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MIRAVALLES CALDERA AND SHALLOW STRUCTURES INFERRED FROM GRAVITY

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ABSTRACT

The Miravalles geothermal field has fourteen years of exploitation hence the knowledge of the roles of faulting and how they constrain its sustainability is well known. We explore applications (and limitations) of gravimetry to study silica calderas. First enable us to determine its possible geometry, then its correlation to similar structures in the Guanacaste volcanic range. The straight forward application was to apply the standard anomaly separation analysis to the structures identified previously. As a result it is expected to perform a better inversion of the gravity data for a detailed structure definition in the near future.

1. INTRODUCTION

The Miravalles volcano is located in a volcanic range of andesitic Quaternary stratovolcanoes trending NW-SE, it grows up after the formation of the "Guayabo Caldera" about 600,000 years ago reaching 2,028 m above sea level. Its products were characterized mainly by lava flows ranging from andesitic to basaltic – andesite and dacite, with normal potassium contents. Six eruptive foci can be recognized in the same edifice; aligned NE-SW.

The volcano has no record of historic eruptive activity, but there are many hot springs and fumaroles on its south-western slopes, where the geothermal field is located. The proven area for the geothermal resource is greater than 21 km^2, 16 km^2 of which were dedicated to production and 5 km^2 to injection. There are 53 geothermal wells, including observation, production and injection wells, whose depths range from 900 to 3,000 meters. The tapped wells produce between 3 and 12 MW each, and the injection wells accept between 70 and 450 kg/s. The reservoir has a temperature of about 240°C and is water-dominated.

2. GEOLOGICAL SETTING

The trend of the Miravalles volcano along with its neighbours Tenorio and Rincón de la Vieja is parallel to the strike of the Middle American trench, attributed to the subduction of the Cocos plate beneath the Pacific plate. Though this simple subduction relationship does not explain locally the alignment of the summit's craters, which are mostly transversal to the trench. The stratigraphy includes units from the Pliocene to the Holocene, mainly constituted by pyroclastic rocks, lava, debris flows and lacustrine deposits, with a local basement that could be associated with tertiary rocks (Eduardo et al. 2005).

Among the more important morphological features is the caldera structure of Guayabo, which is 14 km in diameter and the result of at least three episodes of activity. Its north-eastern and eastern borders are covered, while the western, southern, and northern borders are well exposed, the latter are cut by a N-S system of normal faulting, that causes a depression along the caldera, it is inferred that the N-S and NE-SW faulting has had recent activity.

The more conspicuous fault systems are NW-SE, N-S, NE-SW and E-W, and are key parts of the hydrogeology of the hydrothermal system. The permeability has been defined as secondary in nature, and is controlled by these systems. The E-W trend is associated with a series of horst and graben, well expressed in the deeper units.

3. HISTORICAL SURVEYING

The gravity surveillance has been carried out in three stages, a regional attempt reported in 1976 with a Worden gravimeter, another one in 1984 with a Lacoste & Romberg meter in the Miravalles area and finally a reprocessing and integration of the previous ones with other regional data from the national oil company (RECOPE) reported in 1992 within the framework of geothermal exploration. The last one was a compiling and integrator effort, with all the geophysics available by then (Lezama et al., 1992), including gravity, and was concentrated on the Miravalles and Rincón de La Vieja volcanoes.

A regional survey of a larger area (with 535 stations) and a detailed gravity coverage limited to the area of the Miravalles caldera itself was then available. The main purpose of the first one was to establish the relationship between the basement in Miravalles and the outcropping rocks outside the study area. The gravity data are part of exploration surveys conducted by the Costarrican Institute of Electricity over three consecutive volcanoes; Tenorio, Miravalles, and Rincón de La Vieja, and a national gravity assessment done by the Costa Rican oil company (RECOPE).

In the case of the Miravalles geothermal field, they were the first data set to be acquired (Duprat and Leandro 1986). The stations were levelled by theodolite with an accuracy of 5 cm, and all the data were reduced using the 1930 gravity formula, with a base station at 548.8 meter elevation. The topographic correction uses a reduction density of 2.3 Mgm-3. The base was tied to the IGN and a Lacoste & Romberg model G was used for the surveying. All of the information is organized and stored in the WinGlink 22.02.02 program since from the beginning almost all the information was processed with earlier versions of WinGlink.

