MONITORING SURFACE DEFORMATION IN THE MEXICALI VALLEY, B.C., MEXICO.

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Abstract

Mexicali Valley is situated in the southernmost part of the San Andreas fault system and is characterized by a high level of seismicity, volcanism, geothermal activity and deformation. Analyses of leveling data done since the 70's show that the area is strongly influenced by fluid extraction in the Cerro Prieto Geothermal Field (CPGF).

In 90's regional and local GPS monitoring was done in the Valley every few years. Since 1998, two crackmeters and two tiltmeters have been continuously monitoring deformation changes in the Mexicali Valley. Two crackmeters and one tiltmeter are installed on the Imperial fault, and one tiltmeter in the Cerro Prieto Geothermal Field.

The results show that the area is characterized by a very high signal/noise ratio for surface deformations.

Relations between deformation, local tectonics, local and regional seismicity and fluid extraction in CPGF are discussed.

1. Introduction

The Mexicali Valley (Mexican part of Imperial Valley) is part of the Salton Trough and is situated in the southernmost part of the San Andreas fault system, in the boundary between the Pacific and North American plates. A high level of seismicity, deformation, young volcanism, and geothermal activity characterizes this area. The region discussed here (Fig.1) is a tectonic pull-apart system located between the two major strike-slip, right-lateral, step-over to the right, Imperial and Cerro Prieto faults. The Cerro Prieto Geothermal Field (CPGF), operated by CFE (Comisión Federal de Electricidad), has been extracting geothermal water in this area for a power plant since 1973. During the nineties extraction was of the order of 12,000 ton/hour, from depths between 1,500 and 3,000 m (CFE, 1998).

Geodetic studies in the Valley began in the sixties as part of the geothermal field preparations and evaluation (Velasco 1963, Grannell *et al.*, 1979, Massey, 1983) and as surveys for tectonics (Darby *et al.*, 1984, Lisowski *et al.*, 1991) or earthquake studies (Darby *et al.*, 1981). GPS measurements start in 90's as a part of series of experiments across Pacific-North America plate boundary (Bennett *et al.*, 1996). These measurements confirm that regional crustal deformations in horizontal component are dominated by right lateral shear and that the Imperial and Cerro Prieto faults, with a 35±2 and 42±1 mm/year slip, account for the larger part of the plate boundary motion (49±3 mm/year).

Summarizing local leveling measurements in Mexicali Valley, Glowacka *et al.* (1999) concluded that the observed subsidence rate in the CPGF is mainly induced by geothermal fluid extraction. Subsidence at the CPGF was also measured by SAR (Synthetic Aperture Radar) interferometry between 1993 and 1997 by Carnec and Fabriol (1999), and was interpreted as produced by geothermal water extraction. A comparison of the space and time distribution of subsidence and leveling measurements at the Imperial fault with changes in the fluid production rate at the CPGF, suggested that this fault (situated 10 kilometers from the field) is the eastern boundary of the subsided area and acts as a barrier for groundwater flow. A complete review of vertical deformations in Mexicali Valley and their relation to seismicity, tectonics and fluid exploitation of the CPGF is found in Glowacka *et al.* (1999).

We will present measurements done in the Mexicali Valley during last years and discuss them in a local seismotectonic scale.

