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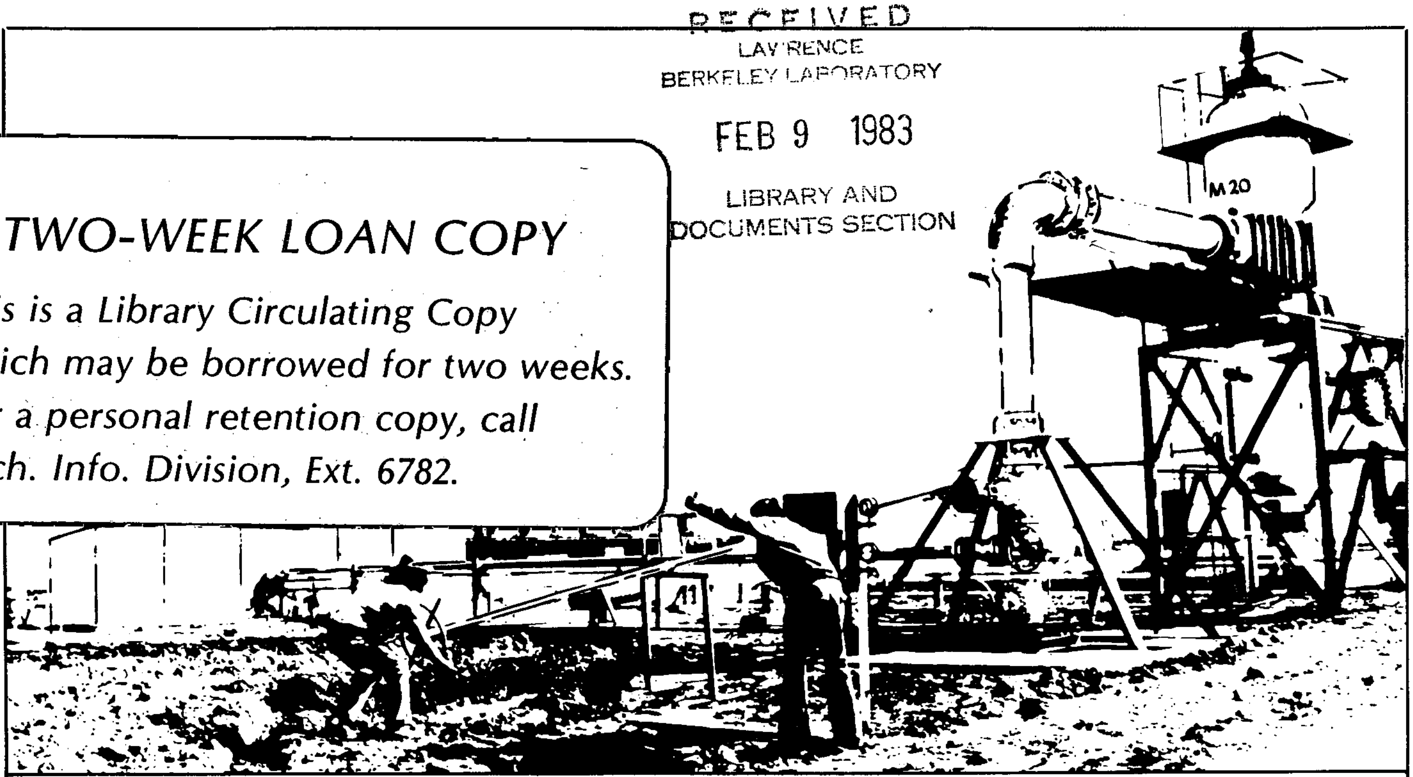

CORRELATION BETWEEN PRECISION GRAVITY AND SUBSIDENCE MEASUREMENTS AT CERRO PRIETO

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ABSTRACT

Precision gravity measurements were made in the region of the Cerro Prieto geothermal field at yearly intervals from 1977 to 1981 to assess the feasibility of using gravity to determine subsurface reservoir changes with time. Among these changes we sought to determine the extent of mass recharge in response to the continued production of fluids from this field.

Changes in gravity and ground elevation were observed throughout the region for the period of observation. Results indicate that the largest changes observed were the result of the Magnitude 6.1 (Caltech) Victoria earthquake of 8 June 1980. The epicenter of this earthquake was located 25 km southeast of the field on the Cerro Prieto Fault, which bounds the field to the southwest. Subsidence of up to 55 cm was measured east of the power plant, in the region between the northern end of the Cerro Prieto Fault and the southern end of the Imperial Fault. This area has been postulated to be the site of an active spreading center or pull-apart basin, and has been characterized by a high level of seismic activity during the last 10 years.