4. PROCESSING AND INTERPRETATION

Tidal, latitude, free air, Bouguer, and terrain corrections were applied. Details of the gravity survey and corresponding data processing are reported in Lezama (1992). Density was measured on samples from outcrops, and selected drilling cores and determined by the Nettleton profiles. The average density of the Quaternay ltihologies constituting the topography of the area was 2.12. Terrain correction was done according to the Hammer zones A, B estimated directly, and up to 160 km using a DEM (digital elevation model) from Guanacaste peninsula in scale 1:50,000 from the IGN (National Geographic Institute).

The processing started by carrying out several regional-residual separations by fitting a least squares surface, adjusting a polynomial of first or second order. The resultant residual anomaly correlated smoothly with the Bouguer anomaly map. Continuing with the anomaly separation, an analysis in the frequency domain follows determining the amplitude spectrum in 1D and 2D as criteria for designing the filter, e.g. low pass, band pass and directional filtering. In each case a characteristic of the whole resource is enhanced specially in terms of the faulting.

In geothermal exploration, the gravity method has been used to differentiate geological formations with different densities, and therefore is considered as a way of analyzing structures. The more outstanding elements considered for the interpretation are:

1. A gravity high of +09 mgal away from the crater of the volcano in correspondence with a crater relictus from older activity.
2. A relative low of -15 mgal toward the centre, aligned with other gravity lows from NNE-SSW.
3. The zone in between correlated with a clear gradient zone which coincides with most of the deep wells.
4. A gravity high of lesser amplitude but greater longitude to south and southeast.
5. A series of gravity highs to the W, in correspondence with the caldera border seen in the morphology.
6. A gravity low outside the caldera border to the southeast corner of the Bouguer map.

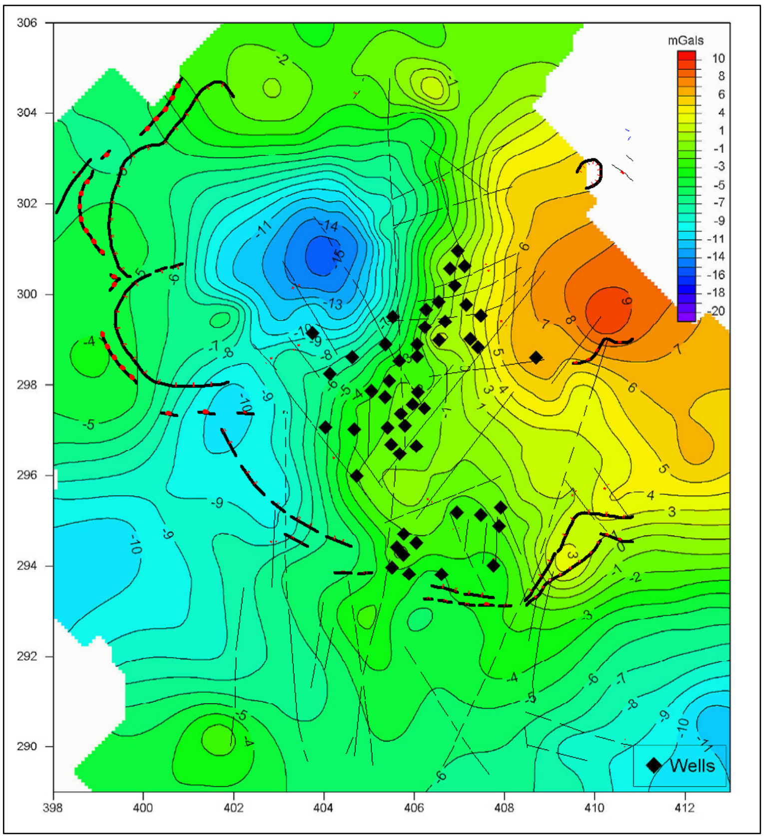


FIGURE 1: Bouguer anomaly map with main structures, the caldera border and faults

The gravity high characterizes a subsurface structure, in this case it is associated with an old crater relict. It is considered a residual intrusion from an old volcanic explosion (Figure 1). This feature is going to be enhanced in the filtering, especially in its wave longitude though the relieve keeps on being highest.