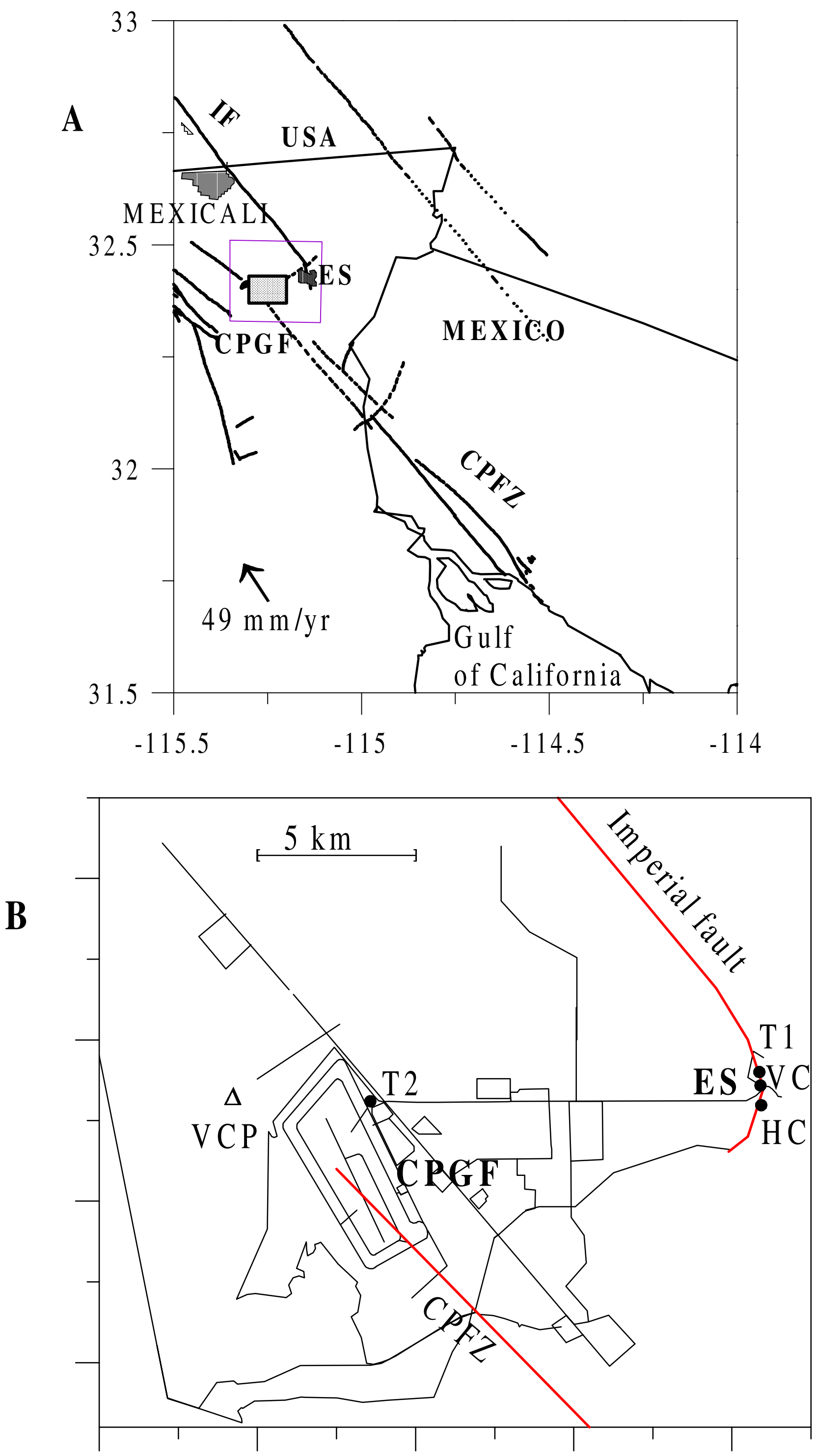

Fig. 1.A. Geographical situation. CPGF - Cerro Prieto Geothermal Field, IF - Imperial Fault, CPFZ - Cerro Prieto Fault Zone, ES - Ejido Saltillo. Violet rectangle - studied area, presented below. B. Instruments: VC, HC - vertical and horizontal crackmeters, T1, T2 - tiltmeters. VCP- Volcano Cerro Prieto.

2. GPS data and results

Figure 2 and Table I present data acquired during 1995 and 1997. They were measured on local bench marks occupied during 1-2 days sessions each. The data obtained were processed using the GAMIT and GLOBK software (King and Bock, 1997, Herring 1995), considering the Puerto Peñasco site, in Sonora, Mexico, as a fixed point belonging to a stable Northamerican plate.