Minor subsidence and small related gravity changes for the period preceeding the Victoria earthquake suggest that in spite of large fluid production rates, the reservoir is being almost completely recharged and that a measurable increase in subsurface density may be taking place.

The results of measurements of horizontal ground motions made in this area are discussed in relation to the gravity and subsidence observations.

INTRODUCTION

The extraction of large amounts of fluids from liquid-dominated fields can cause ground subsidence, with attendant damage to surface installations. Such subsidence has ocurred in areas where extensive exploitation of petroleum and ground water has taken place. Widespread subsidence has also been observed in the liquid-dominated geothermal fields of New Zealand (Stillwell et al., 1976), and to a lesser extent at the vapor dominated The Geysers field in northern California (Isherwood, 1977).

Drawing from the experience with the New Zealand geothermal fields, the Comisión Federal de Electricidad of México (CFE), together with the Dirección General de Estudios del Territorio Nacional (DETENAL) (García, 1978), undertook a program of first order leveling surveys. The purpose of this program was to measure changes in surface elevation in the Mexicali Valley region, including the Cerro Prieto field. Within the immediate region of the field itself, CFE staff also instituted a second order leveling program to monitor local elevation changes.

Among the activities of a joint cooperative program between CFE and the U. S. Department of Energy (DOE) to study of the Cerro Prieto field, initiated in 1977, was a precision gravity monitoring program (Chase et al., 1978; Grannell et al., 1979, 1981a, 1981b, 1982). These observations were carried out in conjunction with CFE's second-order leveling surveys. Also, as part of this cooperative program, horizontal distance measurements were made by the U. S. Geological Survey (USGS) (Massey, 1981).

The use of precise gravity measurements as a tool to monitor water depletion in liquid-dominated geothermal reservoirs was proposed and demonstrated by Hunt (1970, 1977). This approach is based on the supposition that changes in the value of gravity over time can be interpreted in terms of elevation changes and phase changes and/or transport of subsurface fluids, other factors remaining unchanged (Isherwood, 1977)

The gravity measurements at Cerro Prieto had three primary objectives. The first was to make repetitive measurements over time, which, when combined with second order leveling surveys, would provide information about changes in the subsurface with time. The second objective of the gravity measurements was to produce a Bouguer gravity map of the field (Chase et al., 1978; Grannell et al., 1981a). The third objective was to assess field and data reduction procedures. This report deals only with the temporal gravity and elevation changes.

SETTING

The Cerro Prieto field is located in the Mexicali Valley, which is part of the Salton Trough, an area which is tectonically one of the most active in the world. Significant subsidence (3.5 cm/yr [Lofgren, 1978]) due to natural causes has been measured in the Imperial Valley north of the U. S.-Mexican border. These elevation changes are related to the tectonic activity responsible for the formation of the trough. In the vicinity of the Cerro Prieto field, the Mexicali Valley is crossed by major en-echelon strike-slip faults of the San Andreas Fault system.

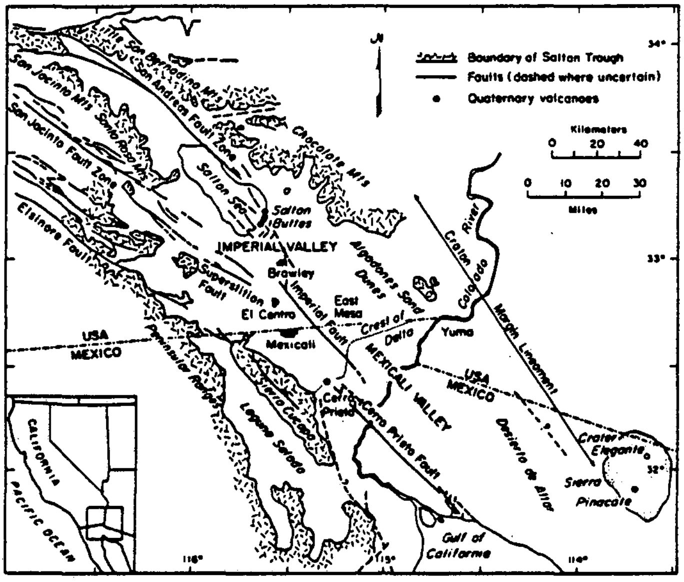

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Figure 1. Location of the Cerro Prieto Field and the Salton Trough.

