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Gravity Changes in the Cerro Prieto Geothermal Field, México

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ABSTRACT

The last gravity precision survey together with a first order precision leveling at Cerro Prieto Geothermal Field (CPGF) was carried out during 1997.

Observed gravity changes, corrected for subsidence, between 1978 and 1997 in CPGF are compared. Differences are related to the mass deficiency after 25 years of exploitation that reached 1,800 million metric tons of fluid.

A widespread mass deficiency is observed in the whole CPGF with three subzones. One enclosed by the Cerro Prieto fault on its west margin and related with the alpha reservoir (>600±200 μGal); the second is related to the beta reservoir in the lifted block of the H fault (>700±200 μGal) and the third is in the southeast flank of H fault with differences up to 1000±200 μGal. Two areas are identified with gravity increases; one associated to the injection of residual brine at Cerro Prieto One (CPI) and other in the northeast border of H fault.

Introduction

Repetitive precision gravity measurements have demonstrated the capability to evaluate transient gravity changes, as small as 5-10 μGal (1 μGal = 0.01 μN/kg). Gravity changes have allowed us to infer changes of mass caused by exploitation-recharge-injection in diverse geothermal fields in the last several years, (Allis and Hunt, 1986; Ehara, et al., 1998; Sugihara and Ishido, 1998). The CPGF is located inside the south portion of the Salton trough in the Mexicali Valley in Baja California, Mexico, (Figure 1). The reservoir is located between 500 and 2300 m depth, is of the liquid-saturated type (T>150°C), and formed by sandstone and clay strata from the Cenozoic era. The Colorado River, deposited these sediments in the Salton trough. This depression contains several spreading centers controlled by a system of transform faults with lateral right displacement, (Biehler et al., 1964). The Cerro Prieto spreading center is controlled to the east by the Imperial fault (Lomnitz et al., 1970; Elders et al., 1972) and to the west by the Cerro Prieto fault, both with northwest strike. Traverse to this fault system, another fault system has been identified as "Volcano". This spreading center is considered as the heat source of CPGF, (Elders et al., 1984).

The CPGF began commercial exploitation in 1973 generating 75 MW in CPI then increasing to 150 MW in 1979 with geothermal fluid extraction increasing from 22.4 to 38.1 million annual tons. During 1981, the installed capacity was increased to 180 MW. In January 1986 Cerro Prieto Two and Three (CPII and CPIII) began generating electric power, 110 MW each. Later, in September 1986 (CPII) and in June 1987 (CPIII) were enlarged, so that the total

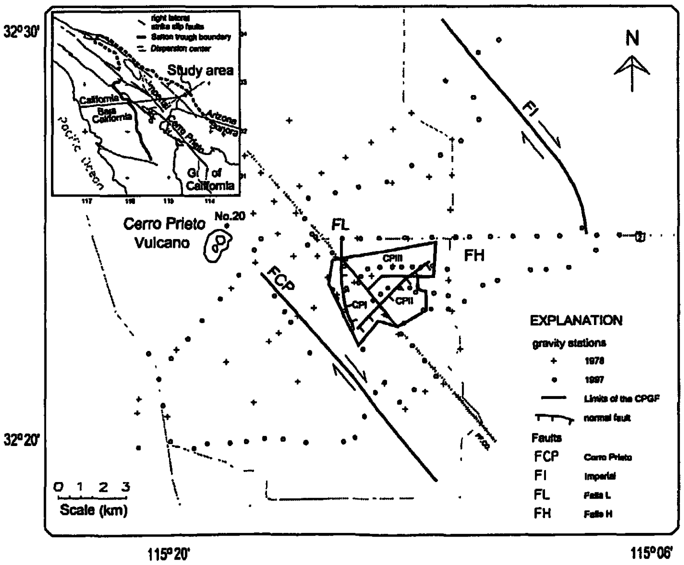

Figure 1. Study area. In the upper box the tectonic settings of reference is shown, the shady areas correspond to the active dispersion centers inside the depression. Crosses indicate the position of the 1978 gravity stations and with circles those of the 1997 survey. Continuous lines indicate the limits of the CPGF divided administratively into CPI, CPII and CPIII. The normal FL and FH faults don't have superficial expressions; they are identified from wells logs (Halfman et al., 1987).

field installed capacity reached 620 MW; this situation persisted until 2001. Today Cerro Prieto Four (CPIV) is operating and total installed capacity has reached 720 MW. The generation of this energy has required the extraction of 1800 million tons of fluid between 1973 and 1997, with only 140 million tons injected to the reservoir, from 1989 to 1998 (Truesdell et al., 1998).