The horizontal results for 8 bench marks presented in figure 2 (blue arrow) clearly show two components of motion. One in NW direction, and another towards the center of the figure. When we eliminate the tectonic component (eq.1 in Johnson and Wyatt, 1994), using S=35 mm/year for slip velocity and a locking depth (H) of 7 km for the Imperial fault, the differences (presented as red arrows) show a displacement parallel to the local subsidence gradient. All points, except 8, LN00, which is situated in the Cucapa mountains, are strongly influenced by subsidence. Since similar phenomena were observed for the 1993 and 1995 campaigns (Gonzalez *et. al.*, 1995) we can conclude that probably the extraction cone around the CPGF is responsible for this effect.

Comparison between *vertical* velocities obtained from radial GPS component (1997-1995) and leveling (1997-1994), normalized for one year, presented in column in Table I show a reasonably good agreement, within 2cm/year or 25%.

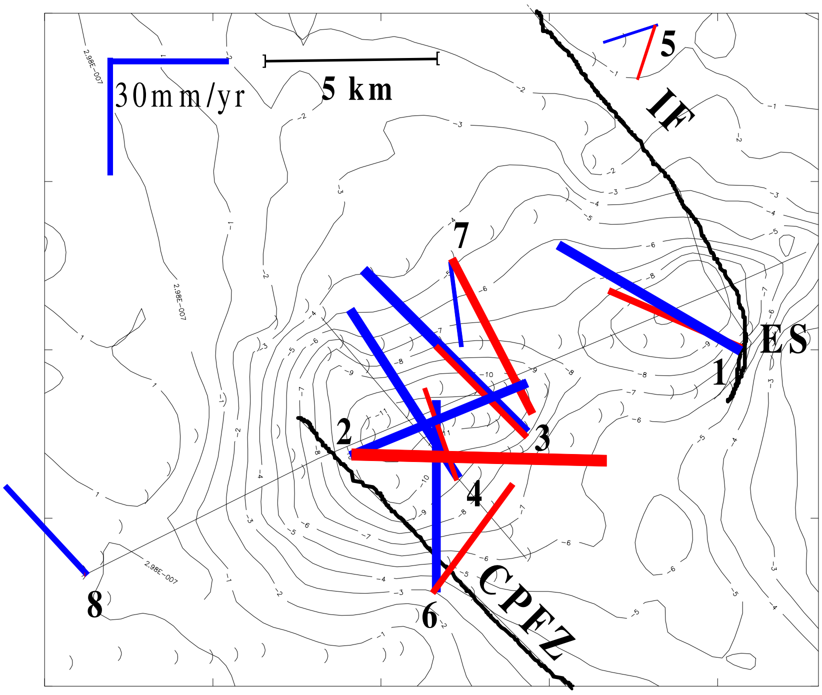

Fig.2. Horizontal GPS component (1995 - 1997) and leveling results (1994 - 1997) normalized for one year. Blue are original data, red are residuals after the tectonic component removal. Commas - bench marks. ES - Ejido Saltillo, IF - Imperial Fault, CPFZ - Cerro Prieto Fault Zone.

Table 1

Site	Horizontal N mm/year	Horizontal W mm/year	Radial GPS mm/year	Leveling mm/year	Number in Figure 3
N100	55.2	94.9	107.2	90.0*	1
CG12	37.9	-92.8	98.3	118.0	2
CG13	85.1	86.7	85.6	104.0	3
CG25	88.9	57.1	93.4	83.7*	4
LN20	-9.7	28.2	21.6		5
BG51	98.6	4.0	38.1	34.4	6
LN11	-45.2	-6.4	62.6	48.5	7
LN00	46.7	43.2			8

