Proceedings World Geothermal Congress 2010
Bali, Indonesia, 25-29 April 2010

Anthropogenic Subsidence in the Mexicali Valley, B.C., Mexico, Caused by the Fluid Extraction in the Cerro Prieto Geothermal Field, and the Role of Faults

Ewa Glowacka, Olga Sarychikhina, Francisco Suárez, F.Alejandro Nava., Francisco Farfan, Guillermo Diaz de Cossio Batani, Miguel Angel Garcia Arthur.

CICESE, km 107 carretera Tijuana – Ensenada, Ensenada, BC, Mexico

glowacka@cicese.mx

Keywords: Cerro Prieto, geothermal fields, anthropogenic subsidence, slip on faults, creep event

ABSTRACT

The Cerro Prieto Geothermal Field (CPGF) is located in the Mexicali Valley in the southern part of the Salton Trough at the boundary between the Pacific and North American plates. The Valley is a zone of continuous tectonic deformation, geothermal activity, and seismicity.

Since 1973, fluid extraction at the CPGF has influenced deformation in the area, accelerating the subsidence and producing slip along tectonic faults. Subsidence and fault rupturing are causing damage to infrastructure like roads, railroad tracks, irrigation channels, and agricultural fields.

Detailed field mapping performed since 1989 in the vicinity of the CPGF shows that many subsidence induced fractures, fissures, collapse features, small grabens, and vertical displacements are related to known tectonic faults. The affected area is localized between the Cerro Prieto and Morelia faults to the NW and the Imperial and Saltillo faults to the SE, which limit the Cerro Prieto pull-apart basin (Suarez et al., 2008).

Since 1996, geotechnical instruments have operated in the Valley for the continuous recording of deformation phenomena. To date, the network includes three crackmeters, eight tiltmeters, and seven piezometers installed in the shallow aquifer. All instruments have sampling intervals ranging from 1 – 20 minutes.

Field and instrumental observations are analyzed in this paper to better understand how deep fluid extraction in the Cerro Prieto Geothermal Field (CPGF) has caused subsidence and produced slip in tectonic faults in the Mexicali Valley (Baja California, Mexico).

1. INTRODUCTION

The Mexicali and Imperial Valleys are part of the Salton Trough tectonic province, which is located at the boundary between the Pacific and the North American plates. The Salton Trough is the connection between the Gulf of California depression to the South and the transform boundary of the San Andreas fault system to the North. It includes the Brawley, Cerro Prieto, and Heber step-to- the-right extensional basins and is characterized by continuous tectonic deformation, geothermal activity, and seismicity. Two main strike-slip faults (Cerro Prieto and Imperial, as shown in Figure 1) limit the Cerro Prieto basin. Geothermal fluid has been extracted from depths of 1500 – 3000 m in this basin since 1973 for electricity production at the Cerrro Prieto Geothermal Field (CPGF). The geothermal field is operated by the Mexican Federal Electricity Commission (Comisión Federal de Electricidad, CFE). At present, the CPGF has a 720 MW capacity and is the world's second largest geothermal field. Cerro Prieto is a high-temperature, fluid-dominated field contained within sedimentary rocks. The geothermal fluid is extracted at temperatures of 260 – 350° C from gray shales, and it is isolated from the unconsolidated rock by layers of mudstone and brown shales which constitute the cap-rock (CFE, 2006). The extracted volume increased from 14 million tons/yr in 1974 to 72 million tons / yr in 2005.

