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SUBSIDENCE IN CERRO PRIETO GEOTHERMAL FIELD, BAJA CALIFORNIA, MEXICO.

Ewa Glowacka, Javier Gonzalez, F. Alejandro Nava

Centro de Investigación Científica y Educación Superior de Ensenada (CICESE), Ap. Postal 2732, Ensenada, B.C., Mexico

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ABSTRACT

During the period 1977 - 1987 the subsidence rate at the center of the Cerro Prieto Geothermal Field (CPGF) increased after every large, sustained production increase. Maps of subsidence rate for 1994 - 1997 show that the area with a subsidence rate ≥ 8 cm/y has an elliptical shape with a NE-SW major axis, which coincides with a thermal anomaly and with the orientation of a pull-apart basin located between the Cerro Prieto and Imperial faults. The area of maximum subsidence rate, around 12 cm/y, coincides with the area of extracting wells, and the subsidence velocity is much higher than the expected tectonic one. The area east of the Imperial Fault has a subsidence rate less then 2 cm/y, suggesting that this fault is an eastern boundary for recharging water. Continuous measurements of vertical deformation made during the last few years at the Imperial Fault show that vertical movement on the fault is not constant, but is concentrated during creep events, separated by months of quiescence. The high value of 11 cm/y for the mean vertical movement, and a pattern of rate changes similar to that of the CPGF, suggest that the movement in the Imperial Fault is influenced by water extraction in the CPGF. The occurrence of creep events, however, seems to have no apparent relation with the almost constant extraction in the field for 1996 - 1998. It seems that the displacement along the fault is influenced in the long-term by the deformation process (by the subsidence induced by fluid extraction), and in the short-term by local elastic phenomena such as friction, triggering and viscoelasticity. The relation between vertical displacement on the fault and seismicity is still not clear.

1. INTRODUCTION

The Cerro Prieto Geothermal Field (CPGF) is operated by the Mexican Comisión Federal de Electricidad (Mexican Federal Electricity Commission — CFE) and has been studied since the late 1950's when the first deep (>1000 m) exploratory wells were drilled. Production of electric power began in 1973, and since then, production growth has been achieved by increases in the number of power plants and wells, resulting in 127 operating wells in 1994, ranging in depth from 1500 to 3000 m, with a total fluid extraction of about 3.2 m^3/s. Injection of the discharged fluid begun in 1989 and reached 45% of the waste water (or ~20% of the extracted fluid) in 1993 (CFE, 1995). The depth range of injection is between 500 and 2600m.

The CPGF is situated in Mexicali Valley, in the southern part of the Salton Trough, at the tectonic boundary between the Pacific and North American Plates (Fig.1). The area located between the two major strike-slip, right-lateral, step-over to the right faults, Imperial and Cerro Prieto, is characterized by rapid geodetic deformation, high heat flow, active seismicity and volcanism, and has been also proposed as a spreading center (Lomnitz *et al.*, 1970; Elders and Sass, 1988).

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). In the case of the CPGF, until the 90's the measured subsidence was interpreted as being due to tectonics, while the lack of extraction related subsidence was explained by the hypothesis that almost all the extracted fluid was replenished by recharge (Narasimhan and Goyal, 1984). In what follows we review old and new evidence about surface deformation in the CPGF.

Precision gravity measurements, accompanied by high-precision leveling, were started at the CPGF in 1978 by California State University (Grannell *et al.*, 1979) in order to detect gravity changes related to fluid extraction. For the period 1981 - 1983 subsidence over the field was coincident with gravity increase. This phenomenon could be explained by several different mechanisms suggested by Wyman (1983), such as rock densification, mass redistribution, and reservoir cooling due to cooler water recharge, all caused by fluid extraction.

A correlation between extraction increases, seismicity and subsidence in CPGF was suggested by Glowacka and Nava (1996) and Glowacka *et al.* (1997). A possible relation between vertical movement in the southern part of the Imperial Fault (situated 8 kilometers east of the field) and geothermal water extraction was proposed by Glowacka and Gonzalez (1995) and Glowacka *et al.* (1997). Subsidence in the CPGF was measured by SAR (synthetic aperture radar) interferometry between 1993 and 1997 (Carnec *et al.*, 1998) and was interpreted as due to geothermal water extraction. A complete review of vertical deformation in Mexicali Valley and their relation with seismicity, tectonics and fluid exploitation of the CPGF is presented in Glowacka et al. (1999).