The gravity low constitutes a major depression located in the northern half of the caldera. The anomaly extends towards and crosses the southern border. It is not clear why these low density lithologies go beyond the caldera as it is consider today.

The Miravalles caldera is characterized by a large negative gravity anomaly almost symmetrical to a positive one. Laterally to the east, it evolves to a gravity high which corresponds to the young Miravalles, the parallel gradients as well as its changes to the south suggest a more complex interaction. The area in between these two anomalies is where most of the wells are concentrated, as well as to the south where the gradient decreases, widens and turns to the southwest. A gravimetric plateau somehow gives continuity to the gradient belt and almost extends to the inferred caldera border.

To the south, the basement presents a structural high, which constitutes a major feature of the geological units underneath Miravalles. The southernmost wells were drilled in this area and are characterized by $CO_3^{=}$ availability. The western border shows relative highs, with a relatively poorly developed gradient, this border constitutes residuals of andesites to basaltic- andesites rocks from previous explosions. The NW-SE and NE-SW systems are well observed affecting the major structures.

The limit of the caldera is not clear in the northeast, and north, it is constituted by a sub vertical and intermediate dip faulting (Figure 1). The subduction dynamics gave origin to a compression that produces a complex faulting system with predominant trends to NW-NE and N.

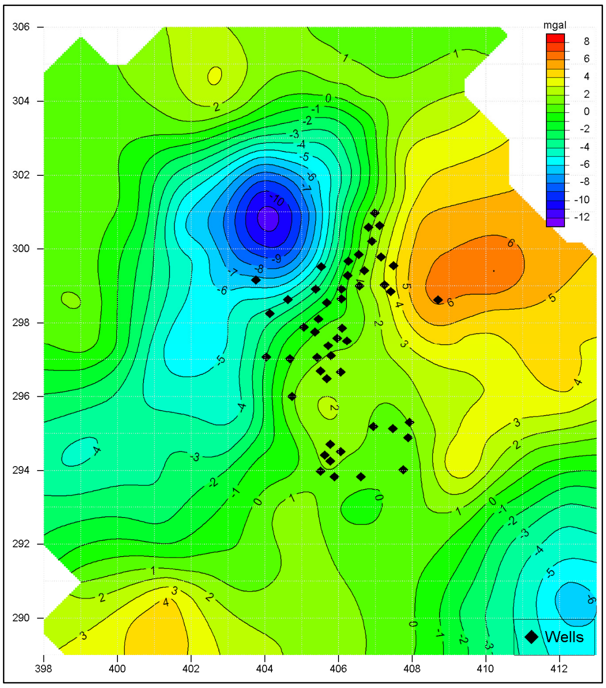


FIGURE 2: Detrended Bouguer map, after a least-squares polynomials of second order

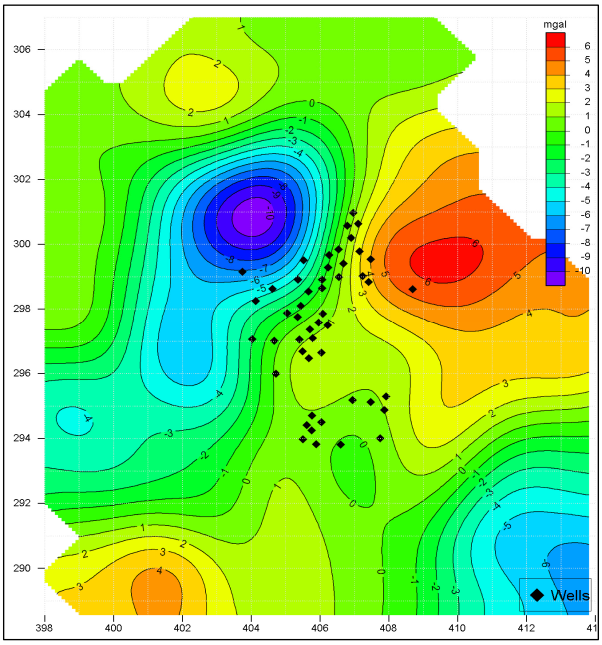


FIGURE 3: Bouguer anomaly, detrended and lowpass filtered (λ=3.5km)