* leveling results from the nearest available bench marks

3. Continuous measurements

In 1996 continuous measurements of vertical motion across the Imperial fault were started at Ejido Saltillo, using a crackmeter (VC, Fig.1B) operating in a semi-vertical direction perpendicular to the fault, with a base anchored to the ground on each side of it (Glowacka 1996, Nava and Glowacka 1999). In July 1998, a second crackmeter (HC, Fig.1B) was installed about 1 km south of VC, also spanning the fault but operating in a horizontal direction about 60º from the fault strike. Both crackmeters measure the variation in the distance between the two anchor points, with 0.1mm resolution and 10 minute sampling interval. In 1998, two biaxial surface tiltmeters were installed in the Valley: one close to VC on the Imperial fault (T1, Fig. 1B), another (T2) in the CPGF area. These tiltmeters have 1 μradian resolution and 1 minute sampling interval. The concrete bases for all instruments are anchored to the ground with three 2-meter long legs, and are built between one and two meters below ground level.

4. Data and Analysis of continuous measurements

4.1. Imperial Fault

The observed deformation rates measured on the Imperial fault are 6 cm/yr and 2 cm/yr for the vertical and horizontal components, respectively. Figure 3 shows the results of three years of observations from all three instruments and indicates that vertical motion on the fault is not continuous, but occurs in steps, separated by months of quiescence. Large slip events are recorded at all three instruments installed on the Imperial fault. Analyzing 5 years of observations from VC, Glowacka *et al*. (2001) showed that fault behavior is slip-predictable for the vertical component. This can be explained by a constant rate of fluid extraction at the CPGF, which causes an almost constant subsidence rate, and results in a constant strain release at the edges of the aquifer. The larger slip events have almost characteristic behavior (they have roughly similar displacements and are much larger than the other events) with a mean displacement value of 18 ± 5mm, and a mean elapsed time of 179 ± 79 days (*op.cit*). A detailed analysis of slip events (Nava and Glowacka, 1999) shows that slip events form groups, or suites, of smaller ones, somewhat like an earthquake sequence. For some events (1,2,3 and 5, Fig.3) there is a time delay of about 6 hours between the slip onset at VC and at HC. This delay indicates that slip events originate closer to VC (possibly north of it) and have an apparent migration velocity of the order of 4 cm/s.

Figure 3 indicates by arrows the times of local (within a 10 kilometers range) earthquakes with magnitude $M \geq 4$. The largest arrow indicates the Hector Mine earthquake (HME) (M=7.1, Oct. 16, 1999) occurred in California 250 kilometers north from the study area. Apart from the HME case, which will be discussed separately below, no relation between seismicity and slip on the Imperial fault is found (Glowacka *et al.*,2001).

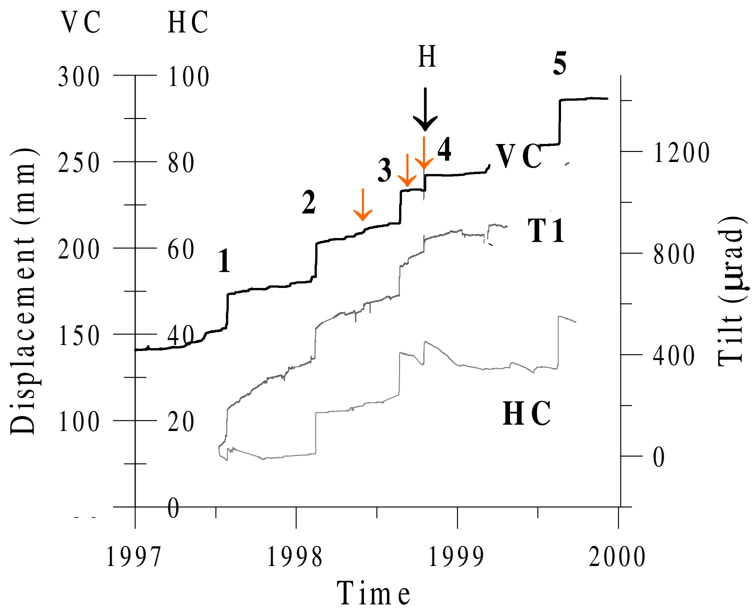

Fig.3. Vertical (VC), horizontal (HC) displacement and tilt (T1) on the Imperial Fault. Numbers denote slip events. Brown arrows mark local earthquakes with M>4, black arrow marks HME.