Reservoir Evolution Under Exploitation

An hydrogeologic model of the geothermal reservoir was described by Halfman et al., (1984, 1986). They identifying three productive strata, called "alpha", "beta" and "gamma", from shallowest to deepest. According to these authors, before exploitation, the geothermal fluid ascended from the deepest strata toward the superior strata through the normal faults L and H (Figure 2) until reaching the surface or mixing with shallow waters. Since exploitation began, the flow direction has reversed and the recharge is from superior strata, through these same structures, toward the reservoir (Lippmann, 1991). Unit CPI exploits mainly the shallowest "alpha" stratum between the railroad line and the Cerro Prieto fault. On the other hand, CPII and CPIII units exploit mainly the "beta" stratum (Figure 2).

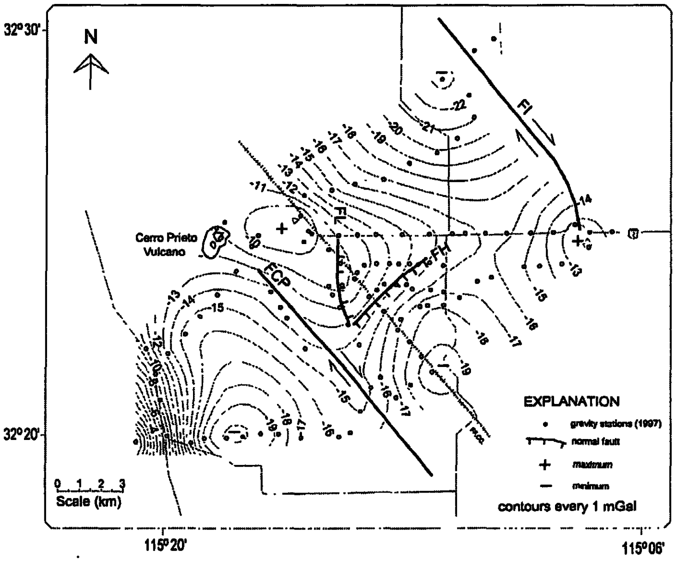

Figure 2. Simple Bouguer gravity anomaly for 1997. The values are relative to station No. 20 of the 1978 study. The contour interval is 1 μGal.

Truesdell et al., (1997) explain that changes in chloride concentrations and steam enthalpy in the shallowest producing stratum (alpha) are caused by the entrance of cold and less saline waters from the upper aquifer, along fault L.

Truesdell et al. (1995), postulate that the flow in the "beta" stratum is controlled by the normal fault H. The "beta" producing stratum, located in a lifted block to the NW of the fault, (700 m of vertical displacement) contained fluid near the boiling point before its exploitation. When fluid extraction began, a widespread area of vapor appeared due to the depression of the pressure and to the reduced recharge from the southeast. On the other hand, the "beta" stratum, inside the fallen block to the SE of the fault, contained fluid below the boiling point before exploitation. When exploitation began it received cold recharge water from the south flank; this recharge allows it to maintain the pressure up of 50 bars more than the stratum in the lifted block, (Truesdell et al., 1997).

Subsidence in the CPGF

By differential first order leveling on a net of level banks distributed around and inside the CPGF, Lira (1998) reported vertical descending movements of up to 0.1 m/year, during 1994-1997. He found a maximum subsidence of 1.861 m, between geothermal plants CPI and CPII during 1977-1997. Glowacka (1998) reported average velocity of superficial vertical movement on the Imperial fault was 0.95 m during 1987-1997. This value is very similar to the CPGF subsidence velocity reported by Lira (1998). Additionally, Glowacka (1998) interpreted that changes of subsidence inside the CPGF could be associated with the increase in the exploitation and that the recorded earthquakes (Imperial Valley in 1979; Victoria in 1980; Cerro Prieto and Superstition Hills in 1987, among others) have worked as triggers of these changes. According to Elders (1979), continuous sedimentation of the area by the Colorado River has prevented a more marked topographical depression.

