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MONITORING CRUSTAL DEFORMATION IN THE GEYSERS-CLEAR LAKE GEOTHERMAL AREA, CALIFORNIA

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ABSTRACT

Geodetic surveys since 1972-73 reveal significant crustal deformation in The Geysers-Clear Lake region. Resurveys of precise control networks are measuring both vertical and horizontal ground movement, with most of the change continuing in the area of geothermal fluid withdrawal. Preliminary evidence suggests right-lateral horizontal movement on northwest-trending fault systems and vertical and horizontal compression of the deep geothermal reservoir system. A direct correlation is suggested between ground-surface deformation and subsurface pressure changes in the reservoir system. Although surface changes appear too small to be of environmental concern in The Geysers-Clear Lake region, they indicate hydrodynamic changes in the reservoir of significant import.

Two types of vertical changes in The Geysers production area are indicated in the 1973-77 data--(a) a regional subsidence between the Collayomi and Mercuryville fault zones and (b) local subsidence directly related to the area of principal steam production. Maximum subsidence of 13 centimeters in 4½ years occurred in the area of most concentrated

steam withdrawals and where fluid-pressure declines were near maximum. Subsidence rates throughout the production area from 1973 to 1975 were about half the 1975-77 rates in apparent correlation with pressure changes measured in the reservoir system. Horizontal ground movement as great as 2.0 centimeters per year, generally inward toward the center of production, was measured around the perimeter of the steam production area.

INTRODUCTION

Significant crustal deformation frequently accompanies the withdrawal of large volumes of fluids from subsurface reservoirs. Induced hydraulic stresses cause rocks to deform, either along well-defined zones of weakness or as a regional compression of the stressed reservoir system. Although the stress changes are generated in the reservoir system at depth, some of the effects are transmitted to the land surface and can be measured by precise field surveys. By proper interpretation of measured surface changes, insight is obtained not only on the nature of the continuing subsurface deformation, but also on the mechanical and recharge characteristics of the reservoir system.

In order to monitor the surface effects of geothermal production in The Geysers area, geodetic networks of precise vertical and horizontal control were established by the Geological Survey and the National

Geodetic Survey in The Geysers-Clear Lake region in 1972-73. Many researchers had theorized that because formation fluid pressures were relatively low in the producing geothermal reservoir, changes caused by continued steam production would be minimal. Subsequent resurveys of the geodetic networks, however, proved this not to be the case. Significant crustal movement has been recorded in the 1972-77 field data. Although the period of recorded change is short, some continuing crustal movement apparently is occurring along major fault zones of the region. More significant, however, are vertical and horizontal surface deformations over the producing part of the geothermal reservoir system in apparent direct response to fluid withdrawals. The magnitude of surface changes is small and suggests no present environmental concern. The rates and areal distribution of surface movements and their correlation with observed fluid pressure and gravity changes, suggest a continuing deformation of the reservoir system heretofore not considered.

The Geysers-Clear Lake geothermal region is characterized by rugged topography, unstable terrain, a complex system of active and inactive faults, and highly folded, fractured, and sheared rocks of the Franciscan Formation of Late Jurassic and Cretaceous age. The principal ridges and valleys, as well as the principal fault systems of the region trend generally northwesterly, and suggest active processes of change. Whatever deformation results from geothermal production, therefore, is superimposed on a background of slope instability, local and regional tectonism, and waning volcanism. The differentiation of induced changes, caused either directly or indirectly by geothermal extractions, from continuing natural processes is one of the challenges of this continuing research program.

If geodetic surveys are to differentiate induced crustal changes from regional tectonism and relate these changes to causes in the reservoir system, not only must networks of vertical and horizontal control be properly designed, but surveys must be precise, frequent, and long term. By precisely measuring surface changes and correlating these with results of seismic, gravity, and reservoir-production research, an improved understanding of the deformation and hydrodynamics of the geothermal reservoir system can be obtained.

LAYOUT OF GEODETIC NETWORKS

Within the area of geothermal production, the following types of land-surface deformation might be induced (Lofgren, 1973) either directly or indirectly by fluid withdrawals:

a. Vertical and horizontal compression or expansion of the reservoir system due to induced fluid pressure gradients and hydraulic stresses. Expected changes would be subsidence in areas of fluid extraction and uplift in areas of fluid injection.

b. Vertical and horizontal movement caused by the thermal expansion or compression of subsurface rocks. Thermal effects would be complex, dependent on movement of fluids in response to production, recharge, and changes in permeability. Conceivably, reservoir rocks could be cooling due to recharge while the overburden is heating in the areas of steam production wells.

c. Increased land sliding or mass wasting due to induced seismicity or induced slope instability.

d. Local natural tectonic faulting or folding triggered by local hydraulic stresses or by induced seismicity.

