Modeling of Subsidence in the Cerro Prieto Geothermal Field, B. C., Mexico

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ABSTRACT
The Cerro Prieto Geothermal Field (CPGF) is located in the Mexicali Valley, in the southern part of Salton Trough. This zone is characterized by high tectonic seismicity, heat flow and surface deformation, related with the tectonic regime of the zone. Besides the tectonic deformation, extraction of fluids in CPGF produces deformation of large magnitude (Glowacka et al., 1999).

In the present work we model both natural and anthropogenic components of subsidence. We model the natural component of subsidence using known data about the seismotectonic situation and the Coulomb 2.0 program (Toda et al., 1998). The resulting model shows that the subsidence due to tectonic movement constitutes approximately 4% of the observed subsidence rate.

The anthropogenic part was simulated using "tensio-nal rectangular cracks" (Yang and Davis, 1986). Modeling was done using the Coulomb 2.0 program with a "trial and error" strategy. The resulting model for anthropogenic subsidence is based on a hydrological model of the CPGF (Halfman et al., 1984; Lippmann et al., 1991) and can explain the observed data with a RMS misfit of 0.79 cm/yr.

To evaluate the influence of deformation in the stress field and in the local seismicity, we calculated the change of the Coulomb stress produced by the closure of cracks in our model, as well as by tectonic movement. Our results show that the magnitude of this stress-field change, caused by extraction of fluids in CPGF, is large enough to trigger earthquakes.

1. INTRODUCTION
The Cerro Prieto geothermal field (CPGF) is located in northern Baja California, Mexico, to the south of Mexicali, in the southern portion of the Salton basin which is considered to be one of the geological provinces with the largest geothermal resources in the world (Fig. 1). Cerro Prieto is a large high-temperature (280-350°C), liquid-dominated field, contained in sedimentary rocks. The field is operated by the Mexican Federal Electricity Commission (Comisión Federal de Electricidad, CFE). Fluid extraction for electricity production began in 1973 at 1500 - 3000 m depths. Currently, the CPGF is the world's second largest geothermal field with a 720 MW capacity. Rejection of residual water began in 1989, and currently about 20% of the extracted fluid is being re-injected at 500 - 2600 m depth.

The CPGF is located within an extremely active tectonic region, in the boundary between the Pacific and North American plate, which consists of a wide zone of transform faults from the San Andreas system with relative interplate motion of 4.9 cm/yr (Bennett et al., 1996). The CPGF lies in a tectonic pull-apart basin located between two major right-lateral, strike-slip faults, the Imperial and Cerro Prieto faults.

It is well documented that ground surface deformation may accompany geothermal fluid production (Narasimhan and Goyal, 1984). Probably the best known example is Wairakei Field in New Zealand, where the maximum total subsidence reached 14 m in 1998 (Allis et al., 1998).

At the CPGF, first-order leveling (Glowacka et al., 1997; Glowacka et al., 1999), precision gravity (Grannell et al., 1979), seis-mological (Fabriol and Munguía, 1997) and interferometric synthetic aperture radar (InSAR) monitoring (Carnec and Fabriol, 1999; Hanssen, 2001) have revealed subsidence and triggered-seismicity, both due to fluid extraction coupled with the specific tectonic context of the zone.

The present work aims to model both the tectonic and the anthropogenic parts of the observed subsidence, and to evaluate the stress changes caused by the anthropogenic component as well as compare them with stress changes caused by the tectonic motion.

2. DATA
We use the leveling data published in Glowacka et al. (1999). The data were recorded during the 1994-1997 period by CFE (Lira and Arellano, 1997) and CICESE (Glowacka et al., 1999). The reference point for the measurements is located in the SE part of the area, in the Cucapah mountains, and is assumed to be stable. The subsidence rate is shown in Fig. 2 (a). The dominant feature is the elliptical area with the highest subsidence rate, oriented NE-SW. This area agrees with the boundary of the geothermal anomaly. The maximum subsidence rate of ~12 cm/yr is located at the center of the extraction zone; while another, local, maximum with a subsidence rate ~9cm/yr is located to the NE of the field. The second maximum was interpreted as a fluid recharging area of the geothermal field (Glowacka et al., 1999).

An estimate of the subsidence rate uncertainty was done using the approach published in Deurisin et al. (2002). The estimation includes two components: the leveling error, which depends on the distance between stations, and the error due to base instability. We obtain a subsidence rate uncertainty of 0.34 cm/yr.