The heat source for the Cerro Prieto field is thought to be associated with a spreading center located between the en-echelon strike-slip Cerro Prieto and Imperial Faults (see Figure 1), as postulated by Lomnitz et al. (1970) and Elders et al. (1972), in accordance with observations of fault-bounded basins found in the Gulf of California (Elders, 1979).

FIELD MEASUREMENTS

Four sets of precision gravity observations were made on an annual basis using La Coste and Romberg G-type gravity meters. The measurements were made during the winter months of 1977-78, 1978-79, 1979-80, and 1980-81. Details on the data acquisition, reduction, and error analysis can be found in Chase et al. (1978), and Grannell et al. (1979,1981a, 1981b, 1982).

Sixty stations were established over an area of approximately 500 km^2 centered on the Cerro Prieto geothermal field (Figure 2). The stations consisted of permanent concrete monuments with deep footings and flat tops, large enough to accomodate the gravimeter. The same monuments were used for the second order leveling surveys carried out at approximately annual intervals by CFE.

The looping technique of station occupation was used for the gravity measurements. Occupation of the base was followed by occupation of several stations, followed by a return to the base (Grannell, 1982). Each station was occupied from 2 to 4 times in separate loops, and during each occupation, a minimum of 4 readings were made. Median standard deviations of base-to-station differences ranged from 7 to 15 microgals. Standard measurement errors for an individual year were about 8 microgals at the 95% confidence level. Precision of observed changes between two years was about 12 microgals. Changes in gravity exceeding 15-20 microgals were clearly significant. To establish the conformance factor and lag time necessary for making tidal corrections, tidal gravity was monitored on the Cerro Prieto Volcano for a period of three days.

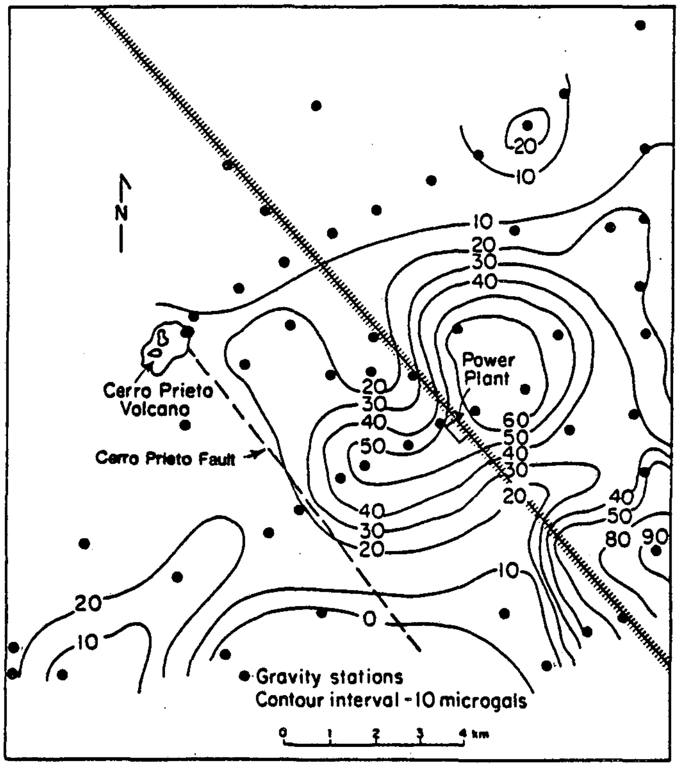

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Figure 2. Gravity changes (in microgals) between 1979-1980 and 1980-81.

Ground elevation measurements were made using standard first- and second-order leveling surveys carried out at approximately annual intervals. The first order leveling surveys covered an area of the Mexicali-Imperial Valleys extending from south of the geothermal field to north of the U.S. border so that it is tied to benchmarks of USGS first order leveling networks (de la Peña, 1981a). The second order surveys were limited to the immediate area of the production field and were carried out in conjunction with the gravity measurements, using the same monuments (de la Peña, 1981b).