Previous Precision Gravity Studies

In 1978, Chase et al., (1978) began the first precision gravity study in the CPGF, and it was repeated in 1979, 1979-80 and 1980-81 (Grannell et al., 1979, 1981a, 1981b, 1982) in order to detect temporal and spatial gravity variations. These could be associated with possible changes in the geothermal field caused by fluid extraction. In order to obtain simple Bouguer anomaly values, free air and latitude corrections were applied, assigning a density of 2.67 g/cm^3. Topographical corrections were not made due to the featureless topography of the area, causing errors of up to 1500 μGal in places near Sierra Cucapás and of 20 μGal in stations located on the road beside of the irrigation channels (Chase at al., 1978). The suppression of the tidal drift was made theoretically using the formulation proposed by Longman (1959). The reported gravity values were relative to a base located in the Sierra Cucapás, (Station 1, in Figure 1 of Chase et al., 1978).

Chase et al., (1978) confirmed the Velasco and Martínez (1963) and Fonseca and Razo (1979) interpretations, showing that the CPGF is located near the southeast termination of an important gravimetric local maximum. They also observed that the Volcano system and the Cerro Prieto volcano lack a gravity expression. Additionally, they interpreted the change of direction of the contour lines, from northwest to west located in the northeast corner of the area, as the border of an area of deeper sedimentary fill (Figure 3 of Chase et al., 1978).

Gravity changes were associated with the Hidalgo fault and caused mainly by fluid extraction from gravity differences during 1979-80 and 1980-81.

The mass deficit due to the fluid extraction combined with the subsidence phenomenon, the presence of a widespread area of vapor in the reservoir, the recharge of cold waters as well as the injection of geothermal fluid from the surface has produced temporal and spatial gravity variations. The purpose of this work is to estimate the temporal and spatial gravity variations during a 19 year period between 1979-1997 and to analyze these variations in terms of subsidence and processes of removal or increase of mass in the location. Identification of the main gravity changes in time and space will allow inferring changes in the reservoir dynamics because of the exploitation and the regional tectonics. 1997 was the last year with precision leveling and repeat gravity surveys in the CPGF.

Gravity Measurements in 1997

Gravity measurements were carried out in 112 banks, of a first order leveling net of Comision Federal de Electricidad (CFE) and of Centro de Investigacion Cientifica y de Educacion Superior de Ensenada (CICESE) (González, 1994) (Figure 2), with a Scintrex model CG-3 gravimeter. The field survey was carried out using loops returning to the base station in time intervals smaller than 3 hours, a period of time in which the tidal drift was considered linear.

First order differential leveling of the level banks was carried out in February, 1997 and the gravity precision survey in June, July, August, September and October during the nighttime, to avoid environmental noise and abrupt variations of temperature as much as possible. Reduction data to simple Bouguer anomaly was carried out following the same methodology reported by Chase et al., (1978) in order to be able to compare the results (Figure 1). Tide correction was done using the formulation proposed by Longman (1959) and applying the same constants used by Chase et al., (1978). A density of 2.67 g/cm^3 was considered for the Bouguer correction and the theoretical gravity formulation, using the international ellipsoid of 1931 (Nettleton, 1979). Both studies were bounded using relative measurements in station No. 20 located in the Cerro Prieto Volcano, (Figure 1). This station, over volcanic rocks, is less exposed to subsidence than the stations located on the sedimentary filling of the Mexicali Valley.

Error Analysis

The number of gravity measurements in each station was defined by occurrence and intensity of earth vibrations caused by the presence of seismic activity, vehicular traffic, extraction of geothermal fluid, etc. in order to reach a predefined standard error of 5 μGal, (Scintrex, 1992).

The average instrumental error in the survey was 9 μGal, with a maximum error of 39 and a minimum of 5 μGal, defining the instrumental error as the standard deviation divided by the square of the number of samples (Bevington, 1969). In places with low vibration levels the preset error was reached in less than 50 gravity readings; 340 readings were the average of the survey with a maximum of 1050 in those with problems of environmental noise.