In Figure 2, a structural NE-SW strike is observed, and is manifested more clearly in the 2D amplitude spectral analysis. For a start, the map is smoother and shows the main trends for at least three sectors that are well delineated, alternating between high and lows. The trend of the gravity anomaly has a close relation to the fluvio-lacustrine and glowing avalanche deposits which is likewise related to the main regional structures.

In Figure 3 the detrended surface was filtered considering a λ of 3.5km, after inspecting the 1D amplitude spectra. There is not much difference with the previous map, with the exception that the less important NW-SE lineament is now more visible. The main features described do not change, but became clearer, to the northeast, west and southeast; the anomalies shown are elongated and smoother.

Most of the positive anomalies are attributed to the paleo Miravalles structure, and in case of the highest value, it is very likely related to an intrusion as was mentioned before. The west border is now showing a well developed gradient zone whose trends are NE and NS, but more to E-W to the southern border (Figure 2).

The negative anomaly is still showing some high frequency "gravity highs", remnants of old crater activities. Finally the southern area of the gravity high corresponds mostly to an injection pole with gradient zones somehow perpendicular to the main gradient belts, seen on the pervious maps.

Lastly a band pass filter from 2-5 km (Figure 4) is showing some high frequencies in relation to the caldera border, enhancing high density spots from the caldera border, the vertical derivative process was done, looking for lateral changes worthy of analysis.

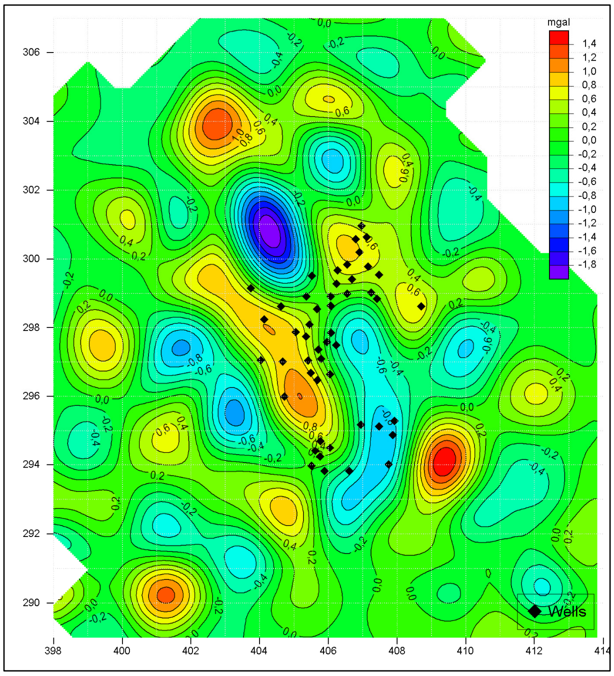
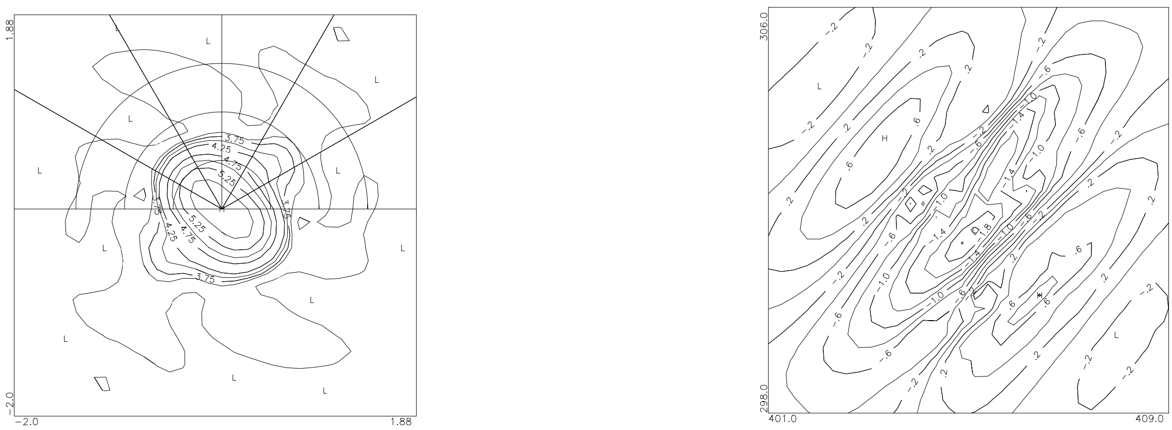


