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SEISMICITY AND FLUID REINJECTION AT CERRO PRIETO GEOTHERMAL FIELD: PRELIMINARY RESULTS

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ABSTRACT

Seismic activity in the Cerro prieto area (Baja California, Mexico) is supposed to be high, due to the proximity of the Cerro Prieto and Imperial active faults. Records of seismicity are usually reported in USGS-Caltech and RESNOM catalogues and local arrays are continuously monitoring seismicity since august **1994.** Reinjection of geothermal fluid began in **1989.** Comparison between the USGS-Caltech catalogue and records of the variation of injection flow rate from **1988** to **1996** suggests that **a** mid-range (i.e. several months) correlation could exist between changes in global flow rate during winter and events of magnitude larger than Ml≥3 occumng the following summer. From August **1994** to December **1995,** seismic monitoring with a local array *(5* analogical recorders) allowed better hypocenter determinations. One case of short-range spatial and temporal correlation was found between a sharp increase of flow rate in well 303 and an event located close by, but at more than **4** km depth. Since february **1996,** monitoring is carried out by a digital array *(5* stations), operated by the Comisión Federal de Electricidad, which allows better hypocentral determinations.

INTRODUCTION

The Cerro Prieto Geothermal Field, the second largest field in the world, is located in the Mexicali Valley (Baja California, Mexico), at the head of the Gulf of California, between the southeast end of the Imperial Fault and the northern end of the Cerro Prieto Fault (Fig. **1).** Exploitation of this field started in **1973** and, at present, the nominal production is **620** MWe. Reinjection of waste brine started in **1989** to avoid discharge of residual brines into surface aquifers. More than **42%** of the extracted fluid was reinjected by **1995,** the other 58% being evaporated in the evaporation pond, the so-called Laguna de Evaporación.

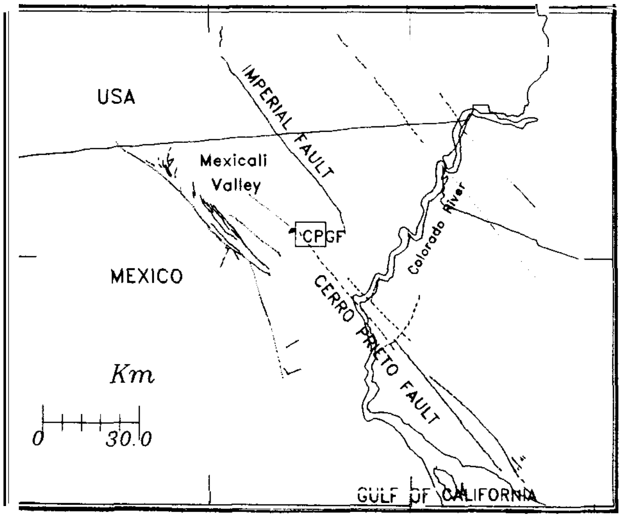

Figure **1:** Location map of the Cerro Prieto geothermal field. The rectangle points out the geothermal field (CPGF).

The geothermal field is situated within the sediments which fill the Colorado River delta. The liquid dominated reservoir is located between **1500** and 4000 m depth in sandstones, sandy shales and shales (Lippmann and **Mañón, 1987).** The heat source is attributed to a pull-apart basin where igneous rocks are being emplaced (Elders et al., **1984).** The Cerro Prieto pull-apart basin is part of the Salton Trough-Gulf of California system of spreading centers and transform faults which link the East Pacific Rise to the San Andreas fault system (Lomnitz et al., **1970).** At a regional scale, this area is well-known to be seismically active and was denominated as the Mexicali seismic zone by Frez and González **(1991).**

