

Deformation Around the Cerro Prieto Geothermal Field Recorded by the Geotechnical Instruments Network REDECVAM during 1996-2009

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Keywords: Cerro Prieto Geothermal Field, Tiltmeters, Creepmeters, Triggered Slip, Subsidence

ABSTRACT

Since 1996, CICESE has been operating a network of geotechnical instruments, REDECVAM (Red de Monitoreo de Deformación de la Corteza en el Valle de Mexicali), for continuous recording of deformation related to tectonic (seismic, aseismic and interseismic) phenomena, as well as anthropogenic deformation caused by deep fluid extraction at the Cerro Prieto Geothermal Field (CPGF).

The instruments are installed along the faults that limit the Cerro Prieto Pull-Apart Basin (CPB). Currently, the network includes 4 extensometers and 9 tiltmeters (two in 5 meters deep boreholes). All instruments have sampling intervals in the 1 to 20 minutes range.

Instrumental records typically show continuous creep, episodic slip events, sometimes triggered slip events and coseismic slip jumps.

The continuous slip rate observed on the Saltillo fault has increased with time, from 5cm/year to 8cm/year, while the location of the larger subsidence rates migrated to the NE. The slip rate at the Cerro Prieto fault slip is about 1 to 4cm/year, with the larger rate closer to the CPGF. In previous works Glowacka et al. (1999, 2005, 2009) suggested that the slip rates observed on both faults are related mainly to subsidence caused by fluid extraction at the CPGF.

Since the network installation, dozens of aseismic slip events on the Saltillo fault and some on the Cerro Prieto fault have been recorded. The episodic fault slip in the Saltillo fault appears mainly as slip-predictable, normal, aseismic slip. The occurrence of slip events in the Saltillo fault appears to have no relation with the small or moderate local earthquakes; except for the stepwise, discontinuous, and permanent deformation caused by the M=5.8, December 2009 earthquake. However, it seems that slip can be triggered in the Saltillo fault by distant earthquakes with magnitude around 7, if these occur close to the end of a slip event cycle. Some of the instruments installed on other faults, however, recorded permanent deformation caused by moderate local earthquakes.

Our results are compared with published evaluation of anthropogenic subsidence in the CPGF.

1. INTRODUCTION

The Cerro Prieto Geothermal Field is located in the Cerro Prieto pull-apart basin, in the southern part of Salton Trough, on the tectonic border between Pacific and North America Plates. The area is characterized by high levels of tectonic deformation, recent volcanism and seismicity. Strong earthquakes (with magnitudes higher than 6) originate along the Cerro Prieto and Imperial faults, which limit the Cerro Prieto basin, while small, to moderately seismicity, largely concentrated in swarms, characterizes the Mexicali Seismic Zone (Anderson and Bodin, 1987; Frez and Gonzalez, 1991; Nava and Glowacka, 1994; Suarez et al., 2008).

The CPGF is a large, high-temperature, 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 from 1500 - 3000 m depths. Rejection of residual water began in 1989, and currently about 20% of the extracted fluid is being reinjected at 500 - 2600 m depth (CFE, 2009). Currently, the CPGF, with 720 MW capacity, is the world's second largest geothermal field.

The possibility that fluid extraction and/or injection in the CPGF is stimulating seismicity in the Mexicali Valley has been mentioned by Majer and McEvilly, (1982); Glowacka and Nava, (1996); and Fabriol and Munguia, (1997).

The subsidence history at the CPGF area has been well documented. Geodetic studies in the Mexicali Valley began in the 1960's. The analysis of measurements from the leveling surveys done in the area of the CPGF and the Mexicali Valley from 1977 to 1997, showed that the extension and shape of the subsidence zone were originally controlled by tectonics; however, the current subsidence rate is mainly related to fluid extraction (Glowacka et al., 1999; Glowacka et al., 2005, Suarez- Vidal et al., 2008). Subsidence in the CPGF was also measured via DInSAR (Differential Synthetic Aperture Radar Interferometry) by Carnec and Fabriol (1999) and Hanssen (2001) using ERS1/2 images acquired during 1993 - 1997 and 1995 - 1997, respectively, and interpreted as anthropogenic effect of fluid extraction. Recently Sarychikhina et al., (2011) applied the DInSAR technique using C-band ENVISAR ASAR data acquired between 2003 and 2006 to determine the extent and amount of land subsidence in the Mexicali Valley near the Cerro Prieto Geothermal Field. The DInSAR results compared with precise leveling surveys and detailed geological information data were modeled to characterize the observed deformation in terms of fluid extraction.