4.2. Tilt in CPGF

Figure 4 presents 3 years of tilt measurements in the area of CPGF. Compared to the T1 tiltmeter the T2 instrument has very noisy record, with high amplitudes at diurnal and annual frequencies. The mean value of tilt suggests inclination towards SSW, and agrees with the shape of a local anomaly in the subsidence cone. Contrary to T1 this instrument records tilt changes related to the local seismicity (anomaly 1, 2 and 3). Large anomalies occur also for periods not related to the seismicity (anomaly 4 and 5). The origin of these anomalies is not known. T2 does not record tilt changes associated with the aseismic slip events at the Imperial fault. This suggest that the slip events on the Imperial fault are shallow (originated probably in less than 3 km depth) phenomena.

4.3. Hector Mine Earthquake (HME)

Effects produced by Hector Mine earthquake (M=7.1, Oct.16, 1999) which occurred 250 km north from Mexicali Valley are shown in figures 3 and 4, as event 4 and 3, respectively. The details are presented in figure 5. Deformation (slip and tilt changes) along the observed part of the Imperial fault starts simultaneously with the passage of the HME seismic waves (Glowacka *et al.*,2000). Significant tilt starts about 30 hours later at the CPGF. Deformations at the fault and at the CPGF return to their long time rates after the occurrence of a local, M=4.1, earthquake, about 50 hours after the main event. Long period tremors and microseismicity accompany deformation on the Imperial fault, and local seismicity (M≥2.5) begins together with the deformations at CPGF (*op.cit*). Our observations confirm that strong earthquakes can trigger seismicity and deformation at large distances, as was observed for the Landers (M=7.2, 1992) earthquake (e.g. Hill *et al*., 1995). However, the amplitude and duration of triggered phenomena depend on local conditions.