3. TECTONIC SUBSIDENCE MODELING
The CPGF is located between the Imperial and Cerro Prieto faults, two major strike-slip, right-lateral, step-over to the right faults, then these structures are probably responsible for natural subsidence in the studied area because they create a pull-apart zone (Fig. 1 a). Since there were no subsidence measurements before extraction began, the only way to estimate the tectonic subsidence is by modeling. We
evaluate the vertical deformation caused by the right-lateral motion between the North America and Pacific plates. We consider horizontal displacements of 3.5 cm/yr for the Imperial fault and 4.2 cm/yr for the Cerro Prieto fault (Bennett et al., 1996). We used the mean value of displacement velocity as an approximation of long term effect of shearing and pulling in the pull-apart center, or as evaluation of a maximum tectonic displacement during period 1994-1997, taking into account that there were not large earthquakes during this time (Sarychikhina, 2003).

Since earthquakes in the study area occur within the top 15 km (Glowacka et al., 1999; Rebollar et al., 2003), we assumed that the Imperial and Cerro Prieto faults extend from the surface to this depth, and that the upper crust is elastic. The focal mechanisms of earthquakes with M > 5 show that these faults are vertical with right-lateral motion (Frez and González, 1991). In order to locate the northern tip of the Cerro Prieto fault, and the southern tip of the Imperial fault, we used the data from González et al. (1998) and GPS field measurements. The possible error from supposing straight fault traces is insignificant and does not affect the final results. To calculate the subsidence we used the Coulomb 2.0 program (King et al., 1994, Toda et al, 1998).

The tectonic subsidence rate relative to the reference point is shown in Figure 2 b. The maximum subsidence rate (0.45 cm/yr) coincides with the CPGF area, while the northeastern anomaly coincides with the previously defined recharging area. According to our results, tectonic subsidence accounts for only ~4% of the total observed subsidence.

We did not take into account the compaction and isostasy effects that can influence the modeled subsidence rate. We estimate, from published works on compaction (Carillo, 2003) and isostasy (Contreras et al., 1997; García Abdeslem, 2003) that these processes together can increase the tectonic subsidence rate by at most 40% of the estimated rate. Even if this additional rate is taken into account, still the tectonic subsidence rate in CPCF is of the order of millimeters per year.

The estimated tectonic subsidence is of the order of those calculated for nearby areas using other methods: 0.16 cm/yr for Laguna Salada 20 km west of Mexicali (Contreras et al., 2002) and 0.55 cm/yr for the Vallecito-Fish Creek basin 50 km north of Mexicali (Johnson et al., 1983).

As it has been concluded in Glowacka et al. (2003) the similarity between fig. 2a and 2b can be explain by a dominant tectonic control on the origin of geothermal field (by producing crust thinning) and on sedimentation process.

4. ANTHROPOGENIC SUBSIDENCE MODELING

We proceed to model the anthropogenic component of subsidence, subtracting the calculated tectonic component from the observed subsidence.

There are several analytical and numerical models of surface deformations produced by deformation of bodies at depth; some of which can be applied to the case of fluid extraction. We modeled the anthropogenic component of subsidence using the model of a tensional rectangular crack in an elastic half-space proposed by Yang and Davies (1986).

Modeling was done using the Coulomb 2.0 program. Three closing cracks were positioned according to a hydrologic model of the field, which consist in two highly exploited reservoirs: a and b (Halfman et al., 1984; Lippmann et al., 1991). b reservoir is divided by normal SE deeping fault H (Fig. 2 a) in two blocks: upper block (b1) and lower block (b2). One small crack was located under the center of the secondary subsidence center (s. r. – small recharge), and a large one (L. R. – large recharge) was located above the reservoirs that extend under a large part of the study area, in order to produce the observed subsidence outside the CPGF (Fig. 3 a).

A comparison of anthropogenic observed versus modeled subsidence rates, is shown in Figure 3(b), and the residual is shown in Figure 3(c).

Modeling was done by trial and error, and the resulting crack parameters are shown in Table I. A comparison of anthropogenic observed versus modeled subsidence rates, is shown in Figure 3(b), and the residual is shown in Figure 3(c). Both shape and magnitude of the modeled subsidence rate are quite similar to the observed; the absolute value of the residual at most observation points is about 0.0 to 0.5 cm/yr, although some local discrepancies show as much as 2.5 cm/yr (Fig. 3(c)).