All occupied stations had identifiable concrete bench marks that which included in the first and second order leveling that implies errors 3-5 mm and of 6-8 mm per kilometer of longitude, respectively, (Kissam, 1986). Maximum free air effect was 12.3 μGals considering an error of 8 mm per kilometer and a maximum closing of 25 km. This leveling error will be reflected in the Bouguer correction in 4.5 μGal considering a density of 2.67 g/cm^3. The total error because of uncertainties in the determination of the elevation is of 16.8 μGal. Location error of the stations has very little influence in the determination of the Bouguer anomaly because maximum errors are 0.005 m.

The comparison among gravity studies was carried out without considering the correction for topographical effects (simple Bouguer anomaly), because of the scarce topographical relief in the area. However, the stations located near irrigation channels have elevation differences from 2 to 2.5 m which would imply maximum differences of 25 μGal according the Hammer formulation, (Telford, 1979). On the other hand, in stations near the Sierra Cucapás errors of 1500 μGal could be expected (Chase et al., 1978).

The associated error to relate both gravity studies is a function of the change in elevation of the common gravimetric station (station No.20 of the study of 1978), located over volcanic rock in the Cerro Prieto volcano. Subsidence intensity associated with the Cerro Prieto volcano can be assumed smaller than the sedimentary filling, probably about 0.001 m/year. This subsidence is 0.019 m, which means 5.8 μGal of free air effect and 2.1 μGals of Bouguer effect, in the entire period considered.

Bouguer gravity anomaly is the algebraic sum of different factors that affect gravity reading. The total error associated to its estimate is calculated from the sum of the errors of each correction.

$$\varepsilon\Delta g_B = \pm\varepsilon g_{obs} \pm \varepsilon g_N \pm \varepsilon g_{a.l.} \pm \varepsilon g_{boug} \pm \varepsilon g_{topog.} \pm \varepsilon g_{enlace}$$

where:

$\varepsilon\Delta g_B$	total Bouguer gravity error (± 60 μGal).
εg_{obs}	instrumental error (± 9 μGal).
εg_N	theoretical gravity error (± 0.7 μGal).
$\varepsilon g_{a.l.}$	Free air anomaly error (± 12.3 μGal).
εg_{boug}	Bouguer correction error (± 4.5 μGal).
$\varepsilon g_{topog.}$	maximum error of terrain correction in gravity stations far from the Sierra Cucapá (± 25 μGal).
εg_{enlace}	bounding error between gravity studies in 1978 and 1997, (± 8 μGal).

Because of the error analysis, only Bouguer gravity anomaly differences (DgB) greater than 60 μGal between the gravity studies can be considered significant. In order to reduce the uncertainty, gravity stations near the Sierra Cucapá were not included.

Simple Bouguer Gravity Anomaly

Simple Bouguer gravity anomaly obtained is presented in Figure 2. The relative gravity Bouguer anomaly map for 1997 shows the same pattern of anomalies as in 1978 (Figure 3 of Chase et al., 1978) and those obtained by Velasco and Martínez (1963) and Fonseca and Razo (1979). The Bouguer gravity configuration for 1997 delineates the tertiary structure constituted by the shales and sandstones of the deltaic environment in the CPGF. A gravity maximum with northwest-southeast axis direction located in the northwest part of the study area stands out. This maximum is coincident with large deposits of sandstone as it is known from lithologic logs of wells M-3, Q-757, M-96, corresponding to the frontal layers of the delta, (Cobo, 1979).

The gravimetric low located between the Laguna Volcano and the town La Puerta has moved approximately 3 km south compared to the one presented by Chase et al., (1978) due to a better space control of this structure, coinciding with the one presented by Velasco and Martínez (1963). The gravity minimum located in the town; estación Delta to the southeast is coincident with the one configured by Velasco and Martínez (1963) and Fonseca and Razo (1979). A saddle effect in the simple Bouguer anomaly is observed in the town Nuevo León presented by Fonseca and Razo, (1979) and sketched by Velasco and Martínez (1963) and Chase et al., (1978).

Gravity Changes: 1978-1997

Because the gravity stations occupied in 1978 do not correspond those of 1997, mapping the gravity changes required interpolation to a regular mesh, interpolating both the gravity differences and the elevation to the same spacing. The interpolation method used was kriging and the mesh was formed by 44×44 separate nodes with 400 m spacing. The area considered was the overlap of both surveys.

