A DEFORMATION MEASURING NETWORK IN THE MEXICALI VALLEY, BAJA CALIFORNIA, MEXICO.

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ABSTRACT

The Cerro Prieto Geothermal Field (CPGF) is located in the Mexicali Valley, in northeastern Baja California, Mexico, in the northern part of a ridge-transform plate margin. The area is characterized by a high level of seismicity, hydrothermal and volcanic phenomena, and both tectonic and anthropogenic deformation.

Since 1996, geotechnical instruments 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 in the 1 to 20 minutes range.

We present the spatial distribution and installation characteristics of the instruments, as well as preliminary interpretations of some observations.

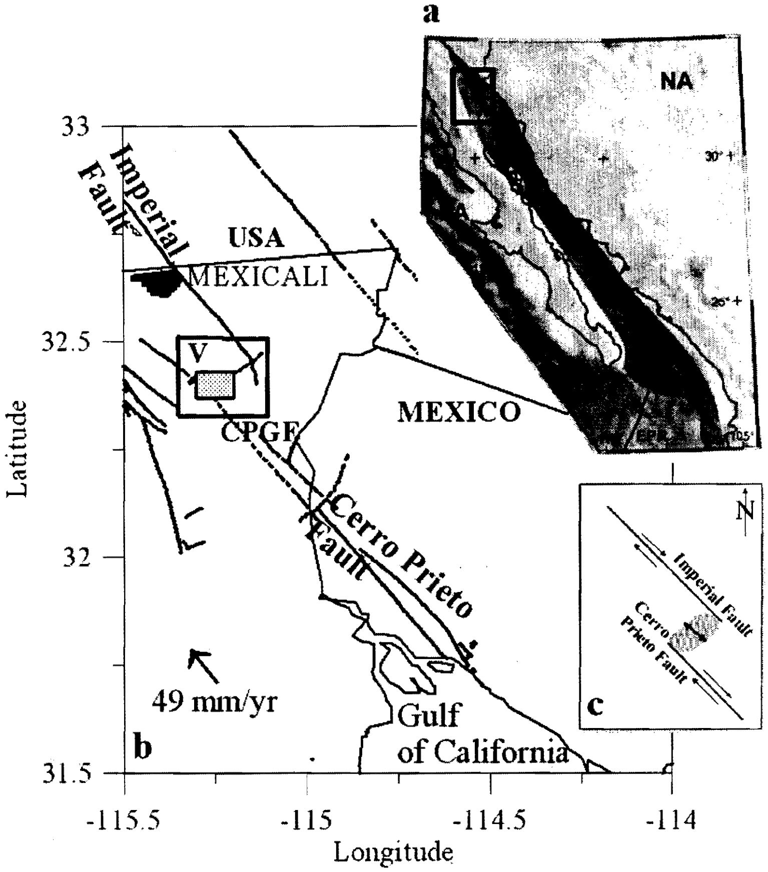
The motion observed at the Imperial and Cerro Prieto faults, which confine the pull-apart system including the CPGF, is mainly vertical, probably related to the subsidence. The Imperial fault slip appears mainly as slip-predictable, aseismic, creep events, related to pressure changes in the shallow aquifer. Transient and permanent deformations related to local and global seismicity are also recorded.

1. INTRODUCTION

The Mexicali Valley, which is part of the Salton Trough, is located within an active tectonic region, in the boundary between the Pacific and North American plates; a region featuring a wide zone of transform faults associated with San Andreas fault system, and a zone of distributed deformation in the pull-apart center of Cerro Prieto (Fig.1b).

The Cerro Prieto pull-apart center (Fig.1c). is the continental extension of the East Pacific Ridge (Fig.1a), deformed by the extensional tectonics of the boundary between the Pacific and North American Plates. The area is characterized by a high level of seismicity, hydrothermal and volcanic phenomena, and both tectonic and anthropogenic deformation.