The subsidence rate calculated from DInSAR stack images for 2005 (Sarychikhina et al., 2011) is presented in figure 1. The subsidence area is limited by the faults, and the maximum of subsidence rate, of the order of 18 cm/year, is observed in the NE part of the Cerro Prieto Pull-apart basin, outside the zone of geothermal wells. An explanation to this phenomenon proposed by Glowacka et al.,(1999, 2005), based on the hydrological models from different studies, (Halfman et al., 1984; Lippmann et al., 1991; Truesdell et al., 1998; Lippmann et al., 2004), is that although geothermal reservoirs are recharged mainly by the flow of hot brine from great depths (~5–6 km) in the eastern portion of the field, geothermal reservoirs are also recharged by cold fresh water from shallow aquifers, located to the east, west, and south, most likely through tectonic faults.

The purpose of this paper is to present records of geotechnical instruments, creepmeters and tiltmeters, operating in and around the CPGF, from 1996 to 2009, and interpret these records in relation to ground subsidence, local and regional seismicity and fluid extraction.

Saltillo fault, mentioned in this work, was referenced before as southern part of Imperial fault (e.g. Glowacka et al., 1999, 2002, 2005, Nava and Glowacka, 1999); the name of the fault was changed since publication of Suarez-Vidal et al., (2008).