GRAVITY CHANGES AND GROUND MOTIONS WITH TIME

The most important gravity and surface elevation changes appeared as a result of the 9 June 1980 Victoria earthquake (described below). Figure 2 shows a contour map of the changes in gravity between 1979-80 and 1980-81, that is, before and after the Victoria earthquake. Tho observed increase in gravity indicates that subsidence took place. Most of the changes ocurred east of the Cerro Prieto Fault. The contours suggest even greater subsidence to the southeast, in a region of intense aftershock activity following the Victoria earthquake (Wong and Frez, 1981). Figure 3 shows the corresponding changes in elevation obtained from second order leveling surveys before

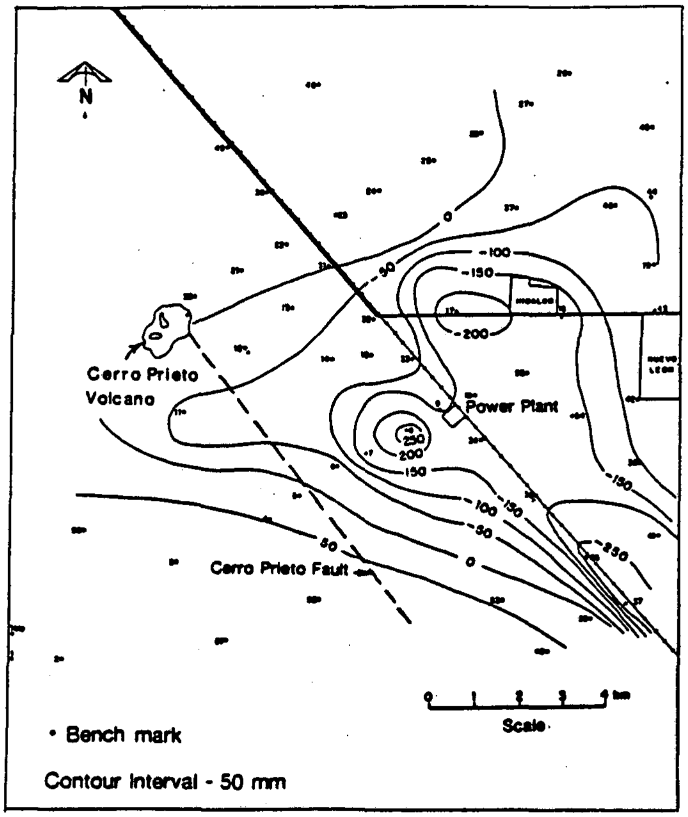

Figure 3. Surface elevation changes (in mm) between 1979 and 1981.

and after the earthquake. The pattern of subsidence agrees with the pattern of gravity increases shown in Figure 2.

The Victoria earthquake had a magnitude of 6.1 (Caltech) and an epicenter near the village of Guadalupe Victoria, about 25 km southeast of Cerro Prieto. This event ocurred near the northwest end of the Cerro Prieto Fault (Wong and Frez, 1981), which bounds the geothermal field to the southwest and ends at the Cerro Prieto Volcano. Between the southeast end of the Imperial Fault and the Northwest end of the Cerro Prieto fault are a series of tectonic features including a series of normal faults roughly perpendicular to the Cerro Prieto-Imperial fault pair called the Volcano Fault System. A crustal spreading center is believed to be located in this area. According to Wong and Frez (1981), the main event of this earthquake excited aftershocks in several pre-existing nests at the northwestern end of the Cerro Prieto Fault, in the southeastern portion of the area shown in Figures 2 and 3. No significant aftershock activity took place in the neighborhood of the main event. The pattern of aftershock activity was interpreted by Wong and Frez (1981) to be related to the higher subsurface temperatures and the spreading center located between the ends of the Imperial and Cerro Prieto Faults.

In the vicinity of the Cerro Prieto field the earthquake caused fissures on the surface, as well as the ejection of ground water and formation of small sand volcanoes. A second order leveling survey was performed over part of the net covered by the previous first order surveys indicating subsidence of up to 55 cm in places (de la Peña, 1981a). These effects were attributed to local liquefaction of unconsolidated sediments.

The pattern of gravity changes for the two years preceding the earthquake is not as clear. The magnitude of the gravity changes was very close to the precision level of the measurements. Grannell (1982) performed a careful analysis of the data for those years and concluded that there is an elliptical-shaped region, shown in Figure 4, where positive changes in gravity exceed the 95 percent confidence level of the measurements. The region agrees roughly with the location of the production area in the field; its major axis is aligned with the NW-SE direction of the dominant strike-slip faults in the region.