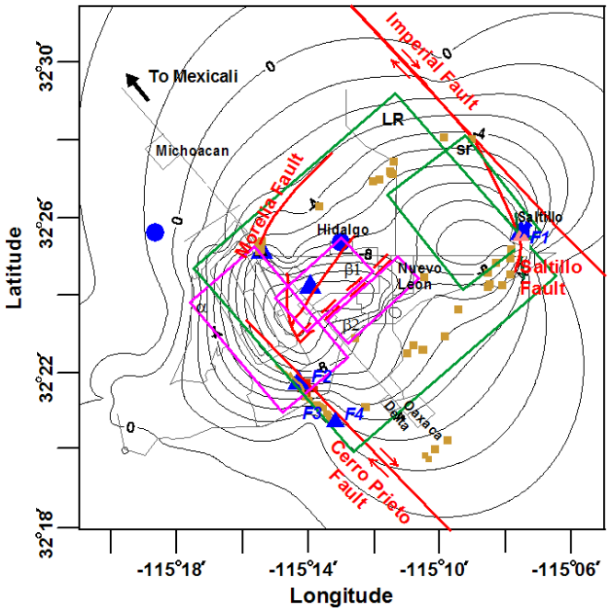

Figure 1: Details of study area. F1- F4: locations of photographs shown in the Figures 2 – 4 and 6. Pink rectangles represent the surface projection of modeled geothermal reservoirs α, β_1 , and β_2, and green rectangles represent modeled aquifers which recharge water to fields sr and RC (modified from Glowacka et al., 2005). Solid brown squares are sites of superficial evidence of subsidence from Suarez et al. (2008) and Glowacka et al. (2009). Blue dots are sites of borehole tiltmeters, blue triangles are sites of surface tiltmeters, orange triangles are crackmeters, and the red cross marks the 3D Witness site.

2. SUBSIDENCE

From the analysis of the leveling surveys performed in the area of CPGF and the Mexicali Valley since 1977, Glowacka et al. (1999) noticed that the CPGF area is characterized by subsidence and that the subsidence caused by anthropogenic fluid extraction. This observation was confirmed by Carnec and Fabriol (1999) and Hanssen (2001) by means of InSAR image analyses; they used ERS1/2 images taken for the 1993—1997 and 1995—1997 periods, respectively. The latest observations of Sarychikhina et al. (2007, 2010) confirmed a similar pattern using Envisat InSAR data recorded between 2003 and 2006. During the 1977-1997 period, the subsidence rate at the center of the field increased after each steam extraction rate increase. In the 1994-1997 period, the maximum subsidence rate was 12 cm/yr, and the ellipsoidal shape of the subsidence zone (elongated SW-NE), coincided with the observed geothermal anomaly and theoretically modeled shape of the pull-apart basin (Glowacka et al., 1999, 2005).

Detailed field mapping completed since 1989 (Gonzalez , 1990; Gonzalez et al.,1998; Suarez et al., 2008) in the vicinity of the CPGF shows that many subsidence induced fractures, fissures, collapse features, small grabens and vertical displacements are related to the known tectonic faults. Subsidence and fault rupturing has caused damage to infrastructure like roads, railroad tracks, irrigation channels, and agricultural fields. Some of the ruptures are pictured in Figures 1 - 4.

Figure 2. Photograph of site F1 (Fig.1) showing the Saltillo fault where the crackmeter is installed as seen from the South. This place was flat in the beginning of the 1970s. A) Photograph taken in 1994. B) Photograph taken in 2007.

Figure 3. 3-D Witness installed over the Cerro Prieto fault in 2004 at point F2 (Fig.1).

Figure 4. The Cerro Prieto fault crossing an irrigation channel at F3 (Fig.1).

Analysis of the extension, amplitude, and time behavior of the slip (relative displacement across the fault) on the Imperial and Cerro Prieto faults, which belong to the Cerro Prieto pull-apart basin from the NE and the SW (Glowacka *et al.*, 1999, 2005), suggested that these faults constitute a boundary of the subsided area (probably a groundwater barrier).