Seismological studies were carried out in the area since 1969, either dedicated to investigate seismicity and structures of the Mexicali Valley, or focused on the geothermal area as an exploration tool (see for a review, Glowacka and Nava, 1996). Otherwise, literature shows examples of seismicity generated by geothermal fluid exploitation (e.g. The Geysers in California, USA, ***Romero et al., 1994,*** and Larderello in Italy, ***Batini et al., 1984).*** In the early eighties, Majer and McEvilly (1982) reported a significant increase of microseismic activity in the Cerro Prieto area, that they attributed to exploitation activities. A three month survey carried out at the beginning of 1993 detected an important microseismic activity beneath the production/reinjection area (Dominguez et al., 1996). Glowacka and Nava, (1996), investigated the correlation between seismicity and fluid extraction, using data from USGS-Caltech catalogues for years 1973-1991. According to these authors, probabilistic analysis can not reject the hypothesis that strong earthquakes could be triggered by a production increase.

In this paper we compare the time and spatial distribution of seismicity with the variations of injection flow rate. Two types of data sets are examinated: the events of magnitude $Ml \geq 3$ from the catalogue of the USGS-Caltech regional array and the events of magnitude $Ml \geq 1.5$ recorded by the local array which started monitoring since August 1994. Qualitative relationships are investigated, on a mid or short range basis.

SEISMICITY FROM 1988 TO 1996: THE USGS-CALTECH CATALOGUE

As fluid reinjection started in 1989, we examined the occurrence of seismicity close to the Cerro Prieto area since 1988. At that time, seismicity was recorded continuously by two regional seismological networks, RESNOM (from Mexico) and USGS-Caltech. All the recording stations of the latter are located on the north side of the USA-Mexico border, which introduces an important bias in the epicenter determination. Despite that location errors of the RESNOM catalogue are lower than USGS-Caltech ones in that particular area, it is worth to use the second since it worked continuously. Location errors of the USGS-Caltech catalogue range from **5** up to 10 km, approximately, and events are generally shifted towards south (Fabriol, 1996). Map of seismicity recorded from 1988 through 1995 by USGS-Caltech network is presented in Figure 2. Seismic activity is spread nearly all over the area. Large clusters of events are observed at the west and the east of the geothermal area. They correspond mainly to the activity recorded during the second semester of 1993, west of the northern end of the Cerro Prieto fault and southeast of the southern end of the Imperial fault. No particular cluster was located close to the exploitation area, but we have to keep in mind that location errors shifted epicenters several kilometers southwards. Then, part of the cluster located south of the geothermal area could be relocated inside of it.

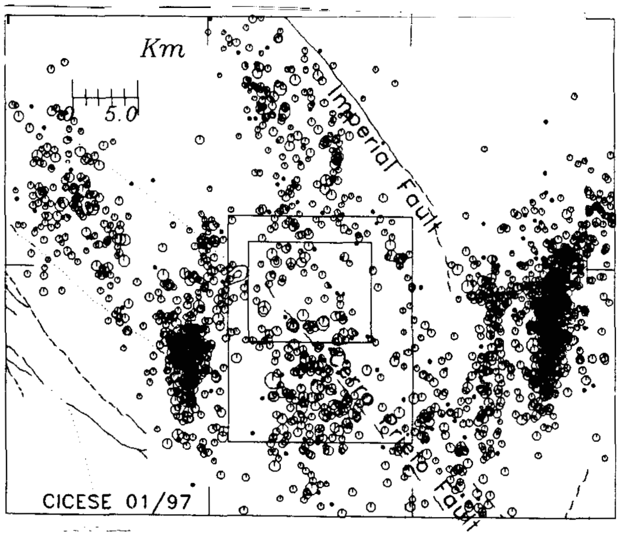

Figure 2: Seismicity recorded by the USGS-Caltech network from 1988 through 1995. The inner rectangle corresponds to the geothermal area. Events of magnitude $Ml \geq 3$ used in Figure 3 are selected inside the outer rectangle.