The relative observed gravity and the elevation of the interpolated meshes of 1997 were subtracted from those of 1978, node by node. Negative signs in the changes of the observed gravity imply decreases in gravity, and negative signs in the difference of elevation reflect subsidence.

Because of the observed gravity changes, product of the subtraction, contain the effect of the difference in elevation among nodes. The observed gravity was corrected by free air effect using 30.86 μGal/m. Allis and Hunt (1986) proposed to consider land subsidence (h_{1997}-h_{1978}) as compaction process removing mass from the location. Considering the rock compressibility and the thickness of the compacted stratum is very difficult because of their variability and difficulty of evaluation. This consideration implies that spaces left by the extracted fluid are filled by sediments in the same proportion. The effect on the gravity changes are expressed:

$$\Delta g = 2\pi G\rho_{water}(h_{1997} - h_{1978})$$

If the extracted fluid corresponds to the saturated area of water $((\rho_{water}=1.0)$, as considered in this work, the effect is: $\Delta g \approx -40$ μGal/m. Nevertheless, if the extracted fluid corresponds to the vapor area the effect is $\Delta g \approx -0.4$ μGal/m.

The configuration of the observed gravity differences corrected for the free air and Bouguer effects is presented in Figure 3. Topographical effects were minimized by considering only the area of the CPGF far from the abrupt topographical relief like the Sierra Cucapás. Figure 3 includes the locations of the Cerro Prieto faults according to Fonseca, (1982) and the area of H and L faults in the roof of the beta reservoir, according to Truesdell et al., (1995). Only subsidence corrected gravity changes exceeding spatial are significant because errors associated with the measurements and data reduction are around 60 μGal and the interpolation scheme could rise the uncertainties to 150 μGal.

A generalized zone of gravity decease (negative gravity change) exists in the CPGF. Three subzones inside the CPGF can be identified as gravimetric lows, another is located to the Northwest, out of the CPGF.

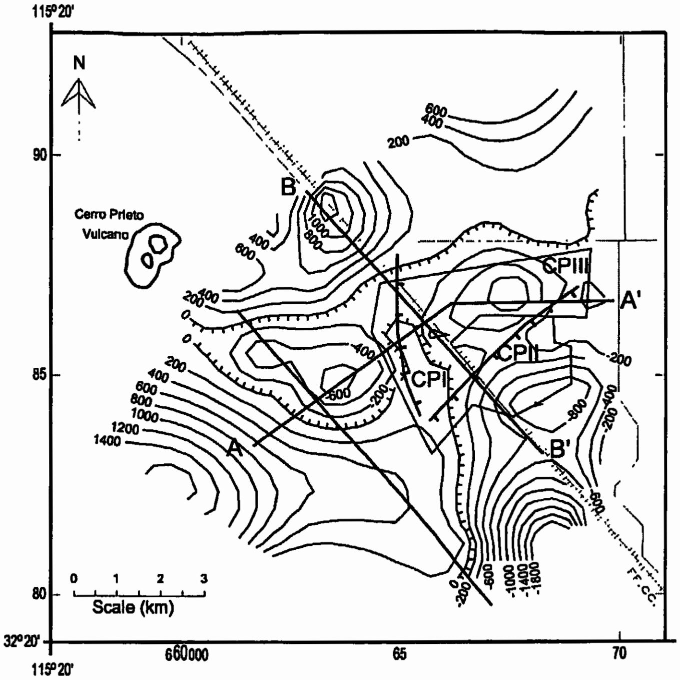

Figure 3. Differences in observed gravity corrected for the period 1978-1997. The negative sign implies decrease of density. The contour interval is 200 μGal. The Cerro Prieto fault position was taken from Fonseca (1982) and L and H faults are from the top of the beta reservoir and were taken from Truesdell et al. (1995). Locations of A-A' and B-B' profiles of the Figure 4 are indicated.

The three subzones with a negative change in the observed gravity inside the CPGF can be associated with:

1. Subzone CPI and area of the Cerro Prieto fault, located to the west of the CPGF with a negative change in the observed gravity of -648±200 μGal. The zero contour extends to the west of the Cerro Prieto fault. The anomaly is controlled by the border lagoon, 1997 gravity stations but without coverage in 1978. For this reason, the extension cannot be delimited accurately.