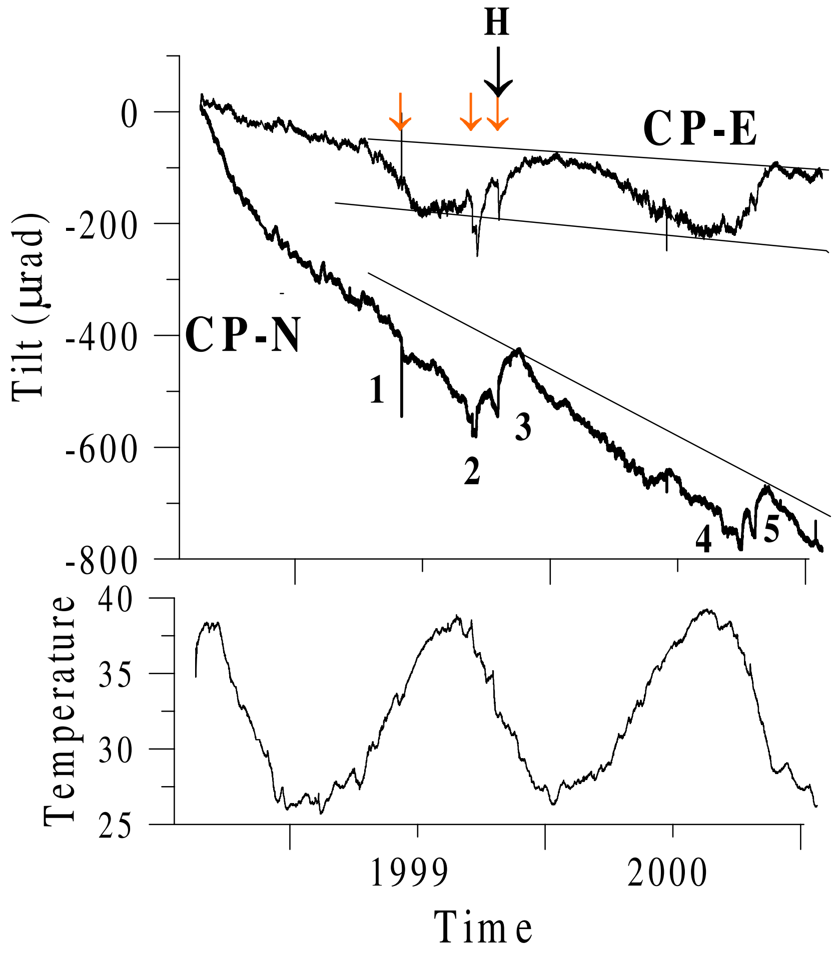

Fig.4. Tilt (T2) and temperature changes in CPGF. Numbers denote anomalies. Brown arrows mark local earthquakes with M>4, black arrow mark HME. Straight lines denote trend in tilt.

5. Conclusions

Deformation measurements in Mexicali valley are affected by tectonic, seismic and human induced activity.

GPS horizontal data show tectonic and subsidence related displacements. Radial data agree with leveling measurements within the expected error, and can be used for subsidence evaluation in the area.

Continuous observations on the Imperial fault show slip-predictable, aseismic vertical slip with a mean slip rate of 6 cm/year, induced probably by fluid extraction in the CPGF. An instrument operated in the CPGF area records tilt changes, part of which are related to the seismicity. The origin of these anomalies is yet to be studied.

All instruments installed in the Mexicali Valley recorded deformation changes triggered by HME originated 250 km away. These changes were accompanied by local seismicity and both were probably triggered by surface seismic waves from the main earthquake.

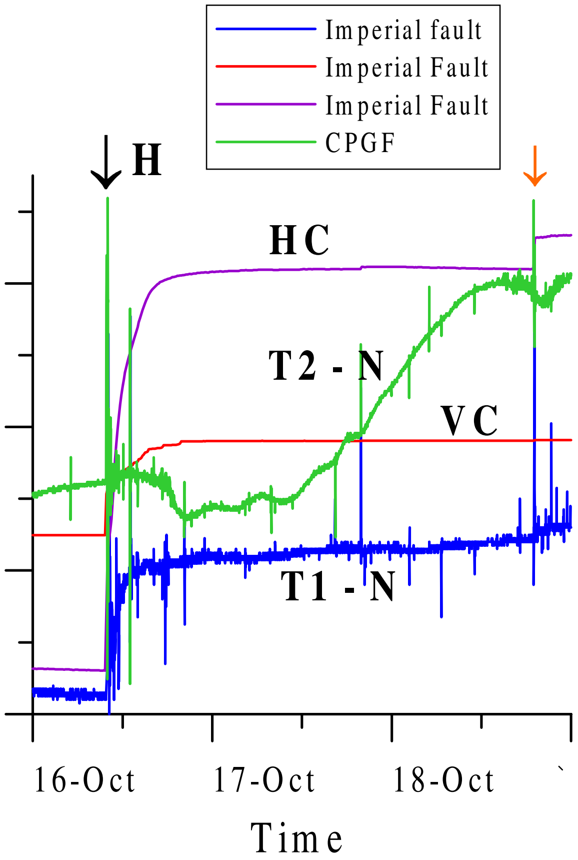

Fig.5. Cumulative slip and tilt for the first 3 days after HME. The large, black arrow labeled H indicates the HME, the brown one the M=4.1 local earthquake.

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Results and conclusions expressed in this paper are solely the authors' and do not necessarily express the point of view of CFE.

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