Figure 1. Geographical situation (a & b). Inset (a) modified from Aragon, 2006. PA is Pacific Plate, NA is North America Plate, EPR is East Pacific Rise.
(b) The black rectangle encloses the studied area. CPGF is Cerro Prieto Geothermal Field.
The pull-apart system is shown in the (c) inset.



The area discussed here (Fig.1) is a tectonic pull-apart basin, located between two major right-lateral, strike-slip faults, the Imperial and Cerro Prieto faults, filled with a very thick layer (1 - 2 km) of alluvial sediments. Part of this area is occupied by the Cerro Prieto geothermal field (CPGF), which has been extracting geothermal water for a power plant since 1973. During the 1990's the extraction was of the order of 12000 ton/hour from depths between 1500 and 3000 m (CFE, 1998). In the 1989 the re-injection started and actually about 20% of the extracted fluid is being re-injected at 500-2600 m depth. The heat source of the field is probably a magmatic body located at a depth of 5 to 6 km below the ground surface (Elders *et al.*, 1984).

The natural seismicity of the area has been continuously monitored since 1932 by the Southern California Seismic Network (SCSN), since 1977 by the Red Sismológica del Noroeste de México (RESNOM), and since 1976 by the Red de Acelerógrafos del Noroeste de México (RANM). Many temporary local seismological arrays have also operated in this area (see Glowacka *et al.*, 1999, for a summary).

The seismicity of the area is dominated by swarms, while strong earthquakes occur along the traces of the main faults (Frez and Gonzalez, 1991). Since the second half of the twentieth century, this area has been the site of the Imperial Valley, (M = 6.6, 1979), Victoria (M = 6.1, 1980), and two Cerro Prieto (M = 5.4, 1987, and M=5.4, 2006) earthquakes. Increases in subsidence rate were observed after each of those earthquakes.

Leveling measurements in Mexicali Valley started in the 1960's, as part of the geothermal field preparations and as surveys for tectonics studies. These measurements have been continued, a few times per decade, up to the present. For the period 1994-1997, the subsidence rate at the center of the geothermal field was around 12cm/year (Glowacka *et al.*, 1999).

Comparing the space and time distribution of subsidence and leveling results across the Imperial fault with changes of the fluid production rate in the CPGF, Glowacka *et al.* (1999a, 2005) concluded that subsidence in CPGF is caused mainly by fluid extraction, and that the Imperial and Cerro Prieto faults are the stratigraphic boundary of the subsided area and acts as a groundwater barrier. This means that the vertical displacement on the Imperial and Cerro Prieto faults is an edge effect of the subsidence processes in the basin. Using a tectonic model of the pull-apart center, and known parameters of tectonic plates motion from GPS measurements (Bennett et al., 1996), Glowacka (et al., 2005) estimated that the tectonic subsidence is responsible for only 4% of the measured subsidence. This means that however tectonic situation has dominant control over the shape of pull-apart center and subsidence zone, true the depositional processes, the magnitude of subsidence is related with fluid extraction.

Interpretation of InSAR (Synthetic Aperture Radar Interferometry) images by Carnec and Fabriol (1999) and Hanssen (2001) also revealed that the observed subsidence is mainly caused by fluid extraction. Many other geothermal fields under extraction have induced subsidence caused by a fluid withdrawal (Narasimhan, and Goyal, 1984).

Because of the many phenomena, both tectonic and anthropogenic, causing deformation in the Mexicali valley, CICESE, with the economic support of CONACYT, has been monitoring these deformation processes since 1996. The CICESE network is intended to record relatively large deformation changes related to subsidence and local tectonics.

2. SPACIAL DISTRIBUTION OF THE INSTRUMENTS AND INSTALLATION TECHNIQUES

The mainly vertical displacement at the southernmost part of the Imperial fault has been measured on a continuous basis since February 1996 by a crackmeter installed in Ejido Saltillo (Glowacka 1996; Nava and Glowacka, 1999). The 3m long crackmeter (Geokon Vibrating Wire, model 8001) spans the fault in a plane perpendicular to it. The crackmeter extends from a base anchored to the eastern (higher) side of the fault to a base within a small graben in the western (lower) side. This instrument's (labeled ES in figure 2) installation diagram is shown in Figure 2a.