The root mean square error per observation point (RMS) of this model is 0.79 cm/yr. It is possible to reduce the RMS using very small cracks to eliminate the local anomalies, but in most cases these anomalies are due to a single point and may be due to measurement errors. After parameter adjustment, to fit the observed subsidence rate, the model is in agreement with the hydrological model on which it was based.

The calculated values of the crack dimensions and their closures let us estimate the change of volume in the reservoirs (without taking cooling into account) shown in Table II. If we compare this change with the rate of net extraction (extraction minus injection), we can estimate the volume of external recharge. For 1994-1997, the average extraction rate is 1.05×10^7 ton/yr, 18% of which (1.88×10^7 ton/yr) has been reinjected. Thus, the crack-induced change of volume corresponds to only ~10% of the volume decrease expected from the extraction figures. Of this 10%, only 3 % is caused by volume decrease in the hot water reservoirs, while 7 % is due to volume decrease in the cold water reservoirs.

Reservoir volume decrease together with injection account for only 28% of the extracted volume, which means that 72% of this volume is compensated by recharge from deep aquifer defined in Pelayo et al. (1991), Glowacka and Nava (1996) (Fig. 1). Unfortunately, this recharge zone cannot be modeled as it is much larger than the leveling network. The recharge volume of the present work is comparable to those from recharge evaluation using a poro-elastic model (Glowacka and Nava, 1996), but contradict the supposition (Pelayo et al, 1991) that all extraction volume is recharged.

5. STRESS CHANGES AND SEISMICITY

Deformation caused by fluid extraction in geothermal reservoirs produces stress changes that may be capable of triggering earthquakes (Segall et al., 1994). As determined above, 96% of the observed subsidence at the CPGF is due to reservoir fluid extraction, and it is important to assess how much this anthropogenic activity changes the stress field and influences seismicity in the area, as compared with the stress change caused by tectonic motion.
The most commonly-used stress formulation is the static Coulomb failure stress (Stein et al., 1992), represented as the Coulomb failure function (CFF). The change in CFF is:

\[ \text{CSC} = \Delta \sigma_s + \mu (\Delta \sigma_n + \Delta \rho) \]  

(1)

where \( \Delta \sigma_s \) is the change in shear stress in the direction of fault slip, \( \Delta \sigma_n \) is the change in normal stress (with tension positive), \( \Delta \rho \) is the change in pore-fluid pressure, and \( \mu \) is an assumed “coefficient of internal friction". Typically, \( \Delta \sigma_n \) and \( \Delta \rho \) are grouped within a new “effective coefficient of friction” \( \mu' \), which is meant to handle the positive correlation between increased pore pressure and tensile normal stress:

\[ \text{CSC} = \Delta \sigma_s + \mu' \Delta \sigma_n \]  

(2)

where \( 0 \leq \mu' \leq \mu \)

All Coulomb stresses were calculated using the Coulomb 2.0 program and a friction coefficient \( \mu' = 0.4 \) (Stein et al., 1992); to calculate the stress change caused by interplate motion, we used the same assumptions as for calculating tectonic subsidence.

We calculate the CSC far 1-8 km depth range. The CSC caused by closure of model cracks for different fault types at 6 km is shown in Figure 4. We obtained the increase of stress for reverse faulting both above and below the reservoir, and for normal and transcurrent faulting at the margins of the studied area. These results are similar to those obtained by Segall (1989) for oil and gas fields, where he modeled ground deformation caused by extraction using a poro-elastic model.

Since we have supposed uniform slip across the fault width from surface to 15 km depth, the change in Coulomb stress caused by motion along the tectonic faults is the same over this depth range. Figure 5 shows the CSC for different faulting mechanisms. The maximum CSC occurs for normal faulting (Fig. 5b) in the area between the faults. In this area stresses are relaxed for reverse faulting (Fig. 5a) and increased for strike-slip faulting (Fig. 5c). The CSC maximum values are listed in Table III.

6. CONCLUSIONS

During 1994-1997, tectonic induced subsidence with a maximum value of 0.45 cm/y represents only 4% of the observed subsidence for the CPGF and the surrounding area.

The anthropogenic subsidence can be modeled using tensional rectangular cracks: two corresponding to cold aquifers and 3 corresponding to the geothermal reservoirs. The crack position agrees with the hydrological model of the field. The volume change produced by the closure of the reservoir cracks accounts for only ~3% of the extracted volume, far the cold aquifers accounts for ~ 7 %. Considering that injection is about 18% of extraction, it turns out that about 72% of the extracted volume must be compensated by water from an external aquifer larger than the study area.