FIGURE 4: Bands pass from 2 to 5 km

4.1 Directional filtering

A spectral analysis in 2D requires dividing the area into three squares, each one forming an equal size grid, the central value is the DC bias, and the Nyquist frequency is reached at the edges. In these cases, areas 1 and 2 are 8 x 8 km and area 3 is 9 x 9 km, the local coordinates are in each square.

Filters were used to isolate anomalies by removing or enhancing linear features or by removing or enhancing spatial frequency ranges. The 2D amplitude spectrum in Figure 5 shows two major linear trends at 40° and 140°, the first one seems to be more relevant, A1 represents a square area centred on the largest negative anomaly, nonetheless it shows what is going to be a characteristic for the whole area. The value of 0 degrees corresponds to the left side of the horizontal line. In the space domain the 0 degrees of the 2D amplitude spectrum is at north and the angles are measured clockwise.



Amplitude Spectrum A1

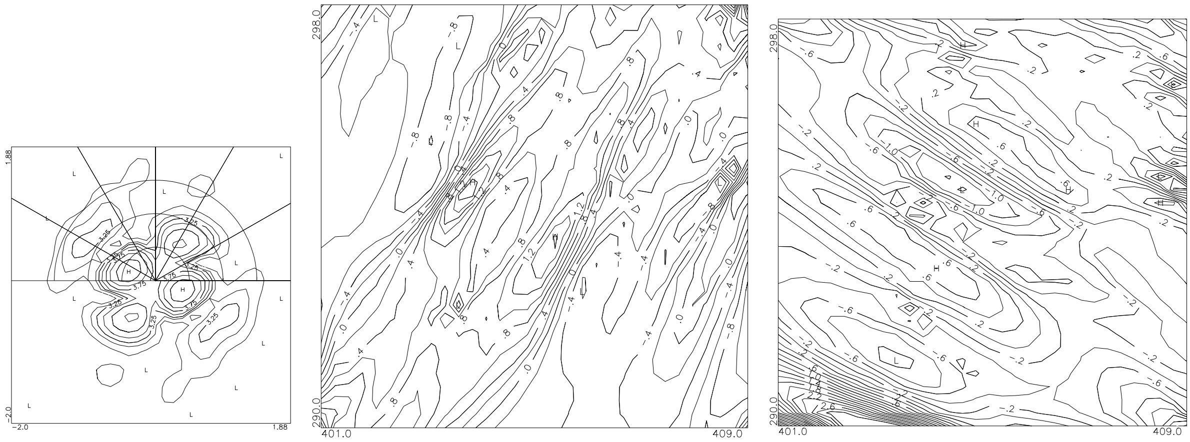
Anomalies in space domain after fan pass filtering (for 40°).

FIGURE 5. Directional filtering in Area 1

Each area's values were obtained after detrending it with a polynomial of the first order, transforming to the frequency domain, windowed with a Hanning window because of the edge effects at the borders and finally transformed back to the space domain.

In Figure 5 the gravity spectrum suggests a broad northeasterly trend, with another smooth high frequency trend not shown at 140°. For the demonstrative purpose of this paper, it was important to establish it as the best developed direction, in coincidence with the gravity low and its limits.

