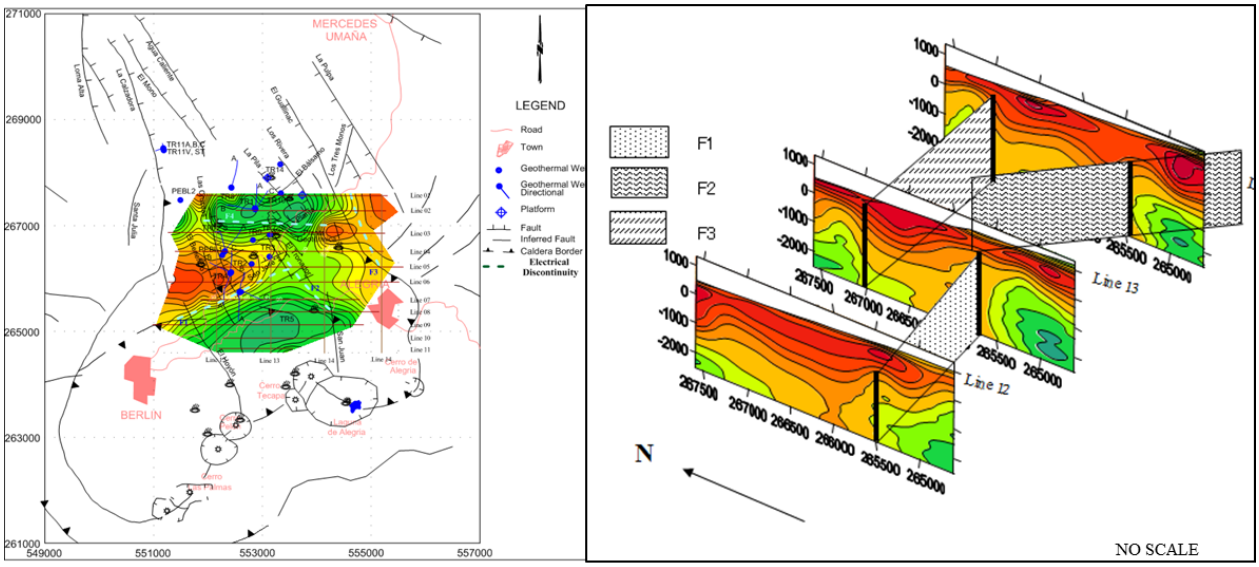


Figure 7: MT Resistivity discontinuity interpreted as possible geological structure (modified from Wesjec 2001)

4. GRAVITY METHOD

The gravity is a structural method used for identifying geological structures, based on the density contrast of subsurface stratus. This is a standard exploration technique implemented in all geothermal prospects in El Salvador with very good results.

In Berlin geothermal field, a total of 560 gravity stations were measured in different campaigns (Figure 8a). The producing reservoir is associated with a high positive gravity anomaly at depth, and correlates well with the zone of production wells, suggesting a possible extension towards the southwestern part of the field, as shown in Figure 8b. The prolongation of some important NW-SE fault systems, in the northern part of the field, is interpreted from the 1D horizontal gravity anomaly map, shown in Figure 9. The inferred faults are shown in dotted red line.

An interesting hydrofracture test was carried out by Shell and LaGeo in 2002. A large volume of water was pumped at high pressure into a reinjection well (TR 8) in Berlin geothermal field. A network of gravity stations was established for measuring before, during and after this injecting test. The resulting gravity maps are shown in Figure 10. It is interesting to see the behavior of the gravity anomaly map during the injection test, showing the preferential fluid distribution along the NW-SE local fault system.

A seismic network was installed for monitoring the induced seismicity for this operation. The result shown in Figure 10 was very consistent with the gravity anomaly maps, discussed earlier.