2. DATA

First-class, first-order leveling was done in the Mexicali Valley, including the Cerro Prieto area, between 1977 and 1980 by DETENAL (Dirección de Estudios del Territorio Nacional: Office of the National Territory Studies). Since 1986 CFE has been repeating part of the local leveling surveys every few years, including new sites inside and outside the area of the CPGF (Lira and Arellano,1997).

In 1977 a local 4.2 magnitude earthquake caused a vertical rupture of the pavement road in Ejido Saltillo (Fig.1), about 8 kilometers east from the CPGF. The rupture, mainly vertical, west side down, was reactivated during consecutive earthquakes and is still growing. At present the rupture can be observed crossing through paved roads, concrete channels and abandoned fields. Since 1989, CICESE (Centro de Investigación Científica y Educación Superior de Ensenada) have measured the vertical slip on the fracture with a ruler, about once a year until 1993. Since then, a short (500m) leveling profile crossing the fault has been measured a few times every year, using first-order, second-class precision leveling (Glowacka and González, 1995, Glowacka *et al.*, 1999). In 1996 continuous vertical slip measurements across the Imperial Fault an Ejido Saltillo were begun, using a crackmeter installed in a vertical plane perpendicular to the fault (Glowacka, 1996, Nava and Glowacka, 1999). The crackmeter (indicated as a star in figure 1) spans the fault from a base anchored to the eastern side to a base within the small graben. The crackmeter measures the extension which is the variation in the distance between the two anchor points. The crackmeter data (presented below) show that for 1996 - 1998 the vertical displacement rate has a mean value of 7 cm/y, and that 70% of the movement is released during “slip events” that have duration of days and amplitude of centimeters, and are separated by periods of weeks or months without slip.

3. LEVELING RESULTS

Subsidence rates determined from leveling surveys in 1994 and 1997 are presented in Figure 2; in this map the dominant feature is the roughly elliptical-shaped area of highest rate, oriented in the NE-SW direction. It includes the maximum rate (>10 cm/y) located at the center of the geothermal field (Glowacka *et al.*, 1999).

A cross section along the AA’ profile of figure 2 is shown in Figure 3a; this profile includes relative velocities measured from short-profile leveling across the Imperial Fault, and shows the location of the geothermal field and the Imperial and Cerro Prieto fault zones. Figure 3b is a geological section between these faults, for kms. 8 to 22, of the AA’ profile. From the profile, it appears that between 1994 and 1997 the whole area of production wells subsided at a mean rate of 11 cm/y, while the area NE from CPII and CPIII outside the wellfield did so by about 9 cm/y.

A large velocity contrast can be seen around kilometer 22, where the profile intersects the Imperial Fault about 8 km east of CPGF. In the field, the fault can be identified as a narrow scarp, 1-2 meters high, west side down, constituting the eastern edge of a 400 m wide graben.

The large subsidence velocity contrast between both areas located on different sides of the Imperial Fault suggests that this fault, which constitutes the eastern boundary of the subsided zone, is a groundwater barrier.

The subsidence of the area between the wellfield and the Imperial Fault, can probably be related to the natural fluid recharge of the wellfield by groundwater flowing from this area down the normal faults (Truesdell et. al., 1998).

Subsidence rates also changes significantly across the Cerro Prieto Fault, located between kilometers 7.5 and 10 of the AA’ profile (Fig. 3a), but the details of the change cannot be assessed due to spatial undersampling. In the field, this fault is characterized by a series of small scarps and fractures over a 25 m wide zone with a slight eastwards dip.

4. SUBSIDENCE RATE AND FLUID EXTRACTION

The subsidence rate for level bank 10061 (located at the center of the field) and the average rate for points 10058 - 10064 (with a longer history of measurement) are plotted in figure 4a for 1973 - 1997. Both rates are almost zero for 1977 - 1978, increase to 6 - 7 cm/y in 1978, to 10 - 12 cm/y in 1986 and, with small deviations, maintain this level until 1994 - 1997. Glowacka *et al*. (1999) showed that the subsidence between 1962 and 1977 was almost zero. The history of gross fluid extraction, injection and net production is plotted in Figure 4b, which shows the beginning of large-scale production in 1973, large extraction increases in 1979 and in 1986, and a slightly smaller net extraction in the present day, due to fluid injection. When comparing values of subsidence rate with the history of production it must be remembered that the exact date of subsidence rate increases cannot be known from the leveling, since leveling is done only every few years; only the general pattern of the production - subsidence relation can be established. Until 1978, the subsidence rate was very small, due to the relatively small rate of fluid production; it increased, probably about 1979, due to the extraction increase in 1979 and to seismicity (Glowacka *et al.*, 1999). The subsidence rate increased again between 1985 and 1987, probably due to the large production increase in 1986.