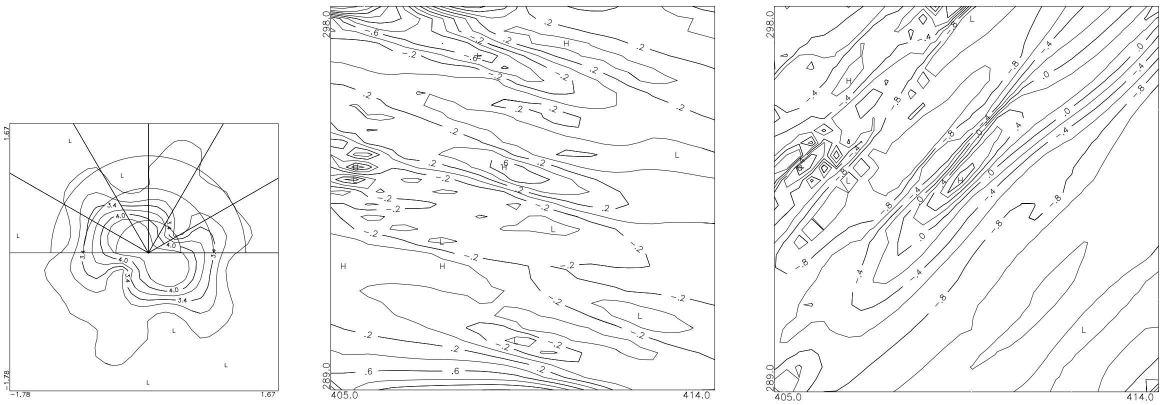
In Figure 6, the two strikes of A1 persist, but this time revealing the gravity high of the south, limited by low density basins. These gravity lows correlate with low density pyroclastics, which extend out of the caldera, the same as the filtered anomalies. At 120° it is possible to look at what could be the inferred caldera border, or either some structure that extends to the southeast.



Amplitude spectrum A2 — Anomalies in the space domain after filtering band pass at 30° — Anomalies in the space domain after fan pass filtering (120°)

FIGURE 6: Directional filtering in Area 2

In Figure 7 again the strike of 45° is well defined, but now two other strikes not consider before appear. There are no faults identified with this direction, furthermore these slight changes form a smoother trend and reache higher frequencies. It is at least plausible that the fan pass filter for 105° corresponds to a larger structure coming from the east - southeast.



Amplitude spectrum A3 — Anomalies in the space domain after fan pass filtering for 105° — Anomalies in the space domain after fan pass filtering for 45°

FIGURE 7: Directional filtering in Area 3

5. CONCLUSIONS

Among the reasons for some gravity changes are: intrusions, low grade metamorphism caused by alteration mineralogy, changes in the porosity, phase changes, faulting, dykes and finally basements depth variations.

The study of the gravity fields associated with volcanic structures has provided valuable information on the geological formations of such structures as well as on the dynamic evolution of active volcanoes as reviewed in Campos-Enriquez (2005) and Rymer and Brown (1986).

Three possible causes of the negative gravity anomaly form the caldera structures are; ash flow silicic infillings, partially molten and occasionally solidified magma chambers, and the activity of geothermal processes of active systems causing a density decrease. For smaller calderas though, the leading role are by the infillings.

The gradient belt between the gravity low and high anomalies described is where most of the successful wells are concentrated, but stepping out of this area increases the risk. A dominant gravity structure became clear, which let us divide the area into three NE-SW zones (domains).

All the amplitude spectra investigated converge in the regional strikes that characterize the Miravalles caldera. Interesting though is that the anomalies continue beyond the caldera border. Additionally the sub-circular gradients featuring the Bouguer map and residual anomaly do not coincide with the mapped caldera rim, suggesting that the original caldera might have been smaller.

Further attention has to be given to the trends not mapped as faults, or a family of faults. The fracturing can be more intense, accounting for more permeability facilitating the alteration mineralogy as was observed in Area 3. The wells from this zone are more massive, richer in non condensable gases and are showing a higher bicarbonate content.

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