A second crackmeter was installed on July 1998 about 1 km south of ES, on the Imperial fault, in a horizontal direction about 60° from the fault strike. This crackmeter recorded dextral movement and extension across the fault. It functioned well until the end of 2000. A third crackemter was installed in the vertical plane crossing Morelia fault, in the geothermal field (CP in figure 2) in 2004. All crackmeters have resolutions of 0.1mm and operate with a 5- 20 minutes sampling interval.

In 1998 two biaxial surface tiltmeters (Applied Geomechanics, model 711) were installed, one close to the Imperial fault near ES, and one in the CPGF area (CP) (Fig.2). The instrument installation diagram is shown in figure 2d. During 2003 and 2004 another two (FCP and PZ) surface tiltmeters and two borehole tiltmeters (EH and RCP) were installed in the area. All tiltmeters operate with 1 μradian resolution and sampling interval of 1-4

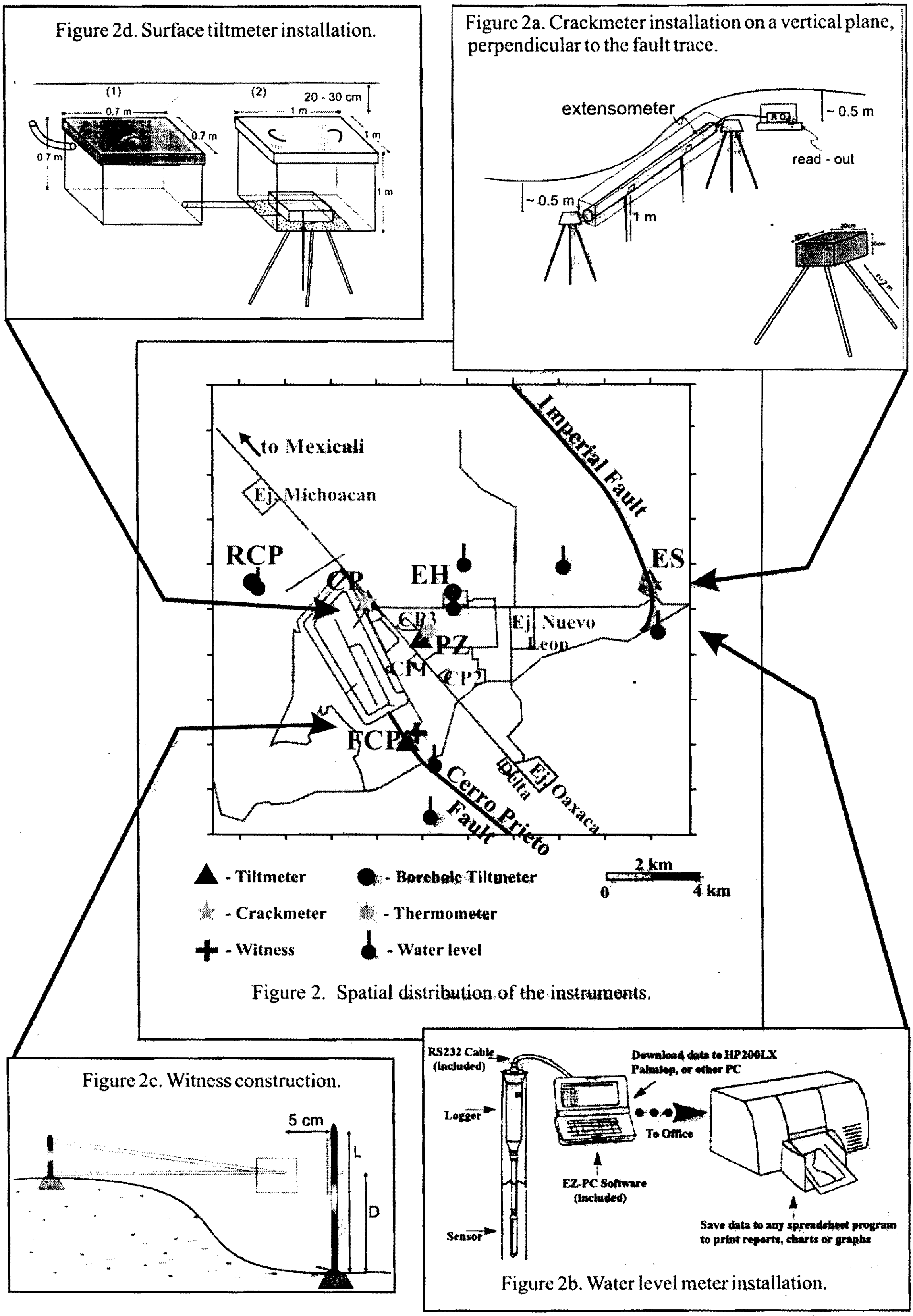


Figure 2d. Surface tiltmeter installation.

Figure 2a. Crackmeter installation on a vertical plane, perpendicular to the fault trace.

Figure 2. Spatial distribution of the instruments.

Figure 2c. Witness construction.

Figure 2b. Water level meter installation.

Figure. 2. Spacial distribution of the instruments and installation technics.

minutes. The FCP and PZ tiltmeters were damaged by the local soil and climate conditions, and so their operation was discontinued in 2005.

In 2004 the 3D *Witness* (Deformation Gages) was installed on the Cerro Prieto fault. Its design is shown in the figure 2c. It measures relative displacement of the higher (NW) side of the fault in relation to the lower part (SE), and is serviced every time technicians go to the field, it means every 1-3 months.

In 2003 seven digital piezometers (Solinist) were installed at depths up to 500 meters in the local piezometric wells, with the purpose of recording aquifer level changes. The installation diagram is presented in Fig.2b. The sampling interval is between 1 and 5 minutes and resolution of the water level measurements is 2cm or less, and 0.15 cm for barometer.

Crackmeters, tiltmeters and piezometers record data onto digital memory, and are serviced every 1 to 3 months. We present, below, some observations and preliminary results from the network.

3. SOME RECORDINGS OF DEFORMATION HISTORY