The first order leveling survey, which crossed the production region along a single line parallel to the railroad track, showed there was some subsidence between 1977 and 1979, with a maximum of 7.5 cm near the Cerro Prieto power plant. Elevation changes between 1977 and 1979 observed by the second order leveling surveys showed a subsidence pattern (Figure 5) that is similar in shape to the one following the Victoria earthquake, but of much lower magnitude. It is worth noting that there is good overlap between the region of greatest subsidence of Figure 5 and the the region of significant gravity changes mapped by Grannell (Figure 4). However, the magnitude of the gravity and elevation changes do not seem to

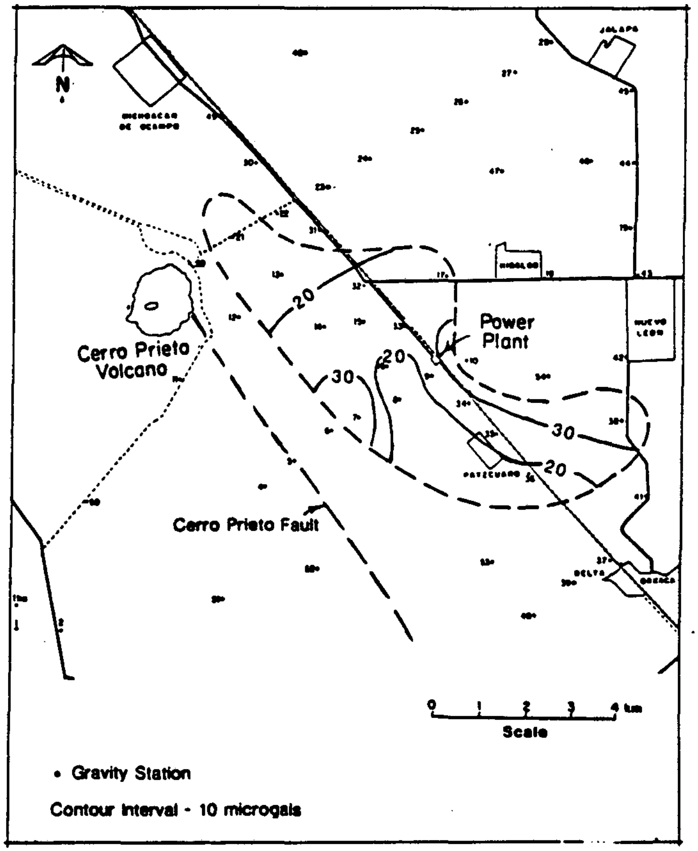

Figure 4. Area of significant gravity increases observed between the springs of 1978 and 1980.

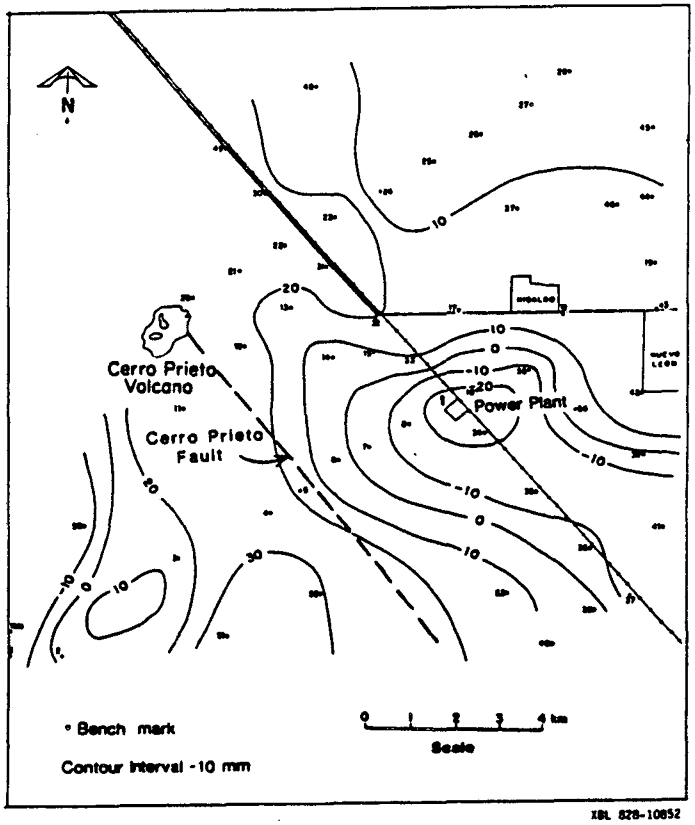

Figure 5. Surface elevation changes (in mm) observed between December 1977 and March 1979.

agree with each other if they are to be explained by subsidence alone. If we assume a vertical gravity gradient of 2.2 microgals/cm, we would expect to see gravity changes of the order of 10 microgals for the observed subsidence. The points within the region defined by Grannell (1982) showed gravity increases ranging from 15 to 34 microgals (Figure 4). Therefore, subsidence accounts for only part of the observed gravity increase.