To compare the time distribution of seismicity and fluid reinjection variations, we plotted in Figure 3 the changes of injected volume per month and the seismic moment cumulated per month of using the earthquakes of magnitude $Ml \geq 3$ selected inside the outer rectangle of Figure 2. This rectangle is larger than the supposed exploitation area and elongated towards south to take into account location errors and the shift towards south of the USGS-Caltech catalogue. The seismic moment M_0 is a scalar quantity which is related to the magnitude Ml through the empirical relation (Pearson, 1982):

$$\log(M_0) = 17.27 + 0.77 \times Ml$$

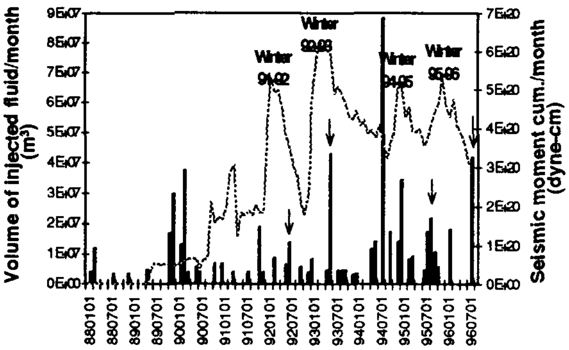

Figure 3: Comparison of seismicity (vertical bars) and variations of total volume of injected fluid (dashed line) per month, from 1988 to 1996. Arrows point out seasonal increases of seismic activity.

Injection started in well 0-473 in June 1989, followed the same year in October by well M-6. Until October 1990, only both wells were used and the sum of flow rates did not exceed 0.1 m^3/s. Then, an increase of seismic activity was observed during the first semester of 1990. Moreover, four noteworthy changes of the injected volume are observed in Figure 3 during winters 91-92, 92-93, 94-95 and 95-96. An increase of reinjection is required in winter, since the evaporation is less at surface, due to low temperatures, and the storage capacity of the evaporation pond is limited. During the summer following those increases, seismic activity increased notably, characterized by several events of magnitude ranging from Ml=3 to Ml=4 and denoted by arrows in Figure 3. There was no increase of injection during the winter 93-94, but the largest event recorded since 1988 occurred on August 12, 1994 (Ml=4.6).

A possible relation exists between the beginning of injection in 1989 and the seismicity occurred during the first months of 1990. Although the volume injected could be considered as no significant, seismicity could have been triggered merely by the initial perburbation to the medium. Apart from this, we suggest that a mid-range causal effect exists between the seismicity occurring during summer and the increase of volume of reinjected fluid during the preceding winter. The delay would be about 6-8 months. Respect to spatial correlation, precise locations of seismic events are available only starting from 1995 and epicenters are located mainly beneath the evaporation pond and west of the northern end of the Cerro Prieto fault. No evident spatial migration is observed from 1995 to 1996. Therefore, it is not possible to deduce any progression of the cold fluid front with those data. More years of recording are needed to confirm the hypothesis of a mid-range seismic effect of fluid reinjection and to explain it. In the case of the August 12, 1994 event, no direct relation with any increase of injected volume during the preceding winter or weeks could be found.

SEISMICITY FROM AUGUST 1994 TO AUGUST 1996: THE LOCAL NETWORKS

In August 1994, CICESE started continuous monitoring with four analog seismographs (MEQ 800, from Sprengnether), in order to study the temporal and spatial distribution of local earthquakes. Permanent stations from regional networks (seismometers and accelerometers) from both sides of the International Border were also available (RESNOM, USGS-Caltech and the Strong Motion Array of Northwest of Mexico). During 16 months, about 490 local seismic events with magnitudes ranging from Md=0 to Md=4.6 were recorded by the analog network. Time distribution of seismicity was erratic, periods of scarce activity (2-3 events per day) alternated with periods of seismic quiescence. Few swarms were recorded, in contrast with what is usual in the Mexicali seismic zone (Frez and Gonzalez, 1991).