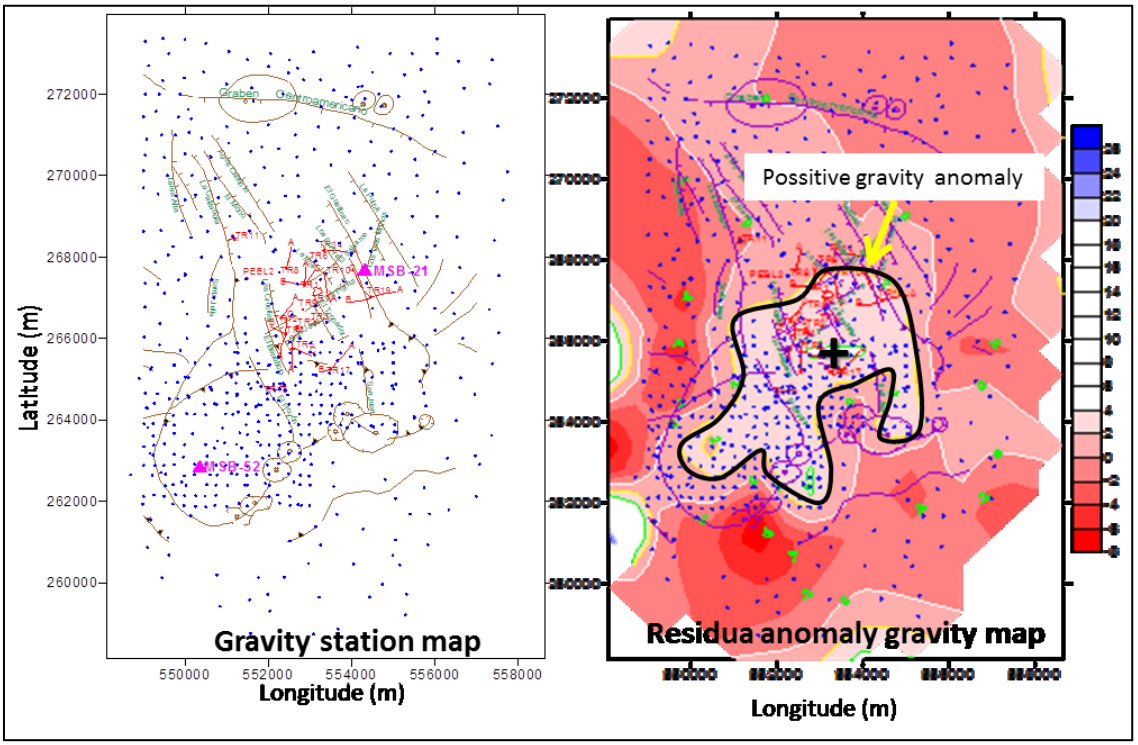


Figure 8 a) Gravity station b) positive gravity anomaly map and c) inferred faults from 1D horizontal gravity anomaly (taken from Santos and Rivas)