Horizontal surface motions were measured by the USGS at repeated intervals with two networks of horizontal control using electronic distance measuring instruments (Massey, 1981). Movements of up to 6-7 cm towards the center of the field were observed during 1978-1979. However, after that period and until the time of the Victoria earthquake, this motion towards the center of the field seemed to have ceased. No movement resulting from fluid extraction was evident outside the production area. An analysis of the horizontal deformation associated with the Victoria earthquake showed that deformation produced by fluid extraction was either not observed or was masked by earthquake related changes (Lisowski and Prescott, 1982).

DISCUSSION

The clear correlation between the patterns of subsidence and gravity increases following the Victoria earthquake suggests that tectonic forces are the dominant cause of subsidence in the region. In fact, if we apply a free air correction using the observed elevation changes and assume a value of 2.1 gm/cm^3 for the density of the unconsolidated sediments, the computed gravity increases match the observed changes very well. This means that the subsidence induced by the Victoria earthquake can account for the largest changes in gravity observed during the study period.

The pattern of seismicity observed in this area from 1971 to 1980 indicates significant small earthquake and aftershock swarm activity in the region between the northern end of the Cerro Prieto Fault and the southern end of the Imperial Fault (Albores et al., 1978; de la Peña, 1981a; Wong and Frez, 1981; Majer and McEvilly, 1981). This region includes the portion east of the Cerro Prieto Fault in the area under study. In view of the geometries associated with other pull-apart basins located between en-echelon faults in the Gulf of California to the south (Elders, 1979), which are characterized by depressions located between the ends of transform faults, it seems reasonable to expect the region under study to show evidence of similar subsidence. According to Elders (1979), continued sedimentation of this area by the Colorado River is the main factor that has kept a more noticeable topographic depression from forming.

One of the main objectives of the present study was to assess the usefulness of precision gravity measurements made in conjunction with accurate leveling to measure subsurface changes in reponse to geothermal production. We were especially interested in whether it was possible to determine the extent of recharge to the reservoir. In order to do this, we examined the observed gravity and elevation changes for the period preceding the Victoria earthquake.

From 1977 to 1979, prior to the earthquake, there was only a slight increase in gravity accompanied by very slight subsidence - in fact, the increase in gravity exceeds what would be expected on the basis of the observed subsidence. This pattern of subsidence and gravity change does not match the behavior observed at either Wairakei or The Geysers fields.

At Wairakei, another liquid-dominated field, the amount of subsidence has been much greater, exceeding 15 feet in places (Stillwell, 1976). On the basis of similar gravity and surface elevation measurements, Hunt (1970, 1977) estimated that in the early years of production, recharge to the reservoir amounted to about 10 percent of the production volume, increasing to about 85 percent in later years. Large pressure drops were observed in the reservoir, although pressure has stabilized in recent years. The thermodynamic and hydrogeologic characteristics of that reservoir are such that production led to the formation of an extensive steam zone or cap in the reservoir (Grant et al., 1981). Hunt (1970, 1977) showed that after correcting for elevation changes, there was a correlation between the zone of gravity decrease and the limits of the field, with the maximum gravity decreases observed near the main well field. This suggests that this is the region of greatest water depletion.

A gravity and elevation monitoring program had also been established at The Geysers field (Isherwood, 1977), a vapor-dominated geothermal field in northern California characterized by minimal natural recharge. Figure 6 shows that over a three year period there were decreases in both gravity and elevation. This would suggest that there has been a net loss of mass or little recharge. If there was 100 percent recharge, a decrease in elevation or subsidence would have been accompanied by an increase in gravity.