2. Subzone CPIII, with a better distribution of gravity stations: limiting to the north with those located on the highway; in their central portion those inside the CPGF; and to the west those located along the railroad. The size of the variations of observed gravity is larger than -774±200 μGal and seems to be limited in depth where the H fault reaches the beta reservoir.

3. Subzone CPII. The largest variation of observed gravity is observed inside the CGCP (-1018±200 μGal). Nevertheless, there are not enough gravity stations covering the area, mainly for the 1978 study. This restricts the definition of its extension to the south.

Its important to note the gravity high observed to the east of the Cerro Prieto Volcano outside the exploitation area along the railroad line. There is not enough coverage of gravity stations to define with certainty its extension in the east and west directions, but the magnitude of the gravity difference is larger than -1200±200 μGal.

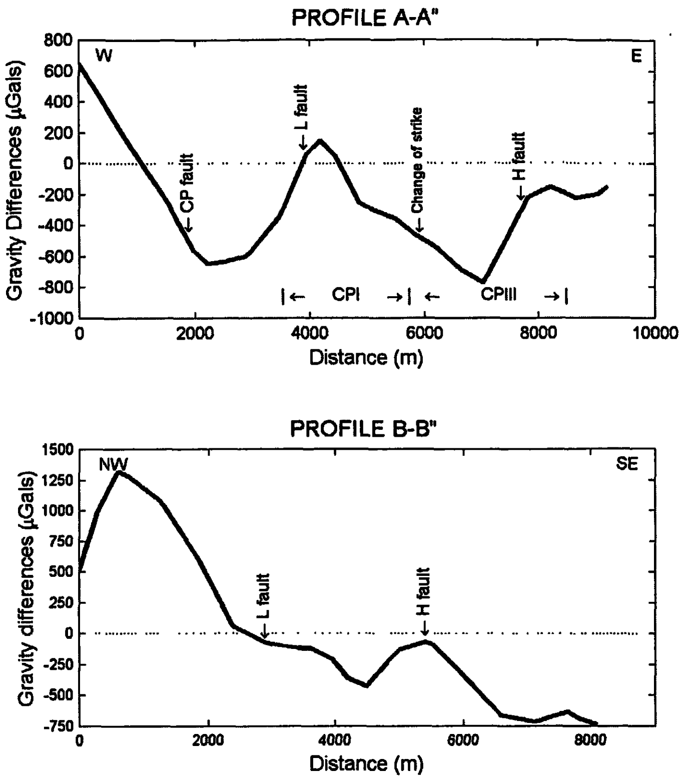

Figure 4. Profiles of differences in observed gravity corrected for subsidence for the period 1978-1997. The location of the profiles is indicated in Figure 3.

Two gravimetric changes minima are present in profile A-A' (Figure 4). The minimum located to the west begins with positive differences in the first section of the profile, diminishing to zero when approaching the area of the Cerro Prieto fault, then reaching values less than -600±200 µGal in the area of superficial manifestations where the evaporation lagoon is located. The values increase gradually toward positive values in the CPI area and the L fault. The values begin to descend again eastern of the fault L until differences in minimum observed gravity of -774±200 µGal in the area of CPIII. East of the CPGF and northeast portion of H fault values rising but without reaching positive differences.

Profile B-B', with the same orientation (NW-SE) as the main structures (Cerro Prieto and Imperial faults) shows positive change to the NW (outside the CPGF) with a relative minimum corresponding with H fault, then decline to the SE, outside of the CPGF (Figure 1 for location).

Interpretation of Gravity Changes

At the subzone of Cerro Prieto fault and CPI the decrease in the gravimetric values probably are due to mass deficiency because of fluid extraction. The loss of geothermal fluid inside the alpha reservoir has been identified by decrease of water levels in wells and enthalpy decrements (Beall et al., 1994), reaching 48 million metric tons of fluid extracted from alpha reservoir up to 1997, (Truesdell et al., 1998), as well as the reversal of the fluid flow direction in this area (Lippmann et al., 1991). However, not all the extracted fluid originate from the geothermal system. The evolution in chloride concentration together with the oxygen-18 and deuterium content of the geothermal fluid has indicated, from the beginning of the exploitation, an area of recharge of cold waters from the west portion of the field, (Stallard et al., 1987; Truesdell et al., 1979). This recharge has been quantified as approximately 50% of the total of the extracted fluid (Truesdell et al., 1998).