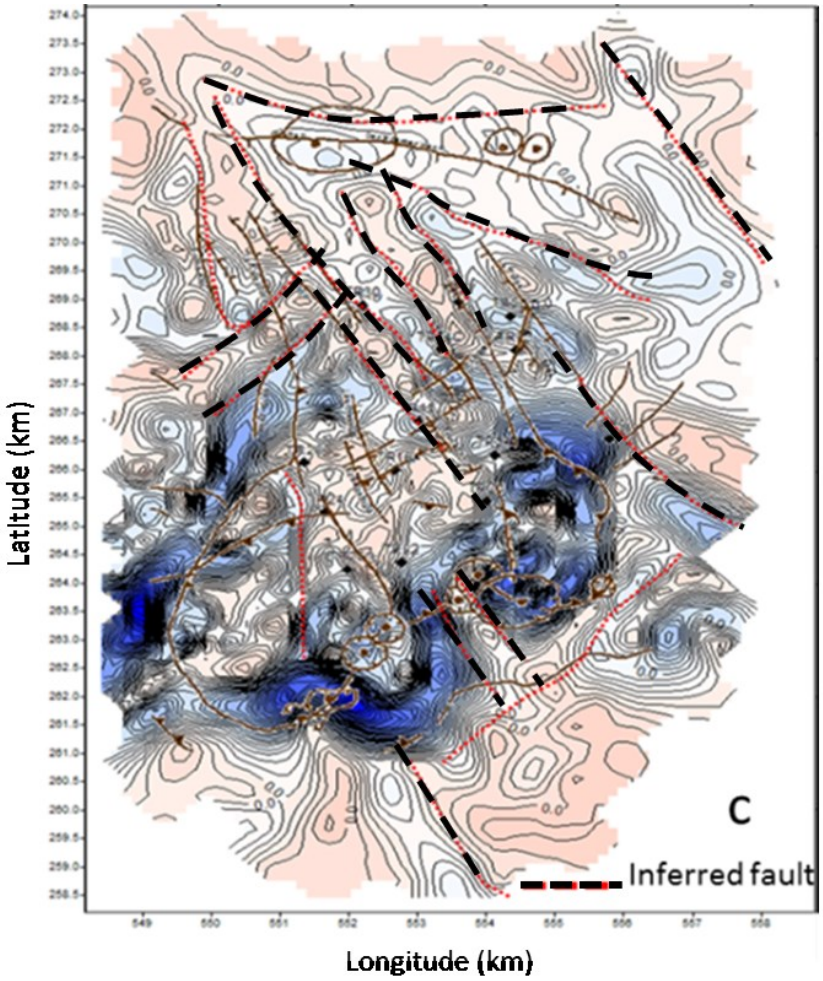


Figure 9: Inferred faults from 1D horizontal gravity anomaly (taken from Santos and Rivas)

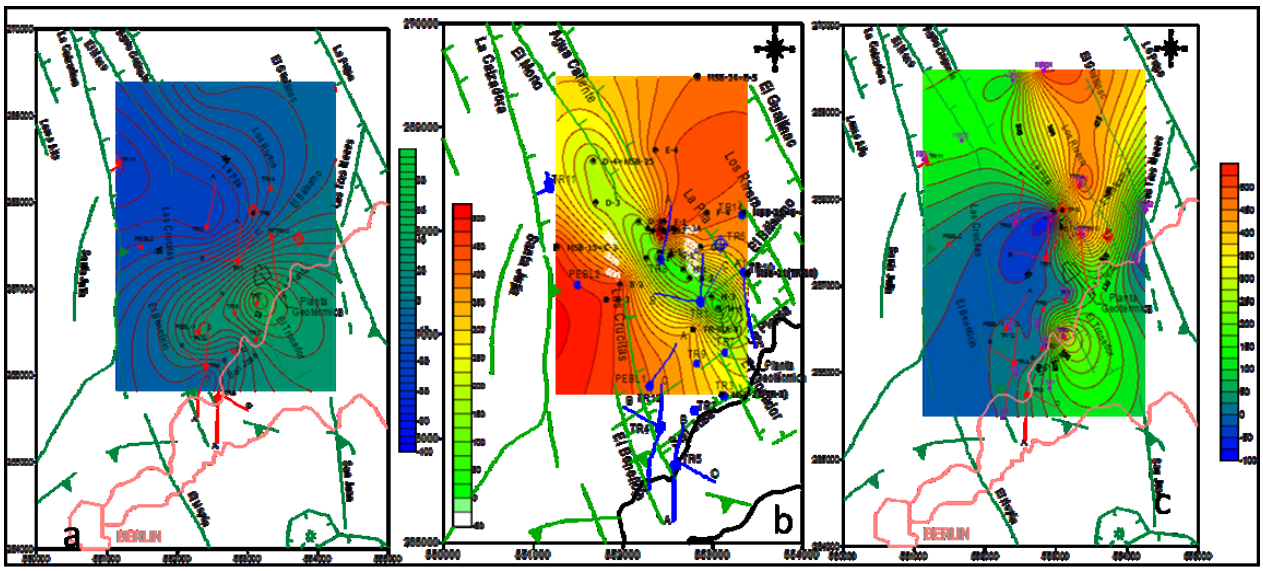


Figure 10: Gravity map anomaly a) before, b) during and c) after the injection test in Berlin Geothermal field.