Hypocenters of 148 earthquakes were calculated with HYPO71 (Lee and Lahr, 1975), using a 8 layer model based on a study by McMechan and Mooney (1980). The average of all the calculated horizontal and vertical errors are lower than 2km. A map of epicenters is presented in Figure 4. Seismicity is mainly concentrated around the northern extremity of the Cerro Prieto fault and within the geothermal zone. No seismic activity appears towards east and north of stations D5 and Oax2, close to the Imperial fault, except both the Md=3.1 earthquakes of October 1, 1995. In fact, many microearthquakes were observed in those stations, but hypocenter determination was not possible, due to the high cultural noise around the geothermal plants. Since February 1996, a digital seismic network of five stations is being operated by the Comisidn Federal de Electricidad, providing epicenters with location errors lower than 1 km. Another 84 events, from February through August 1996, have been located, mainly in the exploitation zone and northwest of Volcán Cerro Prieto (Figure 5).

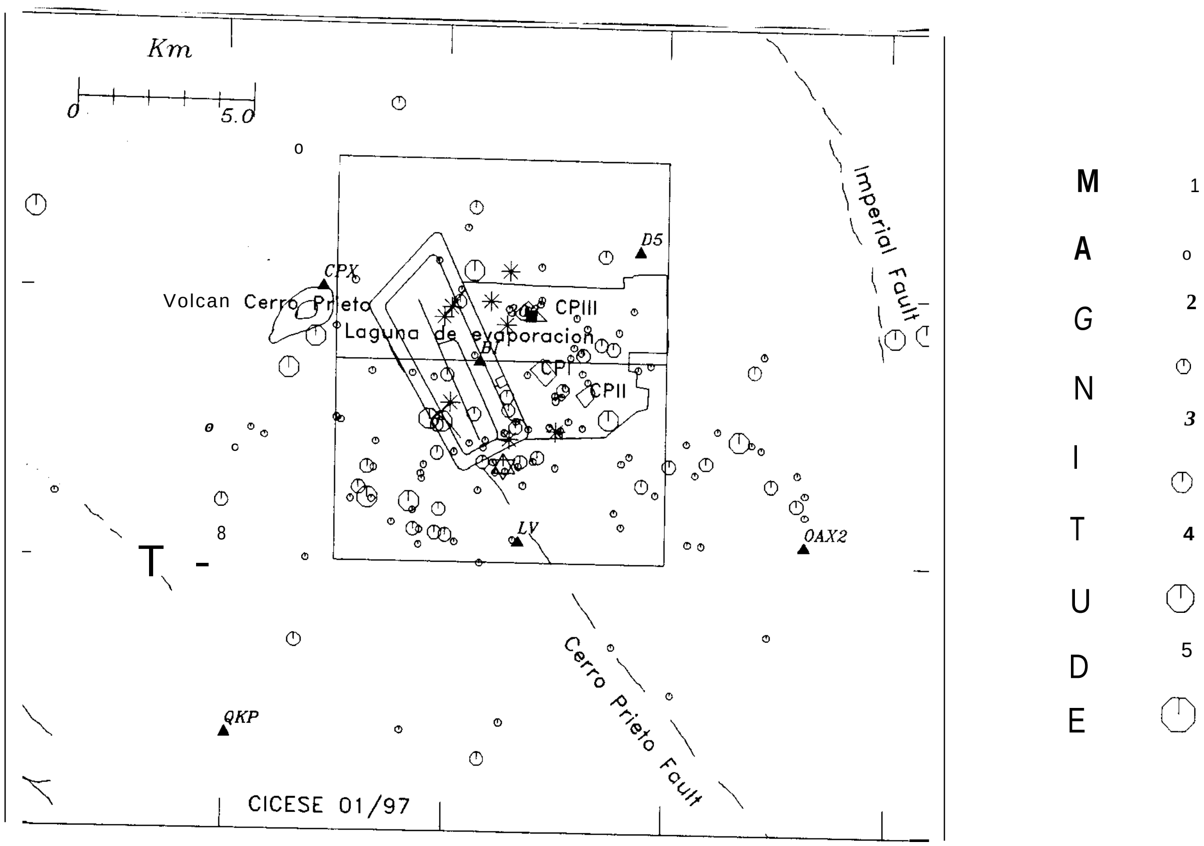

Figure **4:** Epicenter map of seismicity recorded from August **1994** to December **1995.** Black triangles are seismological stations. CPX station belongs to RESNOM network. ✻ are injection wells. Events used in Figure 7 are selected inside the upper rectangle (north area) and in Figure 8 in the lower rectangle (south area). The August **11, 1994** and January **11, 1995** events are denoted by an opened star and a black square, respectively. CPI, CPII and CPIII are power plants.