Vertical Control

Figure 1 shows the regional setting of The Geysers geothermal production area and the network of first-order leveling established to measure both elevations and changes in elevation throughout The Geysers-Clear Lake area. Of particular interest is the pattern of northwest-trending faults (McLaughlin, 1975; Hearn and others, 1976; McLaughlin and Hearn, 1977, written commun.) that dominate the structure of the region, and along which tectonic movement has occurred within the past 500,000 years or less, and might be continuing (Donnelly and others, 1976a; McLaughlin and Stanley, 1976). The Maacama fault zone is active (McLaughlin, 1975) and the Collayomi fault zone contains at least one active fault (Hearn and others, 1976) and continuing seismic activity (Bufe and others,1976) suggest that the Konocti Bay fault zone could be active. There is no evidence that the Mercuryville fault zone is active. Also shown in figure 1 is the boundary of the geothermal steam field (Donnelly and others, 1976b).

Circles of 1.6-km radius have been drawn around each of the producing power plants to approximate the respective areas of geothermal fluid withdrawal (Reed and Campbell, 1975, p. 1405). As shown, these circles overlap in the area of power plants 1 to 8 and 11 (see fig. 3 for locations) to form a compact steam-production area. A separate area of production surrounds power plants 9-10. Also shown in figure 1 is Reed and Campbell's (1975, fig. 2) delineated geothermal resource area, modified to include the Borax Lake area, which has been used to define the area of potential geothermal production in designing the vertical- and horizontal-control networks of this research. All first-order leveling in this area is by the National Geodetic Survey or the Topographic Division of the Geological Survey.

A network of precise vertical control was established in the geothermal production area in mid-1973. It consists of a loop of first-order leveling through the production area (fig. 1) and a line extending northeastward to bench mark Y626 near Lower Lake. This net was resurveyed in fall 1975, and an additional tie line surveyed southwestward from the loop to bench mark D106 (fig. 1) near Lytton (north of Healdsburg). Then in late fall 1977, with financial assistance from the U.S. Department of Energy, all the 1975 net (solid lines, fig. 1) was resurveyed and continuing into spring

1978, the net was further expanded to include all the dashed lines of figure 1. Measured changes in elevation along lines of repeated leveling are summarized in the profiles of figures 4 and 6. All the above surveys were of first-order accuracy--with closure errors less than 1 mm times the square root of the loop distance in kilometers.

In a region as tectonically active as The Geysers, absolute stability of any area is unlikely. Relative movement within the region, however, is of principal concern in detecting both natural or induced surface changes. Thus, all surveys in this investigation have been referenced to bench marks outside the region potentially affected by geothermal steam production. In figure 6, bench mark Y626 near Lower Lake has been assumed to be stable and its elevation, established in 1942, was held fixed for the 1973, 1975, and 1977 surveys. This bench mark is east of the principal fault zones, and near the edge of probable geothermal development. In the interpretive analysis of changes within the loop through the production area, figures 3 and 4, bench mark R1243 was assumed to be stable. Actually, bench mark R1243 had subsided 5.56 centimeters with respect to stable Y626 from 1973 to 1977.

Horizontal Control

Figure 2 shows the network of precise horizontal control established in The Geysers-Clear Lake area in relation to areas of present and potential geothermal production and principal fault systems. Two types of surveys are included in this net, (1) long-distance regional control lines surveyed with highly precise, long-distance, electronic distance measuring (EDM) equipment--with precision better than 3 mm per 10 km of line length (solid lines, fig. 2), and (2) local control lines surveyed with medium-range EDM equipment (dashed lines, fig. 2)--with a precision of better than 3 mm per 1 km of line length. For changes occurring in a relatively narrow zone, the accuracy of highly precise equipment spanning long distances is about the same as the less precise equipment spanning shorter distances.

Layout of the network of first-order horizontal control in The Geysers-Clear Lake area began with several dozen lines surveyed in 1972 and has been progressively expanded through 1977. As of December 1977, the extensive network array of figure 2 is being monitored. Many of the lines have been surveyed three or four times; others have been surveyed only once. Collectively, these lines of control provide baseline references for measuring both the magnitude and the rate of horizontal ground movement occurring in the region.