Ten years of observations by the ES crackmeter are presented in the figure 3a. Results from CP and EH tiltemetrs are shown in figures 3e and 3f. Figure 3d introduces 3 years of records from the witness installed on the Cerro Prieto fault. Figure 3b displays water level changes at the piezometer installed next to the Imperial fault, and Figure 3c displays one of the creep events recorded by the crackmeter and the piezometer. The map on the figure 3 also shows the subsidence rate observed for years 1994-1997, so that instrument observations can be compared with the local deformations.

From the figures and observations published before (Nava and Glowacka, 1999, Glowacka *et al.*,2002) we can see that the observed deformation rates measured on the Imperial fault are 6 cm/yr and 2 cm/yr for the vertical and horizontal components, respectively. Vertical motion on the Imperial fault is not continuous, but occurs in steps (creep events), separated by months of quiescence, and large events account for 70 percent of the vertical displacement. Creep events have amplitudes of 1-3 cm and durations of 1-3 days. The fault behavior for the vertical component is slip-predictable for large slip events and is aseismic. For some events which were recorded by three different instruments installed there is a time delay of about 6 hours between the slip onset at instruments separated by about 1 kilometer. This delay indicates that slip events have an apparent migration velocity of the order of 4 cm/s.

Comparison between occurrence of creep events and the water level record done for the G-1-17 piezometer, shows that in four instances a water level anomaly is associated with a creep event. On three of these occasions the water level change preceded the creep event registration by a few hours (as shown in 3c, for an 21-22 January, 2004 creep event) and once the creep event occurred first. This can probably be explained by the fact that creep originates in different parts of the fault, and migrates with a velocity of ~4mm/s, so that influences the water level in G-1-17 first, if originated south of the well, and later if originated north from the tiltmeter. Water level changes related to creep were observed in California (Roeloffs, 1996) and were interpreted as a pore pressure changes caused by the deformation on the fault.