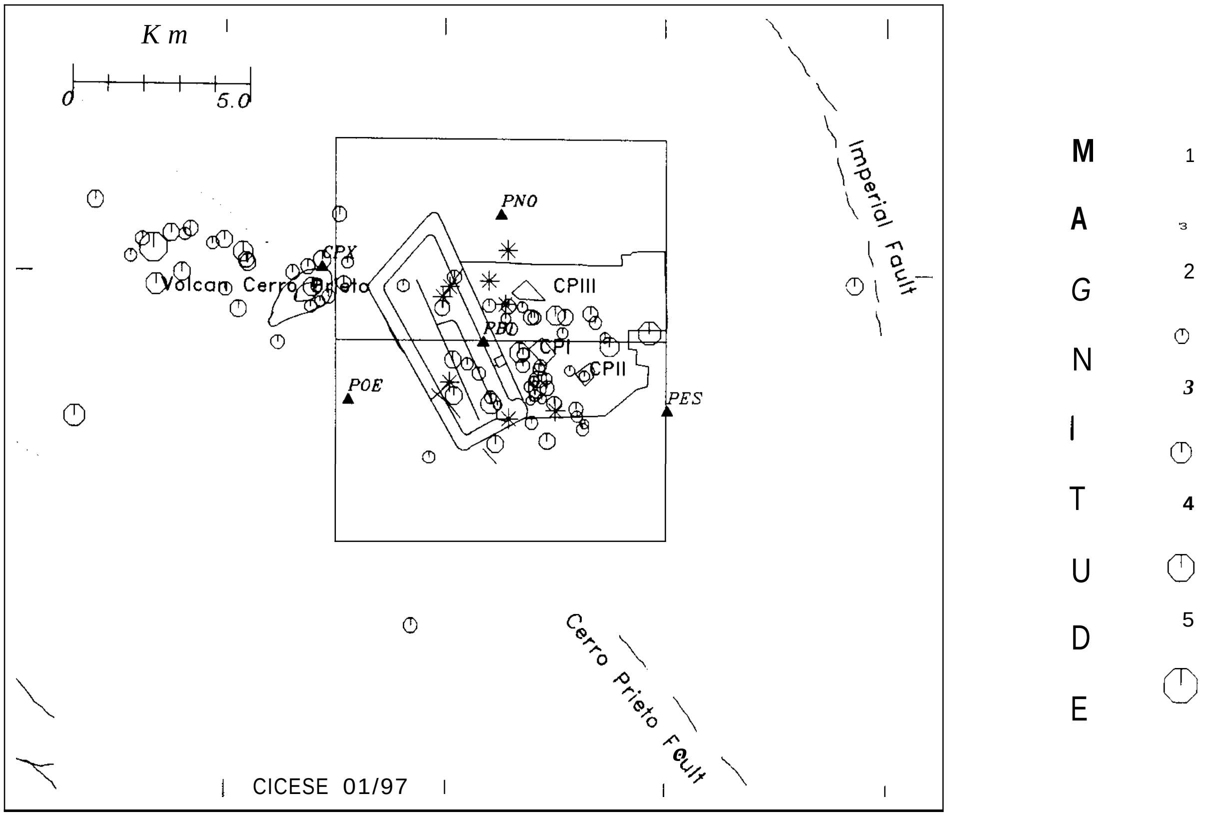

Figure **5:** Epicenter map of seismicity recorded from February to August **1996. Sam** symbols as in Figure **4.**