Three processes are probably occurring to produce the observed fault behavior. According to Sheng and Helm (1998), existing faults are often poorly permeable in the direction perpendicular to the fault, and act as a ground water barrier, increasing differential displacement of both sides of the fault. Secondly, the process of fault breaking is accelerated by fluid extraction when sediments of different thicknesses on both sides of the fault induce differential compaction and tensional and shear stresses on the ground mass. This produces ground failure that leads to vertical displacement of faults, limiting the affected aquifer (op cit.). Finally, a diminution of the normal stresses is to be expected at the fault, due to extension at the edge of a subsidence basin, which reduces the friction that locks the fault (Segall, 1989).

3. INSTRUMENTAL DATA

The trace of the Imperial fault has been recognized since the El Centro earthquake in 1940. In 1977, a local earthquake with a magnitude of 4.2 produced a vertical rupture of the paved road in Ejido Saltillo (González, 1990) in the southernmost part of Imperial fault, which is now known as Saltillo fault. The observed rupture was mainly vertical, with the west side lower. Studies done from 1989 – 2006 (González, 1990; González *et al.*, 1998; Suarez et al., 2008) have shown that the rupture zone is about 10 km long in the southernmost segment. Since 1996, geotechnical instruments installed by CICESE have operated in the Valley for continuous recording of deformation phenomena. To date, the network includes three crackmeters, eight tiltmeters, and seven piezometers installed in the shallow aquifer. All instruments have sampling intervals ranging from 1 – 20 minutes.

In 1996, continuous vertical movement measurements across the Saltillo fault were initiated in Ejido Saltillo (F1 in Figures1 and 2) using a crackmeter installed in the vertical direction (Glowacka *et al.*, 2000). Since then, vertical displacements across the fault (along the 3 m span of extensometer) of 5.3 (for 1996 – 2003) to 7.3 cm/year (2003 – present) have been observed, as shown in Figure 5A. Deformation is not continuous, but occurs in steps (creep/slip events) separated by months of quiescence. Large events account for about 50% of the vertical displacement. Aseismic creep/slip events have amplitudes of 1 – 3 cm and last 1 – 3 days.

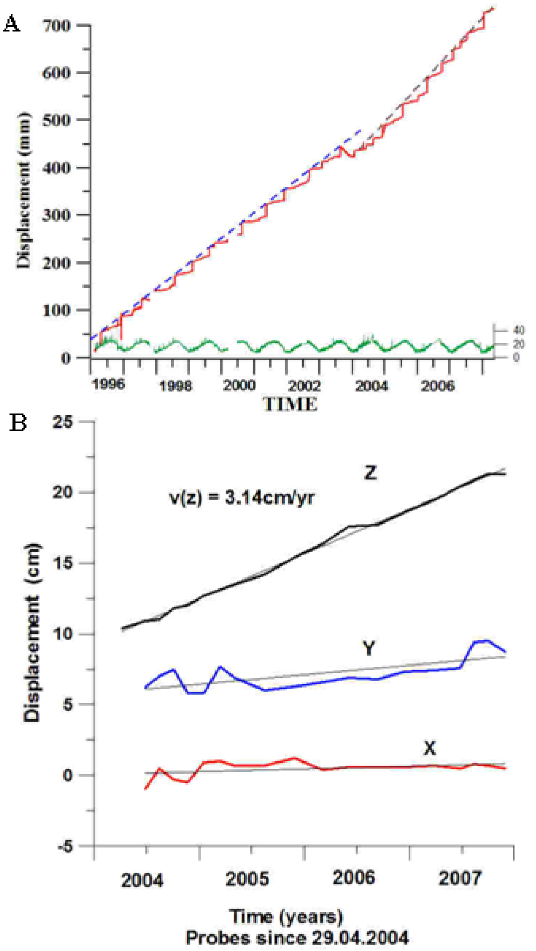

Figure 5. Vertical displacement versus time, A) Vertical displacement (mm/yr) in the Saltillo fault (F1) from 1996 – 2007 – red line, Temperature – green line. B) Vertical displacement (cm/yr) in Cerro Prieto fault (F4) from 2004-2007– black line (z). x and y are right lateral and extension displacement.