The deformation on the Cerro Prieto fault has been observed, for longer time, only at the Witness construction (fig3d). From this figure we can conclude that there is vertical deformation on the fault with velocity around 3.1 cm/yr (within the 2 meters wide zone measured by a witness), NE side down, in agreement with the field subsidence, and the rate does not depend on the local seismicity. Horizontal rates change slightly with the presence of seismicity when very small right lateral deformation (6mm/yr) can be observed. Lack of continuous measurements do not allow to identify if there are creep events on the Cerro Prieto fault, or if the deformation is continuous.

All tiltmeters installed in the network show a constant trend superimposed by the periodic anomalyies related with diurnal and annual temperature changes, and permanent anomalies related to local seismicity (black arrows on figure 3e and 3f). Additionally, the EH tiltmeter record is dominated by tilt caused by changes in the surrounding crop irrigation system. The permanent inclination trend changes are oriented in the direction to South for CP tiltmeter, and SSW for EH tiltmeter, in agreement with the local subsidence gradient. Apart from continuous tilt to the south and annual and daily anomalies, the permanent tilt change related with the M=5.2, May 24, 2006 earthquake can be seen. Until now, three strong earthquakes have been recorded by the network. The October 1999, Hector Mine M=7.1 earthquake, located 250 km away, in California, triggered local seismicity, creep and permanent deformation in the Mexicali Valley (Glowacka et al., 2002). The Sumatra 2004, M=9.2, earthquake caused transient deformation, of about 2 hours duration, recorded by all tiltmeters. The 2006, local earthquake with magnitude 5.4 caused huge permanent deformation recorded by all instruments (Fig. 3e and 3f). Those observations are being evaluated and can yield valuable information about the local site effect and tectonics.

4. CONCLUSIONS

Our network of geotechnical instruments records deformation phenomena caused by subsidence, creep, and transient and permanent deformations related to local and global seismicity.

The tilt, mainly to the south, observed at the CP and EH tiltmeters appears to be caused by anthropogenic subsidence in the CPGF area.

The motion observed at the crackmeter installed on the Imperial fault and at the Witness installed on the Cerro Prieto fault, is mainly vertical, probably related to the subsidence. Both faults constitute subsidence boundaries.

The activity on the Imperial fault slip appears mainly as slip-predictable, aseismic, creep events, with amplitudes of 1-3 cm and durations of 1-3 days.

The abrupt pressure changes observed in the shallow aquifer are related to the occurrence of creep events and to local seismicity, and are due, probably, to compression caused by the dip slip component of the associated displacements.

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Figure 3e. Bi-dimensional tilt and seismicity (M>4.3) on the Cerro Prieto tiltmeter.

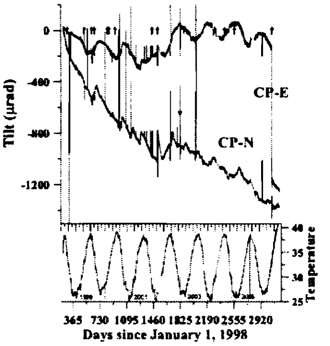
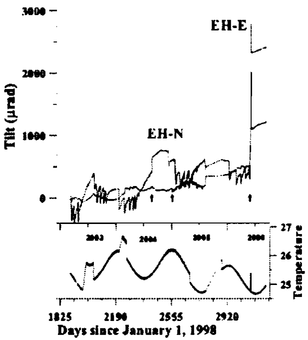


Figure 3f. Bi-dimensional tilt and seismicity (M>4.3) on the Ejido Hidalgo borehole tiltmeter.