It is important to notice that the natural subsidence, expected from tectonic subsidence in the pull-apart basin and from soil compaction, should be of the order of millimeters per year (Glowacka *et al.*, 1999), 10 times less than the rates measured in CPGF. This, plus the agreement between the zone of maximum subsidence and the zone of producing wells, and the fact that subsidence rate increases following large production increases, suggest that the subsidence in the CPGF is mainly induced by fluid extraction.

Vertical displacement rates at the southern end of the Imperial fault (since 1987) are shown in the Figure 4c. Measurements were done about once per year for 1987 -1993, and every 3 - 6 months since then, while the leveling in the field was done every few years. The mean displacement rate for the Imperial Fault for 1987 - 1997 is about 11 cm/y, almost equal to the subsidence rate for the same period at point 10061 in the center of the CPGF.

The vertical motion on the Imperial Fault is concentrated within short time episodes which are separated by months of quiescence. The results from a vertical crackmeter operating at Ejido Saltillo since 1996 (fig. 5a) show that the motion is concentrated in swarms of creep events during 1 - 3 days, with displacements on the order of centimeters for each swarm. At this time we are not able to say if the subsidence in the geothermal field during periods of constant fluid extraction is continuous or is also clustered in time; damage which occurred after the 1980 earthquake (Wong *et al.*, 1997) and the 1987 earthquakes (Corona, 1988), suggest that subsidence in the field can also occur in very short time episodes. The low value of subsidence rate between summer 1987 and summer 1988 (fig. 4a), would be explained if, in fact, subsidence in the CPGF were episodic.

During the period 1996 - 1998, the occurrence of creep events measured by the crackmeter, which appear as “jumps” in Figure 5a, and the mean monthly vertical displacement shown in Figure 5b, seem to have, however, no apparent relation with the extraction and injection rate changes (which are roughly related to climate) in the CPGF (Fig. 5c). The relation between creep events and seismicity is also not clear (Glowacka and Fabriol, 1997). Nava and Glowacka (1999) showed that the extension events, observed in the surface in the form of swarms or suites, probably originate between the surface and the depth of the geothermal aquifer (~3 km), but are apparently triggered and stopped by ground stresses related to temperature changes and to viscoelastic processes near the fault.

5. CONCLUSIONS

The observed subsidence rate in the CPGF is much higher than the expected natural tectonic one. The area of maximum subsidence velocity (~11 cm/y) in the CPGF coincides with the production wellfield. For 1977 - 1997 the subsidence velocity at the center of the CPGF increased after large, sustained, fluid production increases. These facts suggest that subsidence in the CPGF is mainly caused by geothermal fluid extraction. There is no clear evidence that fluid reinjection influences subsidence in the CPGF.

Along a cross section perpendicular to the main faults, subsidence rates are large in the area between the Cerro Prieto and Imperial faults, and greatest over the wellfield. The rate of vertical displacement at the southern end of the Imperial Fault is almost equal to the subsidence rate in the geothermal field for 1987 - 1997. This suggests that the Imperial Fault is both the eastern boundary of the subsided area and acts as a groundwater barrier.

Further studies of the relations between fluid extraction, subsidence, and strain release on the Imperial Fault, is an important subject for seismic hazard evaluation in the Mexicali Valley.