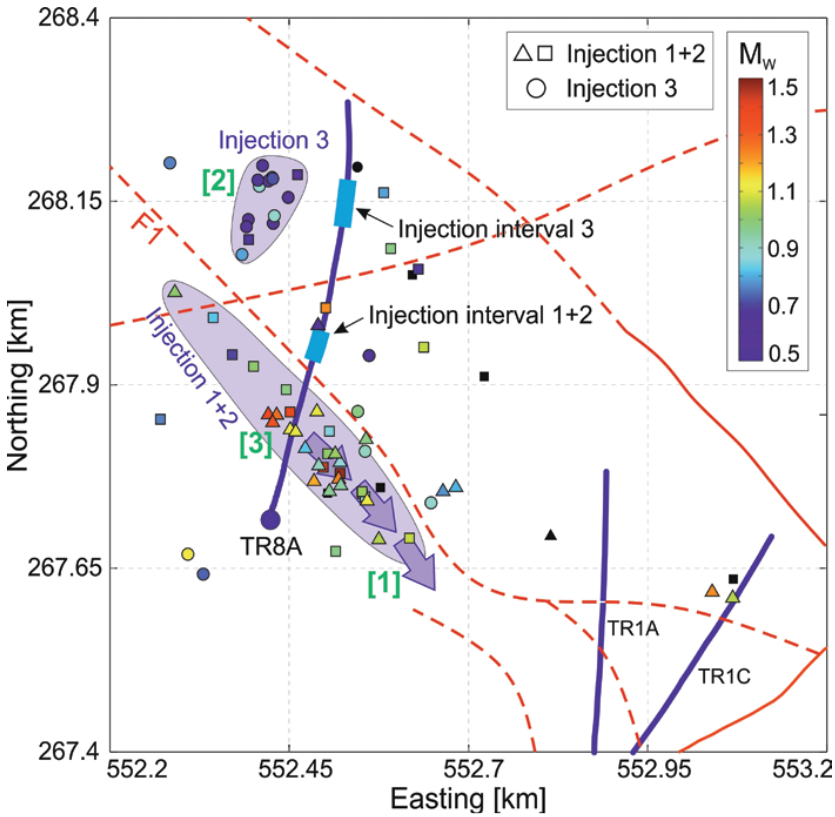


Figure 11: Spatial and temporal changes of seismicity in response to multiple injections in the TR 8A well (taken from Grzegorz Kwiatek et al).

5. CONCLUSIONS

Identifying active faults is very important in a geothermal system, the permeability is mostly associated with the presence of these geological structures, and often contribute to drilling targets either for production or reinjection.

The Mise a la Masse residual resistive anomaly map of Berlin geothermal field shows lateral resistivity discontinuities, correlated with the presence of possible permeable fractures, which is in good agreement with the precise seismic concentration, suggesting the presence of an active NW-SE local fault system.

The good resolution defining lateral resistivity contrast of the Dipole-dipole technique was very helpful in delineating geological structures in Ahuachapán geothermal field.

Head on profile method suggests the possible extension of the NW-SE trend in the northern part of Berlin geothermal field, which is in good agreement with the 1D horizontal gravity anomaly map.

The inferred faults of the resistive discontinuity of the Magnetotelluric method (MT) in Berlin geothermal field were very important in defining drilling targets for production wells, which provided successful results.

A possible increase of the producing reservoir towards the southwest part of Berlin geothermal field was interpreted based on the extension of the high positive gravity anomaly at depth, which extends beyond the Berlin geothermal field.

Gravity mapping during the injection test into a reinjection well of Berlin geothermal field suggests a preferential path through a NW-SE local fault system, which is in good agreement with the high precision epicenter location.

6. ACKNOWLEDGMENT

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