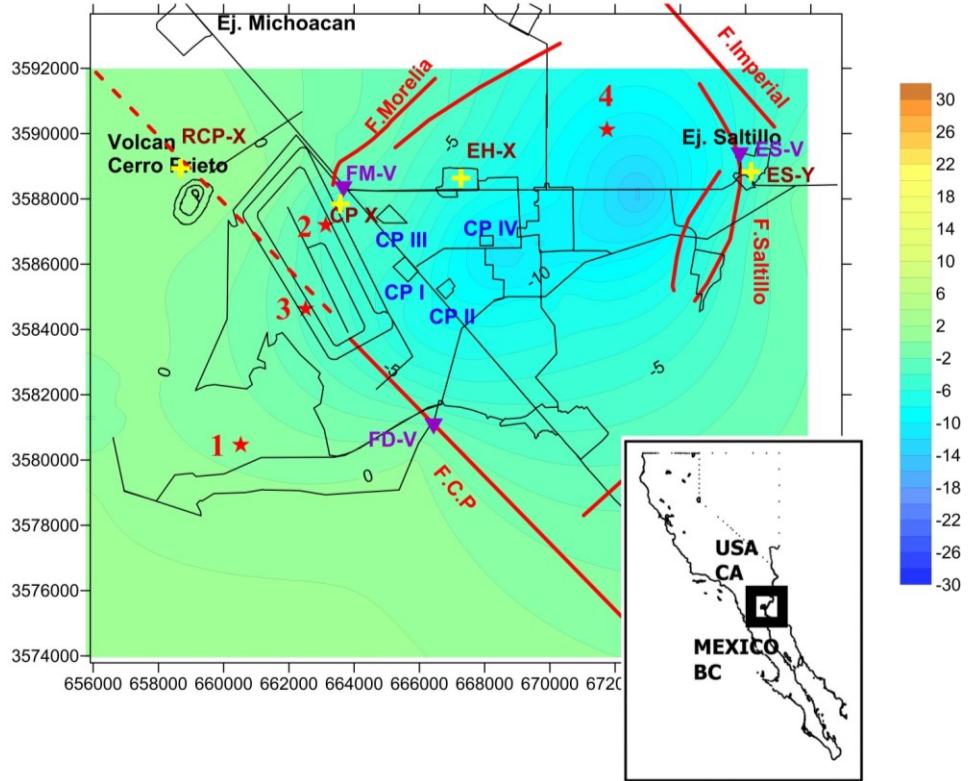


Figure 1: Crackmeters (purple triangles) and tiltmeters (yellow crosses with brown text) over the LOS displacement rate (cm/year, more blue, higher the subsidence rate) calculated for year 2005, from stacking of DInSAR images (modified from figure 8d, of Sarychikhina et al., 2011). Red lines indicate tectonic faults, F.C.P is Cerro Prieto fault, CPI, CPII, CPIII, CPIV are geothermal plants. Inset shows the geographical situation of the study area. Asterisk mark earthquakes 1). Mw=5.5, 2002.02.22, 2). Mw=5.4, 2006.05.24, 3) Mw=5.1, 2009.09.19, 4). Mw=5.8, 2009.12.30.

2. DATA

The results we will present here are based on data from the REDECVAM (Red de Monitoreo de Deformación de la Corteza en el Valle de Mexicali), which began operating in 1996 with one instrument; to date, the network includes 4 extensometers and 9 tiltmeters (two in 5 meters deep boreholes) for continuous recording of deformation related to tectonic (seismic, aseismic and interseismic) phenomena, as well as anthropogenic deformation caused by deep fluid extraction at the CPGF.

The vertical displacement at the southernmost part of the Saltillo fault has been measured on a continuous basis since February 1996 by a crackmeter (wide range creepmeter) installed in Ejido Saltillo (Nava and Glowacka 1999) which samples at intervals of 1 to 20 min. The 3 meters long crackmeter, ES-V (Fig.1), extends from a base anchored to the eastern (higher) side of the fault to a base within a small graben in the western side. The first crackmeter worked continuously, with small corrections and reinstallations, until July 2009.

The instruments are installed mainly along the faults that limit the Cerro Prieto Pull-Apart Basin. All instruments have sampling intervals in the 1 to 20 minutes range. Below, we present results based on records from 7 instruments that have low noise and are sufficiently long to permit drawing important conclusions.

The vertical extension recorded on ES-V is presented in the figure 2. A biaxial tiltmeter (ES-Y) was installed in 1998, very close to the creepmeter and recorded ground tilt, very close to the fault, until 2003, and after a small reconstruction, again since 2008.

Figure 3 shows extension and tilt recorded between 1998 and 2003; very similar patterns can be seen on both instruments. Both instruments present continuous creep and the same episodic slip events. Using criteria from Glowacka et al.(2011) we found that during 1996 -2009 there were 30 slip events with amplitudes larger than 8mm and rupture velocity of 27mm/day. A previous analysis showed that the fault normal movement is a border effect of the subsidence observed in the Cerro Prieto pull-apart basin, (Glowacka et al.,1999), and that the vertical slip observed on the ES-V is slip predictable and aseismic (Nava and Glowacka, 1999; Glowacka et al., 2009). The change in the slip rate, from 5.3cm/year to 8cm/year was interpreted as a delayed accommodation of subsidence bowl migration towards the Saltillo fault, caused by the production changes in the CPGF (Glowacka et al., 2009).