An analysis of the change in Coulomb stress indicates that, in the natural state, seismicity in the area is dominated by normal and transcurrent earthquakes, a well known behavior of pull-apart basin. Under fluid extraction conditions, Coulomb stress increases by more than 0.1 bar, for all faulting types. According to Harris (1998), a Coulomb stress change of 0.1 bars can trigger an earthquake. Hence the stress change caused by extraction could trigger earthquakes of all types; this supports the possibility that same seismicity at the CPGF is related to fluid extraction, as proposed by Majer and McEvilly (1982) and Glowacka and Nava (1996).

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Table I: Model cracks parameters.

<table>
<thead>
<tr>
<th>Crack</th>
<th>Parameters</th>
<th>(m)</th>
<th>(°)</th>
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<tbody>
<tr>
<td>x</td>
<td>y</td>
<td>z</td>
<td>p</td>
</tr>
<tr>
<td>α</td>
<td>664032</td>
<td>3584530</td>
<td>1100</td>
</tr>
<tr>
<td>β1</td>
<td>666667</td>
<td>3586700</td>
<td>2100</td>
</tr>
<tr>
<td>β2</td>
<td>669000</td>
<td>3586000</td>
<td>2250</td>
</tr>
<tr>
<td>s. r.</td>
<td>673352</td>
<td>3590150</td>
<td>1500</td>
</tr>
<tr>
<td>L. R.</td>
<td>669057</td>
<td>3587291</td>
<td>996</td>
</tr>
</tbody>
</table>

x, y, z (center of crack), p (crack closure), c and c1 (crack dimensions), and azm (azimuth) and ang (dip) (crack orientation)

Table II: Volume change caused by model cracks closure.

<table>
<thead>
<tr>
<th>Crack</th>
<th>Volume change (m$^3$)</th>
<th>3.2×10$^6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>α</td>
<td>1.4×10$^6$</td>
<td></td>
</tr>
<tr>
<td>β1</td>
<td>1×10$^6$</td>
<td>3.2×10$^6$</td>
</tr>
<tr>
<td>β2</td>
<td>0.8×10$^6$</td>
<td></td>
</tr>
<tr>
<td>s. r.</td>
<td>2.1×10$^6$</td>
<td>8.1×10$^6$</td>
</tr>
<tr>
<td>L. R.</td>
<td>6×10$^6$</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>1.1×10$^7$</td>
<td></td>
</tr>
</tbody>
</table>

Table III: Coulomb Stress Change (bars).

<table>
<thead>
<tr>
<th>Fault mechanism</th>
<th>Tectonic faults</th>
<th>Model cracks</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>minima</td>
<td>maxima</td>
</tr>
<tr>
<td>Strike-Slip</td>
<td>-3.2</td>
<td>3.6</td>
</tr>
<tr>
<td>Normal</td>
<td>-0.3</td>
<td>4.0</td>
</tr>
<tr>
<td>Reverse</td>
<td>-1.1</td>
<td>1.1</td>
</tr>
</tbody>
</table>

* - CSC at depth of 6 km
Figure 1: Location map. CPGF - Cerro Prieto Geothermal Field (small rectangle), Large rectangle - study area, Imp - Imperial fault, CP - Cerro Prieto fault, V - Cerro Prieto volcano, blue polygon - deep aquifer area. (a) Schematic presentation of the pull-apart basin. (Modified from Glowacka et al., 2003).

Figure 2: (a) Observed subsidence rate (1994 - 1997) in cm/yr. Light blue triangles — extraction wells. Rectangle — CPGF. Dotted yellow line — T ≥ 300° isotherm. Brown crosses — leveling points. F. P. — fixed point. FH — surface projection of H fault, FHb — intersection of H fault with the top of the β reservoir, FL — L fault. (b) Tectonic subsidence rate relative to the fixed point in cm/yr. (Modified from Glowacka et al., 2003).
Figure 3: Modeling of anthropogenic subsidence. (a) Surface projection of cracks. Isolines are observed subsidence rate (minus tectonic component). (b) Comparison of observed (black) to modeled (green) subsidence rates. (c) Residual (cm/yr).
Figure 4: Coulomb stress change at 6 km depth caused by closure of cracks model for (a) — Reverse, (b) — Normal, (c) — Strike-Slip fault mechanism

Figure 5: Coulomb stress change caused by slip along the Imperial and Cerro Prieto faults for (a) — Reverse, (b) — Normal, (c) — Strike-Slip fault mechanism.