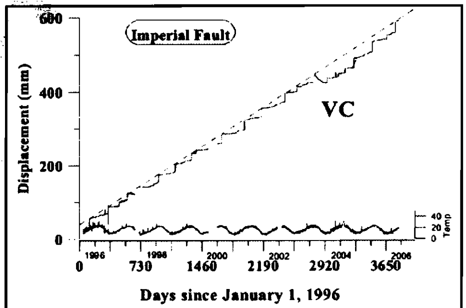


Figure 3a. Vertical displacement and temperature on the Imperial Fault.

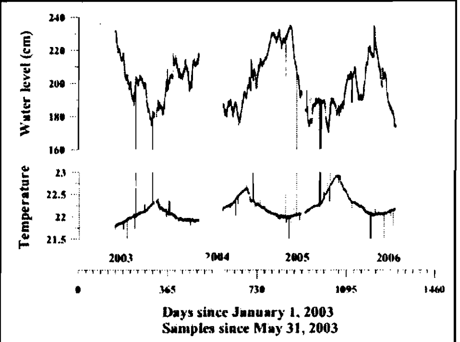


Figure 3b. Water level changes at the G-1-17 piezometer.

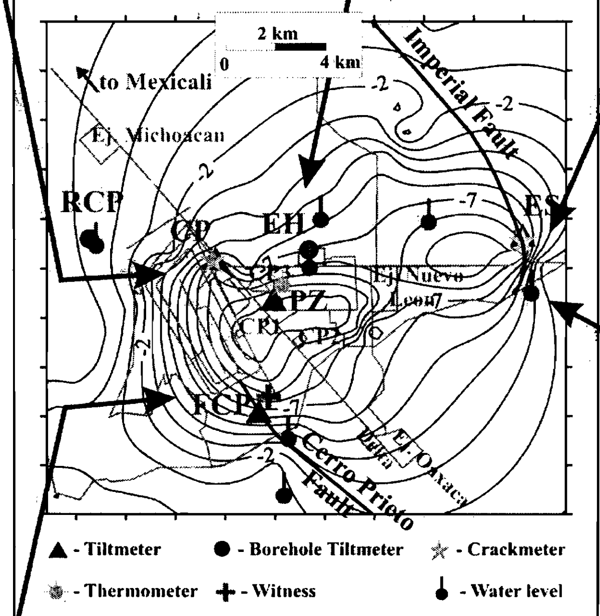


Figure 3. Vertical deformation in the studied area.

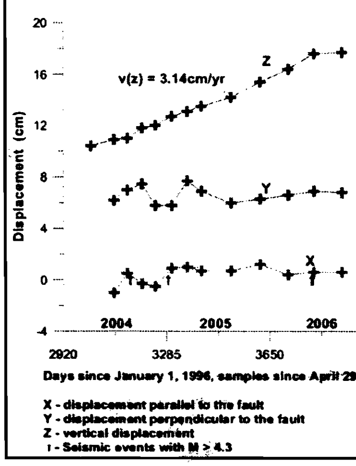


Figure 3d. Vertical and horizontal displacement and seismicity (M>4.3) observed at the Witness on the Cerro Prieto Fault.

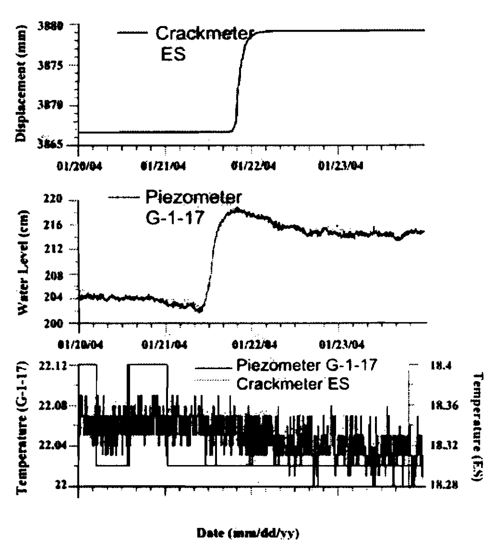


Figure 3c. Vertical creep event recorded on the Imperial fault and water level change at the G-1-17 piezometer during days 21-22.01.2004.

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