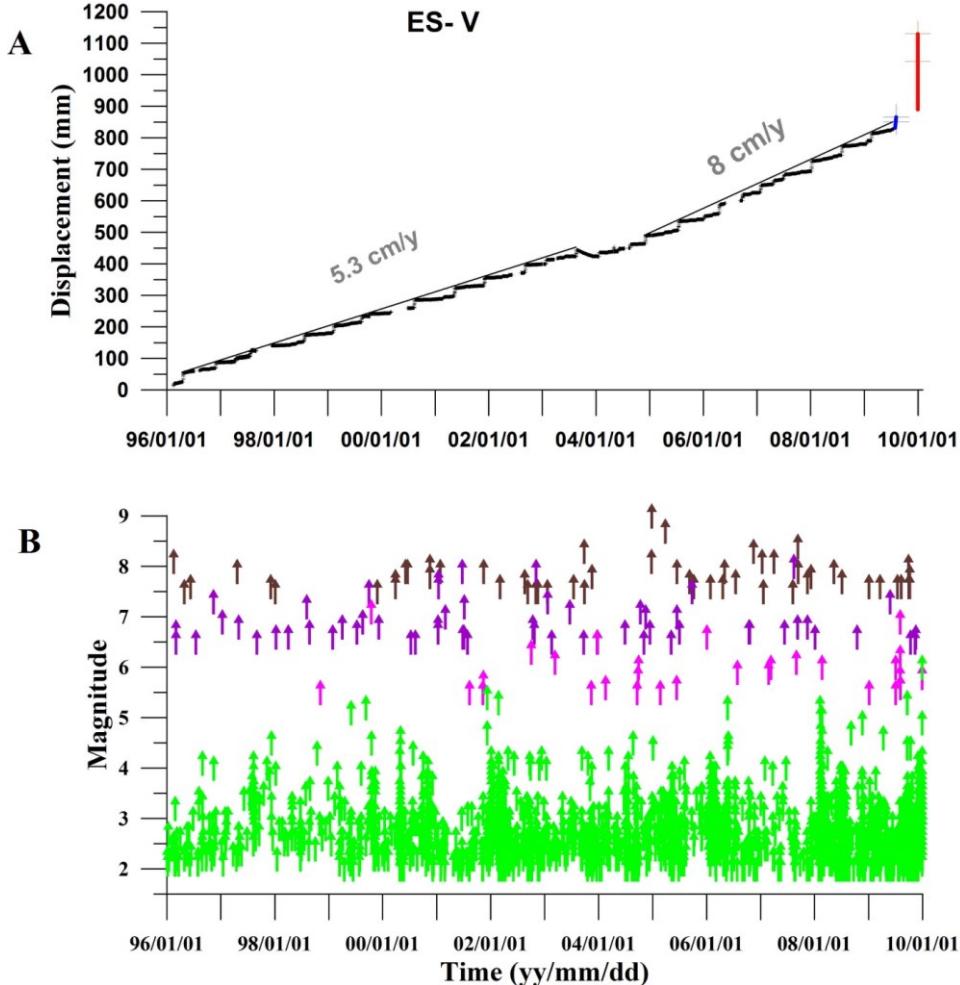


Figure 2: A. Vertical extension measured by crackmeter ES_V, black line. Displacement envelop in gray line. Blue and red lines mark the slip calculated for August 3, 2009 and December 30, 2009. See text for details. B. Seismicity: arrows label seismic events: green, $M \geq 2$, (located in the rectangle $32.1^\circ, 32.7^\circ, - 115.4^\circ; -114.9^\circ$), pink, regional ($M \geq 5.5, \Delta \leq 10^\circ$ and purple, $M \geq 6.5, \Delta \leq 50^\circ$), and brown, from global ($M \geq 7.4$) catalogs.

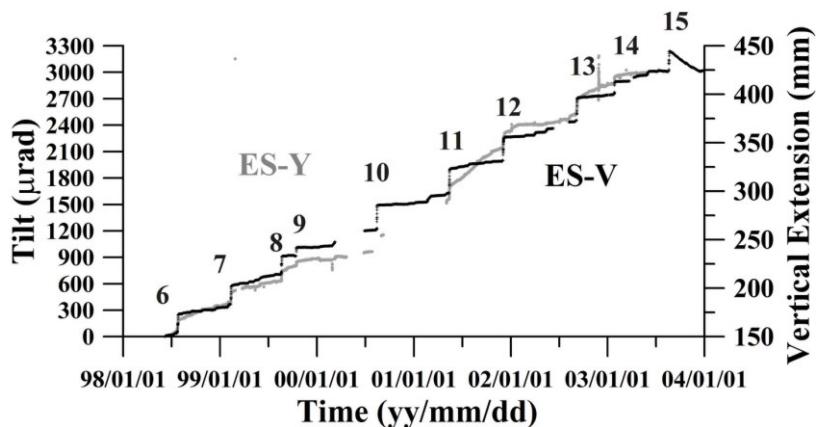


Figure 3: ES-V (mm) and ES-Y (μ rad) records during the 1998-2003 period. Numbers indicate the significant slip events recorded by both instruments.