The concentration of events in Figure **5,** compared with Figure **4,** could be explained by the better quality of locations in the former case. A NE-SW cross-section is shown in Figure 6, where all the located events from **1994** through **1996** with vertical error lower than 2 km, are included. Depths range mostly from 2 to 6 km, which suggests that seismicity occurs at the bottom of sediments and at the top of basement, beneath the reservoir. Several events are deeper, particularly those which epicenters are located southeast of the field

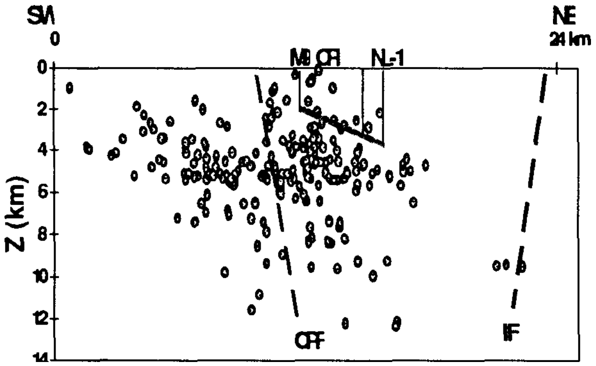

Figure **6:** Vertical section of hypocenters, along a SW-NE plane. CPF and I F Cerro Prieto and Imperial faults; CPI: geothermal power plant: M9 and **NL-1:** geothermal wells. The gray line at the bottom of the wells represents the top of the reservoir, schematically. Traces of faults are approximate.

SPATIAL DISTRIBUTION OF SEISMICITY AND ITS RELATIONSHIP WITH INJECTION

A concentration of events is observed in Figure **4,** south of the Laguna de Evaporación and around the three geothermal plants, CPI, CPII and CPIII. This cloud of seismicity could be associated to the bundle of NS, NNE-SSW and NNW-SSE faults that have been detected by drilling in the geothermal zone (CFE, pers. comm. **1995)** and to the NNE-SSW H fault of Halfman et **al. (1984),** through which deep hot fluids recharge the geothermal system from the heat source, located to the east and northeast of the field (Lippmann et **al., 1991,** Elders et **al., 1984).** Deepening of the top of the basement between the Cerro Prieto and Imperial faults and isotherms of temperature at depth show a NE-SW pattern (Lippmann and **Mañón, 1987).** Nevertheless, the seismicity occurring during **1996** in the exploitation area lines up preferently along a NNW-SSE pattern (Figure 5).

As we know that the structural framework is complex and those faults are seismically active, we propose that the origin of seismicity in Cerro Prieto area could be threefold

- linked to fault tectonics : that is likely the main part of the seismicity observed close to Cerro Prieto fault and to the west of it. Into the geothermal zone, deep geothermal fluid circulation through the faults intersected by drilling could be also involved in earthquake generation.

- linked to exploitation: that is seismicity occurring beneath and close to the reinjection/production zone, along the faults above mentioned, and triggered by reinjection of geothermal fluid (or possibly also by extraction, but that is difficult to prove since production is supposed to be constant on average since **1987)**

-linked to the ascent of magma in dikes within the brittle upper crust, as suggested by Hill **(1977)** to explain swarms occurrence in the central part of Imperial Valley. That corresponds to the few events occurring in the deepest part of the gap existing between the Cerro Prieto and Imperial faults, towards the southeast of the field. For the period of time of our study, these events are the only evidences of seismic activity linked directly to the pull-apart basin.

As both the first mechanisms are strongly interdependant, it is difficult to state which of them predominates. Only a clear correlation in time and space between the start of an injection process and the increase of seismicity around the injection well could be qualified as an evidence of induced seismicity.

We investigated time and spatial correlation between seismicity and injection through the comparison of seismic moment and daily variations of flow rate, from August **1994** to August **1996.** We selected events located inside two rectangles of **10x5** km, as shown in Figures **4** and **5**, and centered around two group of injecting wells: **0-473, E-6** and **E-16** for the south part of the reinjection area, and **M-94,** 303, I-1, 1-2, I-3 and I-4 for the north part. For each group, the daily sum of flow rate of the corresponding wells is plotted together with the daily sum of the seismic moment of the events located in the corresponding rectangle (Figures 7 and 8).