In light of the above, the best explanation that can be advanced for the observed gravity increases and related subsidence at Cerro Prieto is that there must be close to 100 percent recharge of the producing aquifers to replace the extracted fluids. If there had been little recharge, the estimated mass extracted (of the order of 75 x 10^6 tons), together with the observed subsidence would have resulted in a gravity decrease.

Support for widespread recharge of the reservoir comes from many sources. Dipole-dipole resistivity monitoring over the same period of time (Wilt and Goldstein, 1981, 1982) noted an increase in resistivity over the central portion of the reservoir, suggesting inflow of fresher Colorado River-originated water. Theoretical calculations by Whitcomb in Grannell et al. (1981b) also show that if there were no replacement or recharge, the gravity decrease would have been quite large and easily measurable. Geochemical measurements have shown a sharp decline, to about one half the original value, in the concentration of chlorides in the central portion of the reservoir, also suggestive of fresh water inflow (Fausto et al., 1981). Grant et al., (1981) showed that no generalized steam zone has formed which would be indicative of a large net mass loss due to lack of replacement of the extracted fluids.

As a result of production there has been some drawdown, i. e., loss of pressure, in the reservoir. Figure 7 shows the behavior of downhole pressure as a function of time for some typical wells. Although the pressures declined rapidly in the early years, they seem to have stabilized in the most recent years (Goyal et al., 1981). The data seem to indicate a trend towards an equilibrium condition which might suggest that during the time in which our measurements were made, the rate of mass loss to the reservoir is approximately balanced by a natural recharge rate of similar magnitude. Analysis of water level and production data indicates that the natural recharge to the western part of the field is of the order of 2500 tons/hr (M. J. Lippmann, 1982, personal communication).

The lack of continued horizontal motion at Cerro Prieto described above can also be used as an argument for full recharge. In contrast, similar measurements made at Wairakei (Grimsrud et al., 1978) showed horizontal motions of the order of tens of centimeters as a result of production and accompanying the large subsidence occurring there.

The fact that the measured increase in gravity prior to the Victoria earthquake is greater than expected on the basis of subsidence suggests that in addition to full recharge of the reservoir, an increase in density may have taken place in recent years in response to production. Several mechanisms could account for this increase. One of these could be the rapid densification of sediments due to mineral precipitation produced by local boiling associated with production. Densification is the main cause for the Bouguer anomaly observed in the region of the geothermal field. This process may have accelerated as a result of production.

Another, an perhaps more likely, cause of a density increase is the recharge of the reservoir by colder and denser waters. Using a two-dimensional gravity modeling computer program we examined the effect of recharge by cooler waters into a body whose dimensions correspond roughly to the α (upper) reservoir in Cerro Prieto. The results are shown in Figure 8. The calculated

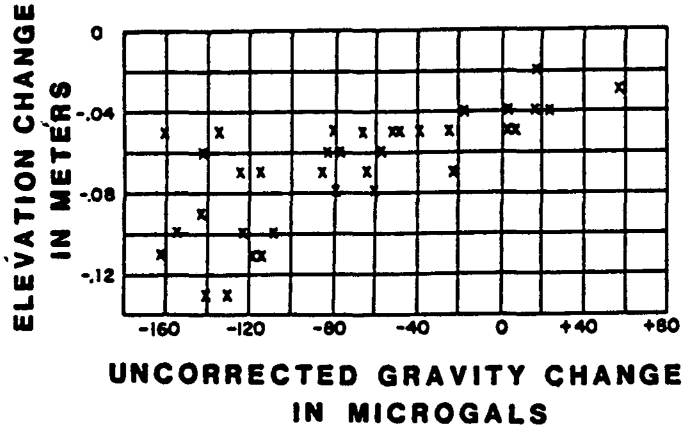

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Figure 6. Relation between gravity change (July 1974 to February 1977) and elevation change (late 1973 to late 1975) observed at The Geysers (taken from Isherwood, 1977).