The Cerro Prieto fault, which crosses the CPGF area in a series of small scarps and cracks, was surveyed by CFE between 1995 and 1998, and east side down displacement of 4 cm/year was observed for this period in the 50 m between the benchmarks across the fault (Lira, 1999). Data from a 3-D Witness (surveyed every 2-3 months) installed at the Cerro Prieto fault at point F3 (shown in Figures 1 and 4) since 2004, show vertical displacement of 3.1 cm/year along the 3 m span of the instrument, while the horizontal component perpendicular to the fault is ~0.7 cm/year (extension), and the horizontal strike-slip component is negligible (see Figure 5B). The crackmeter installed in vertical position at point F4 (Figures 1 and 6) in 2007 indicated small slip events during 2008.

4. DISCUSSION

The slip rate observed in the Cerro Prieto fault is about two times smaller than that observed in the Saltillo fault. In previous works, Glowacka et al. (1999, 2005) suggested that the slip rates observed in both analyzed faults are related to subsidence caused by the fluid extraction from the CPGF. Sarychikhina (2003) and Glowacka et al. (2005) modeled the observed deformation using rectangular compressible reservoirs, as shown in Figure 1 and Table 1. Additionally, the distance-time relationship between changes in extraction at the CPGF and the displacement rate found in the Saltillo fault suggest that the fault is affected by extraction through diffusive transmission of pore pressure changes, with a characteristic hydraulic diffusivity (Glowacka et al., 2009a,b).

The thickness of sediment below the eastern part of the Cerro Prieto fault is about two times smaller than that below the western part of the Saltillo fault. The thickness of the unconsolidated sediments in the Cerro Prieto fault is four times smaller than that of the Saltillo fault. Furthermore, the aquifer closure calculated by Glowacka et al. (2005, 2009) predicts less compaction along the Cerro Prieto fault (5 cm/yr in reservoir **α**, and 4 cm/yr in **LR**) than along the Saltillo fault (7.9 cm/yr for reservoir **sr** and 4cm/yr for reservoir **LR**), as shown in Table 1.

Table 1. Model parameters: z is depth to the center of reservoir or fault, p is the yearly rate of aperture of reservoir or fault slip where reverse slip is positive (modified from Glowacka et al., 2009), and α β_1,β_2, sr and RC are the reservoirs and aquifers presented in Figure 1.

Fracture/ Fault	Parameters		
	z (m)	p (cm/y)	Color (Fig.1)
α	1100	-5.0	pink
β1	2100	-10.0	pink
β2	2250	-12.0	pink
s r	1500	-7.9	green
L R	996	-4.0	green
SF′	600	-7.0	black

Figure 6. Preparation for crackmeter installation over the Cerro Prieto fault at F4 (Fig.1).

However, the short time of continuous instrumental observation along the Cerro Prieto fault limits the precision of the analysis of the slip. The comparison presented above suggests that this process may be similar to that observed at the Saltillo fault.

ACKNOWLEDGMENTS

The results and conclusions explained in this paper are solely the authors' and do not necessarily express the point of view of CFE. Authors are grateful to MC Miguel Guzman and Dr. Jorge Ramirez from UABC, Gilberto Gillen from CFE, and Luis Adame for logistic help during the project. This research was sponsored in by CONACYT, project number 45997-F, and CICESE internal funds.

REFERENCES

Carnec, C. and Fabriol, H., (1999), Monitoring and modeling land subsidence at the Cerro Prieto geothermal field, Baja California, Mexico, using SAR interferometry, Geophysical Research Letters 26 (9):1211-1214.

CFE, (2006), Cerro Prieto geothermal field (CFE, Mexico 2006).

Glowacka,E. ,Sarychikhina,O., Suarez,F., Mendoza,R., and Nava,F. (2006), Estudio geológico para definir la zona de hundimiento con el fin de relocalización del canal Nuevo Delta en el Valle de Mexicali. P. 505. Reporte Tecnico. CICESE, Mexico.