Figure 4 shows deformation changes recorded by FM-V across de Morelia fault, FD-V installed across de Cerro Prieto fault, and X and/or (whichever less noisy) Y components of tilt recorded by CP (installed close to Morelia fault), RCP (installed close to a possible northern extension of the Cerro Prieto fault) and EH (installed between CP and ES). The Cerro Prieto fault (FD-V) presents continuous creep and small slip events (Glowacka et al., 2010a, b) with a total displacement rate of the order of 1cm/year, and 4cm/year, closer to center of CPGF (op. cit), the Morelia fault has no creep according to FM-V and CP-X, but exhibits abrupt changes related to local seismicity, while CP-Y displays steady tilt change related probably to the subsidence. EH-X shows both continuous creep, probably related to subsidence, and abrupt changes related to seismicity. RCP has no creep, only very small abrupt changes related to local seismicity.

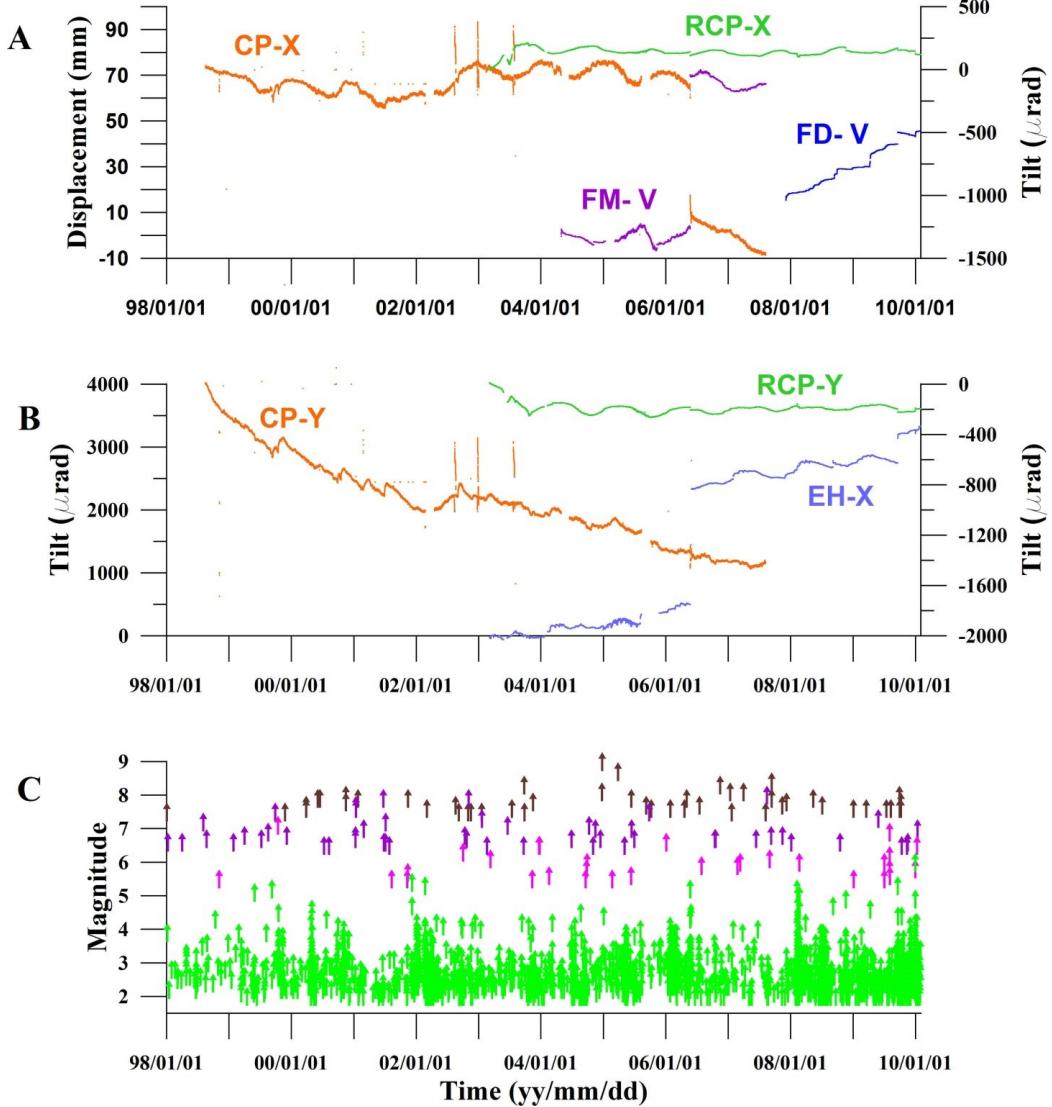


Figure 4: A. Vertical extension recorded on the FD-V and FM-V creepmeters, and tilt recorded on the CP-X and RCP-X during duration of the study. The creepmeter FM-V was separated from its benchmark during the 2006 earthquake and the value of coseismic displacement of 20-25 cm was estimated by Sarychikhina *et al.* (2009). **B.** Tilt record for CP-Y, RCP-Y and EH-X. Tilt and extension values are relative. **C.** Seismicity. See figure 2 for details.

3. RESULTS