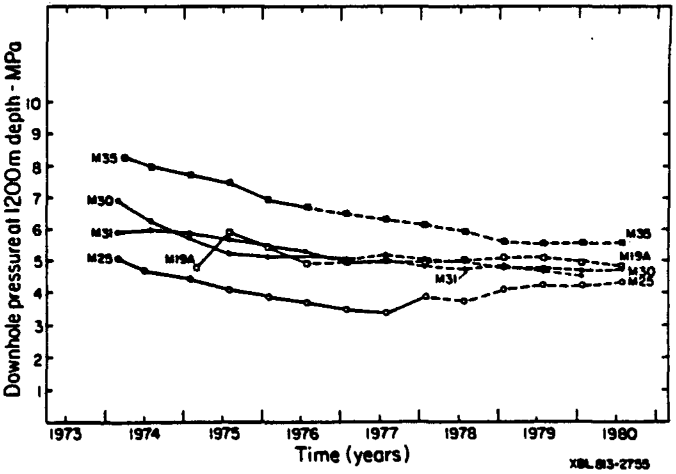

Figure 7. Computed downhole pressures at 1200 m depth in several Cerro Prieto production wells under flowing conditions (from Goyal et al., 1981).

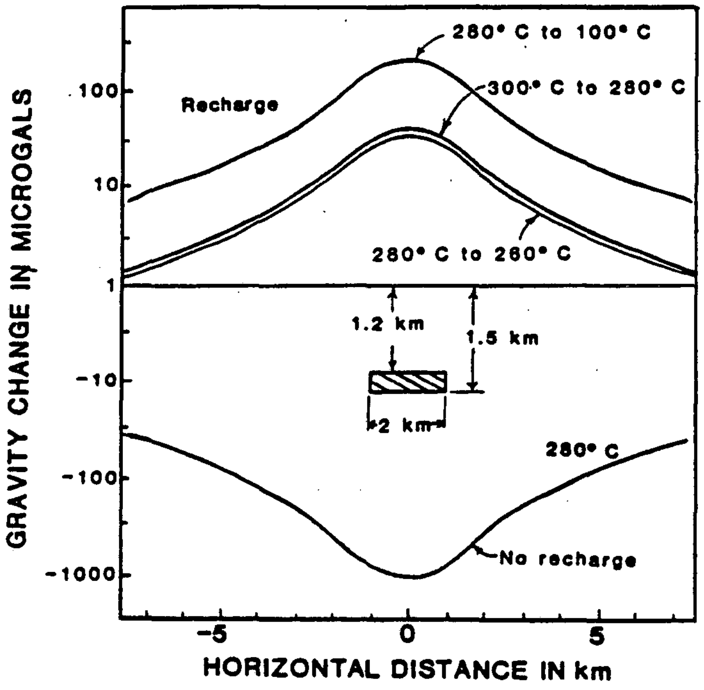

Figure 8. Two dimensional model of the effect of replacing water of a certain temperature by cooler water. The body represents the α reservoir, with 25 percent porosity. The top 3 curves show the effects of replacing the hot waters with colder waters. The lower curve shows the effect of production without recharge.

gravity values were obtained by assuming the body to have 25 percent porosity and that its insterstitial waters, having some initial temperature and density, were completely replaced by the cooler waters, all at 100 bars pressure.

The model gives some idea about the effect of recharging the reservoir with cooler water. For instance, if 280°C water is replaced by 260°C water there will be a maximum gravity increase of 30 microgals, which is of the same order of magnitude as the observed gravity increases. This temperature drop is very close to those actually observed in the field (Fausto et al., 1981). If 280°C water is replaced by 100°C water, the gravity increase would be much greater, of the order of 170 microgals. If, on the other hand, all the fluids were extracted from the rock pores (i. e., no recharge) and there was no compaction, there would be a gravity decrease of around 1000 microgals.

Although the effects of salinity change on fluid density were not investigated, they are expected to be of significantly lower magnitude than those resulting from temperature changes.

These ideas should be viewed with a certain amount of caution on two grounds. First, tectonic activity may affect the ground motions in the vicinity of Cerro Prieto so strongly that perhaps all the changes we have observed are only a reflection of this activity. Secondly, the period of observation has been relatively short.

CONCLUSIONS AND RECOMMENDATIONS

Simultaneous measurements of gravity and surface elevation changes at the Cerro Prieto geothermal field over a four-year-period have shown that they were primarily produced by tectonic activity in the area. The aseismic patterns of change in gravity and elevation suggest that the reservoir is being almost completely recharged as production continues. The data also suggests that a density increase is taking place in the reservoir region.

Given the relatively short duration of this monitoring study, it is recommended that additional measurements be made in the years to come, perhaps at two year intervals rather than at yearly intervals as in the past. Also, more precise quantitative analysis should be made to better characterize the processes occurring in the Cerro Prieto geothermal system, such as the extent of fluid recharge and the likely densification mechanisms.

ACKNOWLEDGEMENTS

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