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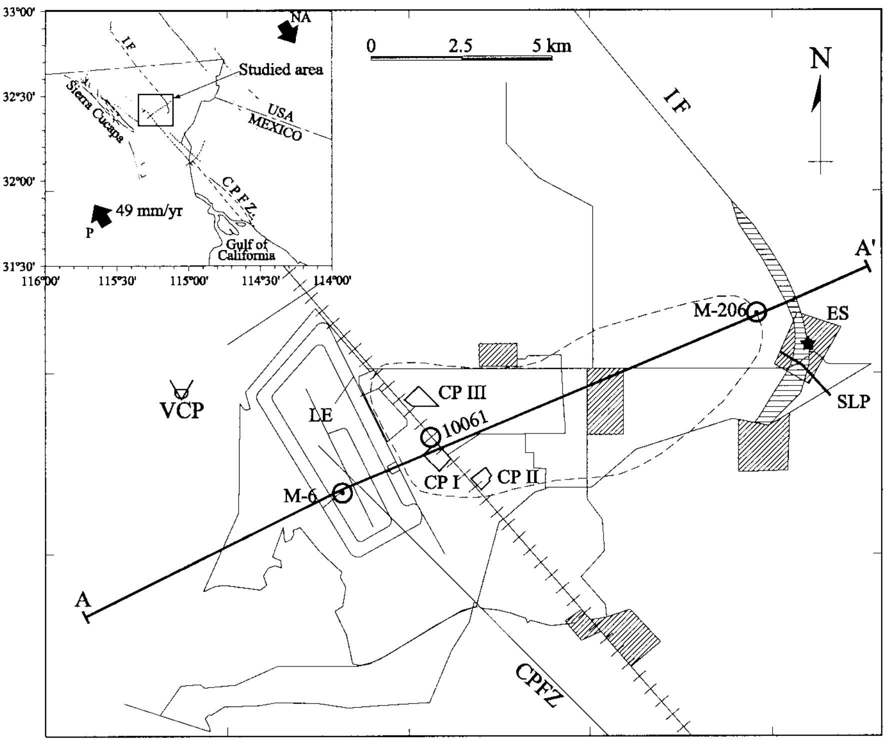

Figure 1. The Cerro Prieto geothermal field area: CPI, CPII, CPIII—production areas, CPFZ— Cerro Prieto Fault Zone, rectangles— towns, ES— Ejido Saltillo, VCP—Cerro Prieto Volcano. AA'— profile discussed in the text. SLP—short leveling profile across Imperial fault, LE (shaded area)— evaporation pond, hatchured area—Imperial Graben. Inset: Geographical location and tectonic setting CPGF. P and NA—Pacific and North American Plates.

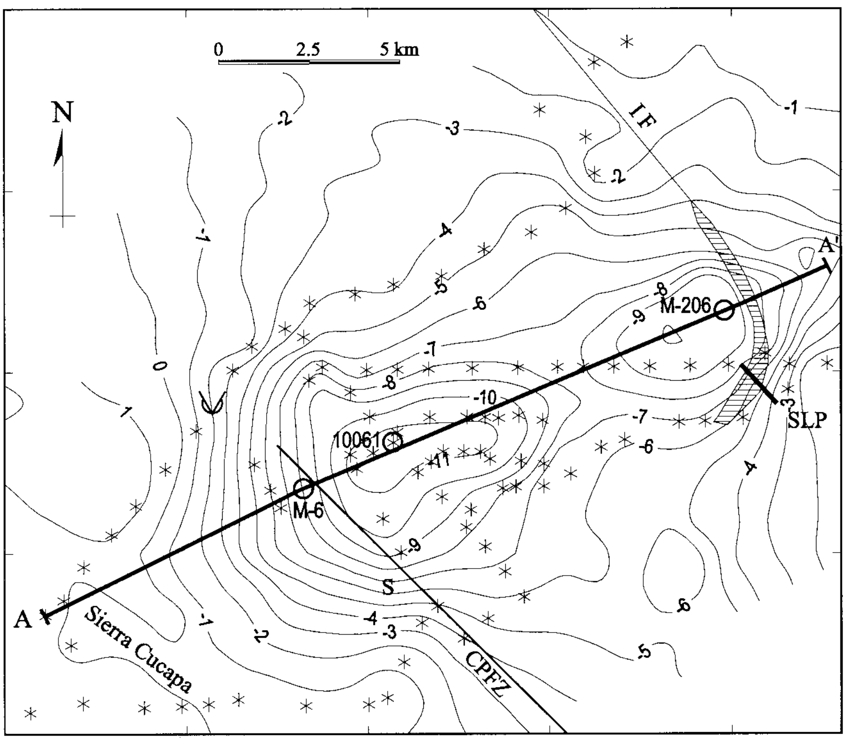

Figure 2. Subsidence rates for 1994-1997 in cm/y; Asterisks—bench marks, circles—wells and points mentioned in the text and in the next figures. Modified from Glowacka *et al.* (1999).