Glowacka E., J. Gonzalez, Fabriol H., (1999), Recent Vertical deformation in Mexicali Valley and its Relationship with Tectonics, Seismcity and Fluid Operation in the Cerro Prieto Geothermal Field. Pure and Applied Geophysics. 156:591-614

Glowacka E., Nava F.A., Diaz de Cossio G., Farfán F., (2001), Monitoring the response of the Imperial Fault to fluid extraction in the Cerro Prieto Geothermal Field, Baja California, Mexico. Rockbursts and Seismcity in Mines - RASiM 5.eds. Van Aswegen, G., Durrheim R.J., Ortlepp W.D:143-147.

Glowacka E., Sarychikhina O., Nava A.F., (2005), Subsidence and stress change in the Cerro Prieto Geothermal Field, B.C., Mexico. Pure and Applied Geophysics. 162: 2095-2110.

Glowacka E., Sarychikhina O., Suarez F., Nava A, Guzman M., F. Farfan, G. Diaz de Cossi.Batani, M.A. Garcia Arthur. (2009a), Fluid extraction in the Cerro Prieto Geothermal Field and the slip on Saltillo fault. GRC, submitted

Glowacka E., Sarychikhina O., Suarez-Vidal F., Nava Pichardo F.A., Mellors R. (2009 b), Anthropogenic subsidence in the Mexicali Valley, Baja California, Mexico, and slip on the Saltillo fault, *Environmental Earth Sciences*, doi:10.1007/s12665-009-0137-y.

González, J. J., Glowacka, E., Suárez, F., Quiñónez, G., Guzmán, M., Castro, J. M., Riviera, F., and Félix, M. G., (1998), Movimiento reciente de la falla Imperial, Mexicali, B. C., Divulgare, Ciencia para todos, Mexicali, B. C. 6 (22):4-15.

Hanssen, R. F., *Radar Interferometry* (Kluwer Academic Publisher, Netherlands 2001).

Lira H.(1999), Resultados de monitoreo de desplazamiento de la falla Cerro Prieto en 1998. Informe Tecnico RE 05/99. CFE

Lira H., (2005), Actualización del modelo geológico conceptual de yacimiento geotérmico de Cerro Prieto, B.C. Geotermia, 18:37-46

Lira, H., and Arellano, J. F., (1997), Resultados de la nivelación de precisión realizada en 1997, en el campo geotérmico Cerro Prieto (Informe técnico RE 07/97, CFE 1997).

Sarychikhina, O.,(2003), Modelación de subsidencia en el campo geotérmico Cerro Prieto (MSc. thesis, CICESE, México 2003).

Sarychikhina O., E. Glowacka and R. Mellors, (2007), Preliminary results of the surface deformation study, using Differential InSAR technique at the Cerro Prieto Geothermal Field, B.C., México. GRC meeting, Reno 2007, proceedings CD: 581-584.

Sarychikhina O., Mellors R. and Glowacka E., (2010), Analysis of Spatial and Temporal Evolution of the Ground Deformation in the Cerro Prieto Geothermal Field (Mexicali Valley, B.C., Mexico) Using DInSAR and Leveling Data. Submitted to WGC.

Segall, P., (1989), Earthquakes triggered by fluid extraction, Geology 17: 942 - 946.

Sheng Z., and Helm D.C., Multiple Steps of Earth Fissuring Caused by Ground Water Withdrawal. Tectonic Controls of Geomorphic Processes in Land Subsidence Area, In Land Subsidence (ed. J. W. Borchers) (Star Publishing Company 1998): 149-154.

Suarez-Vidal F, Mendoza-Borunda R., Naffarrete-Zamarripa L.M., Ramirez J., Glowacka E., (2008), Shape and dimensions of the Cerro Prieto pull-apart basin, Mexicali, Baja California, México, based on the regional seismic record and surface structures. International Geology Review, 50 (7):636-649