The phenomenon of seismicity triggered by teleseismic large earthquakes was first noticed in the area of geothermal activity (Hill et al., 1993); since there have been many papers, published recently, about seismicity and fault slip triggered by teleseismic (e.g. Shelly et al., 2011) and regional (e.g. Glowacka et al., 2002) earthquakes, so that we decided to check our database for triggered slip. For this purpose we analyzed catalogs of local ($M \geq 2$, with epicenter within $32.1^\circ, 32.7^\circ, -115.4^\circ; -114.9^\circ$), regional ($M \geq 5.5$, $\Delta \leq 10^\circ$ and $M \geq 6.5$, $\Delta \leq 50^\circ$), and global ($M \geq 7.4$) catalogs (Fig. 3c and 4c). We confirmed that Hector Mine Earthquake (HME) from California (Fig. 5a, $M=7.1$, 1999, $\Delta=260$ km, Glowacka et al., 2002), triggered slip event on the Saltillo fault, and found that $M=6.9$, August 3, 2009 earthquake, from Gulf of California (Fig. 5b, $\Delta \sim 400$ km) and, possibly, $M=6.9$, 1999 earthquake from Costa Rica ($\Delta \sim 4000$ km), and the 2006, $M=6.6$, Gulf of California earthquake also triggered slip events on the Saltillo fault. We also checked for correlation between local earthquakes and slip on fault and found that there is a possibility that 5 local earthquakes triggered slip events (example in figure 5c), while possibly 6 slip events triggered local earthquakes. There are 2233 earthquakes with $M \geq 2$ in our local 5066 days long catalog, so for 30 slip events there is high probability that the associations between local earthquakes and slip

events occurred by pure coincidence. Up to the July 2009, neither regional nor local triggering earthquakes changed the displacement rate along the Saltillo fault, so, did not change the subsidence rate in the NE part of the subsidence area.