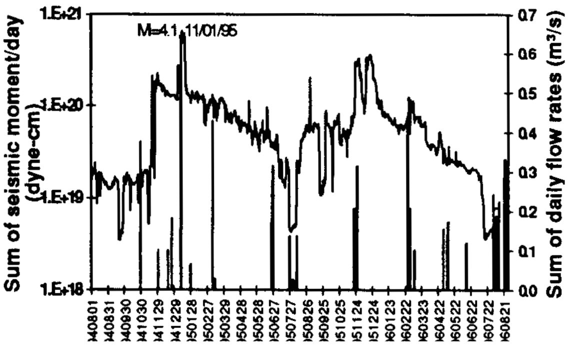

Figure 7: Comparison of sum of daily flow rate (wells 303, I-1, 1-2, 1-3, 1-4 and M-94) and sum of seismic moment per day (vertical bars), north area.

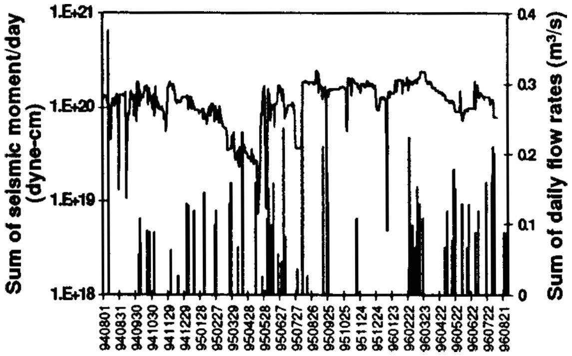

Figure 8: Comparison of sum of daily flow rate (wells O-473, E-16 and E-6) and sum of seismic moment per day (vertical bars), south area.

One example of a possible correlation in time and space between the increase of reinjection in well 303, on January 5,1995, and the Md=4.1 earthquake of January 11, 1995 is observed in Figure 7. In this case, it is likely that a sharp increase in flow rate, made possible by the high permeability of the well (fluid was injected by gravity), added to the proximity of a fractured zone, are responsible of the earthquake triggering. The focal mechanism of this event is of normal type with nodal planes aligned in NS direction (Fabriol and Munguia, 1996), which is in agreement with the structural map of the epicentral zone (CFE, pers. comm., 1995). The August 12, 1994, Ml=4.6 event, has a similar focal mechanism.

CONCLUSIONS

The results presented here about the relation between seismicity and reinjection in Cerro Prieto depends on the characteristics of the monitoring array, whether it is local or not, the precision of locations and the number of available examples to setup significant statistics. Based on the earthquake catalogue of USGS-Caltech for the 1988-1996 period and the recordings of the local array since 1994, we propose that a mid-range effect could exist between the increase of injected volume of fluid in winter and the seismicity occurring during the following summer. Up to now, magnitude of those events did not exceed Ml=4 and more years of recordings would be necessary to confirm this hypothesis. Moreover, there is only one example of a possible correlation in time and space between a sharp increase of flow rate and a magnitude Ml=4.1 event. That is insufficient to state about the existence of a short-range effect. Respect to microseismicity, that is events of magnitude lower than Ml=3, it occurred continuously in the exploitation area but, it is not possible, up to now, to affirm that part of it was triggered or not by reinjection.

The lack of immediate effects of reinjection in term of events of magnitude Ml≥3, except the January 11, 1995 event, could be explained by the reinjection by gravity in most of the cases, which means high permeability in the reinjection zone, and by the slow increase of flow rates when it is necessary to reinject larger volumes of fluid. The only example of a possible short-range effect could be due to a sudden increase of flow rate in January 1995. Further studies should indicate if some areas are more sensitive than others to fluid reinjection and which patterns of seismic activity (that is time and spatial distribution and magnitudes) can be produced.

ACKNOWLEDGEMENTS

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