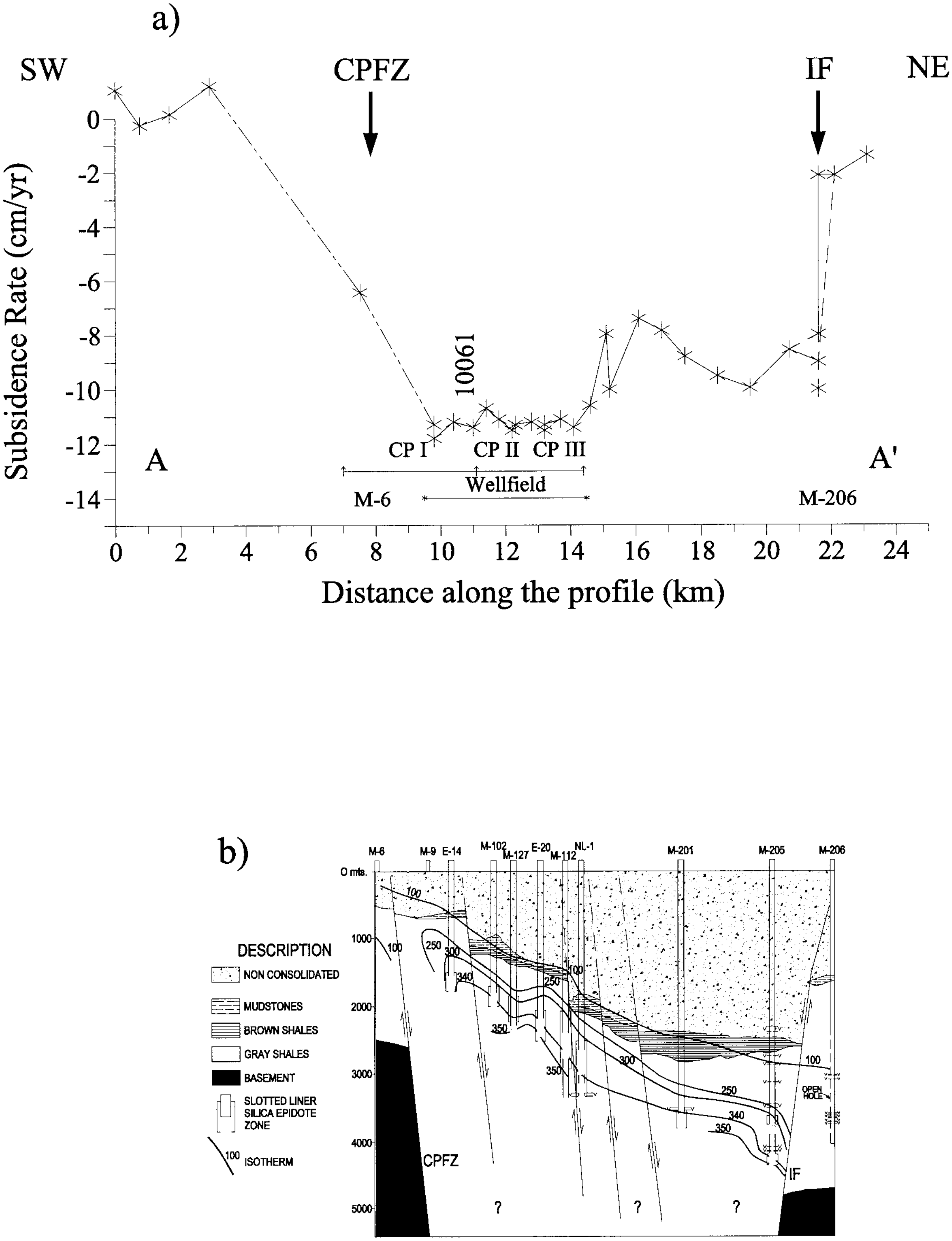

Figure 3. a) Ground surface subsidence rate for 1994-1997 along the AA' profile. Negative values indicate downward movement. b) Geological section of CPGF. Isotherms in °C. Modified from Glowacka *et al.* (1999).