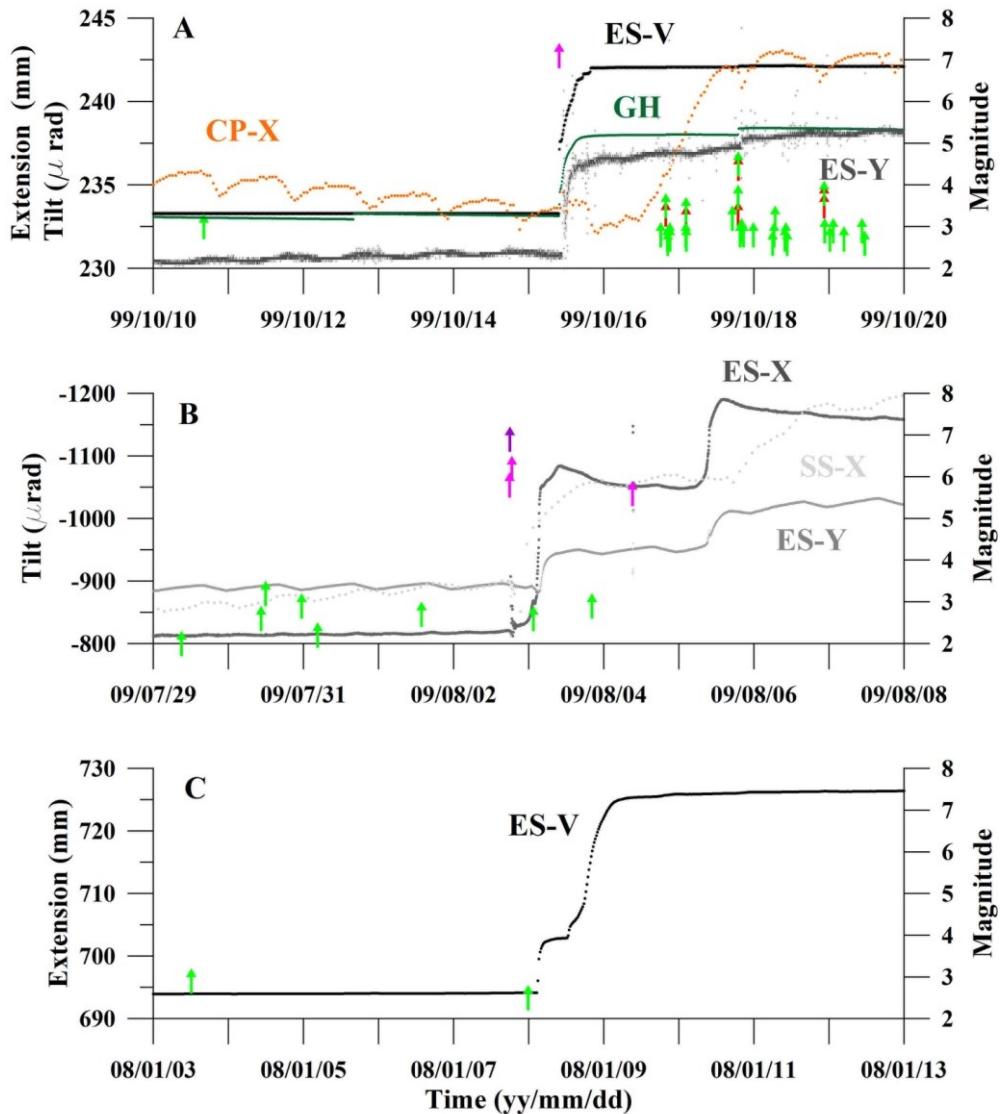


Figure 5: Extension and tilt recorded during the slip event triggered by the Hector Mine Earthquake M=7.1, 1999 (modified from Glowacka et al., 2002). B. Extension and tilt recorded during the slip event triggered by the M=6.9, 2009, Gulf of California earthquake. C. Slip event possibly triggered by a local earthquake. Arrows mark earthquake. See figure 2 for details.

The ES-V record ends in July 2009. Two tiltmeters installed close to the Saltillo fault continue recording. Using the tiltmeter closest to the ES-V, Sarychikhina et al. (2014) calculated that for 1998-2009 the amount of slip recorded on the ES-V, during slip events, D, is proportional to $\Delta\alpha$, the tilt recorded on the ES-Y tiltmeter, as $D=C\Delta\alpha$, where C is between 0.083 and 0.117. Using this relation we can estimate the slip triggered by the 2009, Gulf of California event (Fig. 5b), to be between 27.3 and 38.5mm, and for the M=5.8, 30 of December 2009, local event, we estimate coseismic displacement between 187 and 263 mm. Both, the slip event of August 3, 2009, and the coseismic displacement are shown in figure 2a. It is noticeable that, while the triggered slip of August 2009 agrees with the slip-predictable behavior of Saltillo fault, the coseismic displacement of December 30, 2009, does not; coseismic displacement is significantly larger than displacement expected from slip-predictable behavior. The December earthquake had a strike-slip focal mechanism (CMT, <http://www.globalcmt.org/CMTsearch.html>) with agreement with the tectonics of the Imperial fault (strike-slip fault), but since the Saltillo (normal) fault is an extension of the Imperial fault inside de pull-apart center, the coseismic deformation caused by the earthquake probably continues towards the Saltillo fault with a normal mechanism of slip.