The relative gravity high, shown in the profile A-A' (Figure 4. to 4000 m from the profile start) along L fault (Figure 2), could be related to the injection of residual brine (T <25°C). This contribution of mass, although of smaller quantity (approximately 30% of the total extracted fluid from alpha reservoir: Truesdell et al., 1998), could cause an increase in the net mass. This is possible because this salty water is denser than the geothermal fluid.

Subzone CPIII: this minimum in the gravity changes shows the deficiency of mass in the geothermal reservoir. This subzone is associated with the lifted block of the beta stratum. The presence of vapor areas around wells, isotopes, and chemical evolution of the production fluid are evidence of inadequate recharge (Truesdell et al., 1998). The NE limit of this relative minimum (smaller than -250±200 µGal) corresponds to the recharge area of the beta stratum through H fault. SE limit of gravimetric low corresponds with H fault and beta reservoir contact, which serves as a barrier to recharge (Truesdell et al., 1995). In the same sense, the zero contour is the mass deficit limit on the north side of the CPGF.

Subzone CPII: the more extensive negative gravity change inside the CPGF is related to beta reservoir located in the fallen block of H fault. However, the stations coverage is insufficient to delimit the anomalous to the southeast. Truesdell et al., (1998) estimated that approximately 20% of the total geothermal fluid extracted from this reservoir comes from outside of the geothermal system and that the net extraction reaches $1.3X10^9$ metric tons. This mass deficit conforms with the negative evolution of gravimetric changes since 1978, practically the beginning of the reservoir exploitation.

From 1978 to 1997 numerous earthquakes have taken place, inside and outside the CPGF, (Frez and Friaz-Camacho, 1998). Many could have worked as triggers of subsidence producing a compaction and density increases, just as with other earthquakes: Victoria in 1980, Blackish Hill and Superstition Hills in 1987, among others (Glowacka, 1998). This phenomenon is not restricted to the local CPGF area, because earthquakes are related to tectonic movements. The gravity correction for subsidence proposed by Allis and Hunt (1986) supposes that the compaction only displaces water. This could be happening partially, because in some areas of the reservoir (producing beta stratum to the NW of H fault) steam has formed overestimating the gravity differences. Additionally, it supposes that the system has responded immediately to subsidence, compacting all the intergranular spaces evacuated by the fluid extraction. It implies that the earthquakes would not work as triggers of the compaction as was interpreted for the Victoria 1980 event by Grannell, et al., (1981).

Conclusions

The principal gravity features identified in previous studies were reproduced in the 1997 survey. The seat feature was delineated in the Town Nuevo Leon to the east of the study area, sketched by Chase et al., (1978), Velasco and Martínez (1963) and Fonseca and Razo (1979). The principal difference in the observed gravity from the 1978 study was a minimum to the SW of the study area and a maximum to the SE (Chase et al., 1978).

The observed gravity differences, corrected for subsidence according to the scheme proposed by Allis and Hunt (1986) in the period 1978-1997, are larger than the estimated error, including data acquisition, reduction and interpolation to a regular mesh (±200 μGal).

Differences in observed gravity between 1978 and 1997 are in accord with the interpretation of isotopic, geochemical and thermodynamic studies. A widespread area of loss of mass in the CPGF was found; it can be divided in three subzones. One is related with the Cerro Prieto fault and the alpha reservoir, showing differences in observed gravity of -648±200 μGal. The two others are related to beta reservoir and both sides of the normal H fault.

The northwest side of H fault corresponds to the lifted block; gravity differences of -774±200 μGal were observed, while in the southeast flank (in the sunken block) observed gravity differences are -1018±200 μGal. The extension of these negative observed gravity differences could only be delimited in the subzone corresponding to the lifted block to the NW of the H fault because of the gravity station coverage.

Additionally, two areas with mass contributions to the geothermal system (recharge areas) are correlated with positive differences of observed gravity (relative maxima). One maximum is correlated with injection of residual brine into the alpha reservoir and L fault. The second peak is correlated with the flank NE of H fault when it cuts reservoir beta, where evidence of recharge exists.

Mass changes in the reservoir due to the combined effect of extraction-injection-subsidence can be inferred evaluating changes in gravity. Repetitive gravity precision observations could help to infer the evolution of the CPGF reservoir.

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