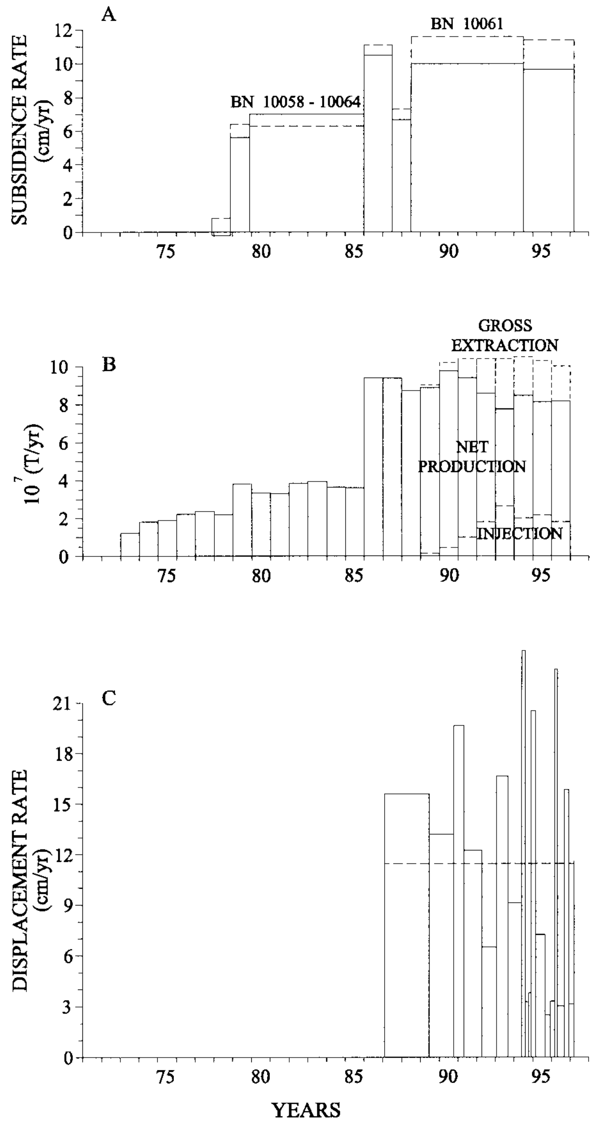

Figure 4. a) Subsidence rate vs. time for level points 10061 (dashed line) and averaged 10058 - 10064. b) Fluid production in CPGF for 1973-1996. c) Monthly vertical displacement rate at the Imperial Fault for 1987 - 1997. Modified from Glowacka *et al.* (1999).

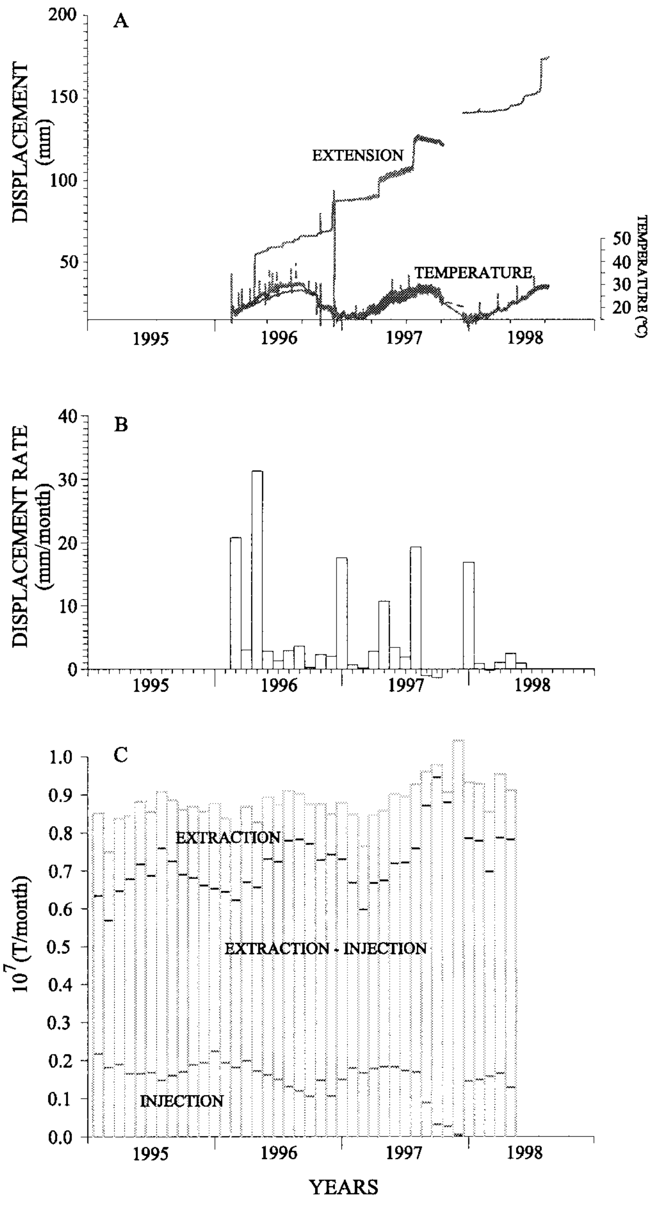

Figure 5. a) Extension and temperature recorded at the crackmeter at Ejido Saltillo. b) Vertical displacement rate at the southern end of the Imperial Fault. c) Fluid extraction and injection at CPGF. Modified from Glowacka (1999).