Detailed analysis of figure 4 shows that local seismic events with magnitude higher than 5 can cause coseismic displacement on the Cerro Prieto and Morelia faults. Coseismic displacement and tilt recorded during the M=5.4, May 24, 2006 Morelia fault earthquake is presented in figure 6. The Morelia fault earthquake caused about 20cm (Sarychikhina et al., 2009) of fault

displacement, and hundreds of μ radians of tilt change recorded by CP-X and EH-X (Fig. 6). If the direction of the coseismic slip observed on the instrument record, agrees with a trend observed in the long term record, related to the subsidence, as in case the EH-X, we can state that coseismic deformation caused coseismic subsidence.

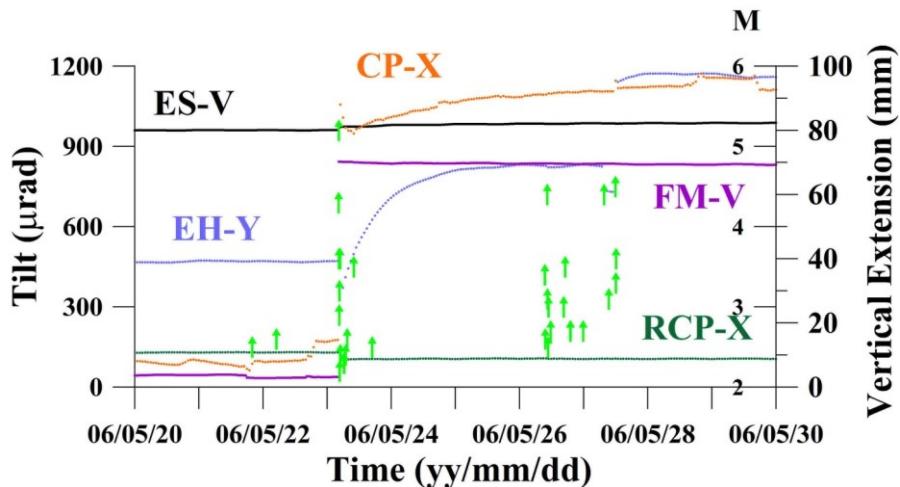


Figure 6: Coseismic displacement and tilt recorded during the M=5.4, May 24, 2006 Morelia fault earthquake. The creepmeter FM-V was separated from its benchmark during the 2006 earthquake and the value of coseismic displacement of 20-25 cm was estimated by Sarychikhina et al. (2009). Arrows mark seismicity, as in figure 2.

From analyzing details from the instrumental records shown in Fig.4, together with local seismicity, we can conclude that 100% of the subsidence observed on the FM-V crackmeter and the CP-X tilt is of coseismic origin, while CP-Y shows no coseismic component, so it is 100% due to anthropogenic subsidence. EH-X presents around 70% of coseismic subsidence. FD-V, on the Cerro Prieto fault, shows 20% of coseismic subsidence. The RCP tiltmeter signal is very small, but 100%, coseismic displacement, obvious, taking into account that it is installed outside the subsidence area. Taking into account the coseismic displacement on the Saltillo fault calculated for M=5.8 of December 2009, we can conclude that the Saltillo fault displays between 18% and 23% of coseismic subsidence.

Finally, we can summarize that, from the observations of slip or tilt recorded on the Saltillo and Cerro Prieto faults, which limit the subsidence area, we can estimate that, for the analyzed period, the anthropogenic subsidence is of the order of 80%, which is close to the $\sim 70\%$ estimated by Sarychikhina et al. (2014) using DInSAR images for 2006 – 2009 period after eliminating coseismic subsidence. It is less than the 95 % estimated by Glowacka et al. (2005) using tectonic deformation modeling and observations for the 1994-1997 period, but is similar to the 82-90% estimated by Camacho Ibarra (2006) for the 1977-2001 period.

4 ACKNOWLEDGMENTS

This research was sponsored in part by CONACYT, project 105907 and CICESE internal funds.

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