As shown in figure 2, the network of horizontal control is concentrated in the area of geothermal production and becomes less dense in outlying areas. The net is designed to monitor horizontal ground movement throughout the region, with special emphasis on areas of suspected movement--areas of active steam production and principal fault zones. Horizontal movement measured during the first 5 years of this research program is summarized in figure 7.

MEASURED GROUND MOVEMENT

Although measured rates of ground movement are small and the length of records is short, significant crustal changes have occurred both in the area of geothermal production and in the surrounding region. From these measured changes, tentative conclusions can be drawn. The reliability and predictive capability of the observed trends, however, will increase substantially as the length of record increases.

Vertical Changes

Figure 3 shows the location of bench marks around the survey loop through the geothermal production area and the measured vertical changes in relation to areas of fluid withdrawal, generalized by circles of 1.6-km radius around each producing power plant. Changes shown at each bench mark are for 1973-75, 1975-77, and 1973-77, calculated relative to bench mark R1243 (at the south end of the loop) assumed to be stable during the $4\frac{1}{2}$-year period. Bench mark R1243 was arbitrarily selected because it is outside the area of steam production, is common to control lines of figures 4 and 6, and appears as stable as any mark of the region. Also shown in figure 3 is the northwest-trending line of profile A-A" (fig. 4) which graphically shows the relative change in elevation of bench marks along the southwestern limb of the survey loop near Big Sulphur Creek.

Vertical changes during 1973-75 and 1975-77 along profile A-A'-A" (fig. 4) suggest two types of ground movement: (1) a tectonic local tilt, apparently downward toward the northwest, for about 3.5 km and (2) substantial subsidence in areas of steam production for power plants 1-2, 3-4, 5-6, 7-8, and 11. Maximum subsidence rates occurred where the circles of influence of power plants 1-2, 3-4, 5-6, and 7-8 overlap, and decreased from about 4.0 centimeters per year (bench mark W1244 at power plants 5-6) in 1973-75 to 2.0 centimeters per year in 1975-77. The more or less uniform apparent relative uplift from 1975 to 1977 (fig. 4) southeast of the area of fluid withdrawal may be real--possibly due in part to thermal expansion of the overburden in areas of new drilling, or may be computational--resulting from holding bench mark R1243 stable. It is interesting that vertical changes in the vicinity of power plants 9-10 are minimal (fig. 3), even though large-scale steam production began in 1972.

Recently released data on reservoir pressure changes in the principal steam reservoir system at The Geysers (Lipman, Strobel, and Gulati, 1977), correlate with crustal changes reported above. Both the areal extent and magnitude of reported pressure change in the vicinity of power plants 1-8 closely agree with measured subsidence, and suggest a direct causal relationship. Also, the marked change in subsidence rates between the 1973-75 and the 1975-77 periods agrees in time and magnitude with stepped pressure drops caused by periodic increases in steam production (Lipman, Strobel, and Gulati, 1977, fig. 9). These data suggest that declines in deep reservoir pressure and rates of subsidence a) are greatest soon after new sources of steam are put on line, and b) diminish as recharge gradients tend to reach steady-state conditions. It is interesting that in the vicinity of power plants 9-10, even though steam withdrawals had produced a sizable cone of pressure decline by 1977 (Lipman, Strobel, and Gulati, 1977, fig. 8), most of the pressure change and thus most of the net fluid extractions were considerably west of the line of control bench marks through the area.

Figure 5 shows the relation between subsidence of bench marks along line A-A' (fig. 3) and fluid pressures in the geothermal-reservoir system (Lipman, Strobel, and Gulati, 1977, fig. 7). In the area of maximum subsidence, reservoir pressures had declined about 126 meters of hydraulic head (180 psia) from 1969 to 1977 due to steam extractions. Also, 13.7 centimeters of subsidence, largely due to reservoir compaction, occurred from 1973 to 1977. This suggests a crude correlation of about 1 centimeter of subsidence (reservoir compaction) per 5 meters of hydraulic head decline or a ratio of 2.0×10^{-3} meters of subsidence per meter of head decline. Although neither the length of record nor the accuracy of data (reservoir compaction and pressure change) in this computation are adequate to predict long-term trends, this type of correlation has proved effective in defining the relationships of stress and strain related to fluid production and the compressibility characteristics of subsurface reservoir systems (Lofgren and Klausing, 1969; Poland and others, 1975).

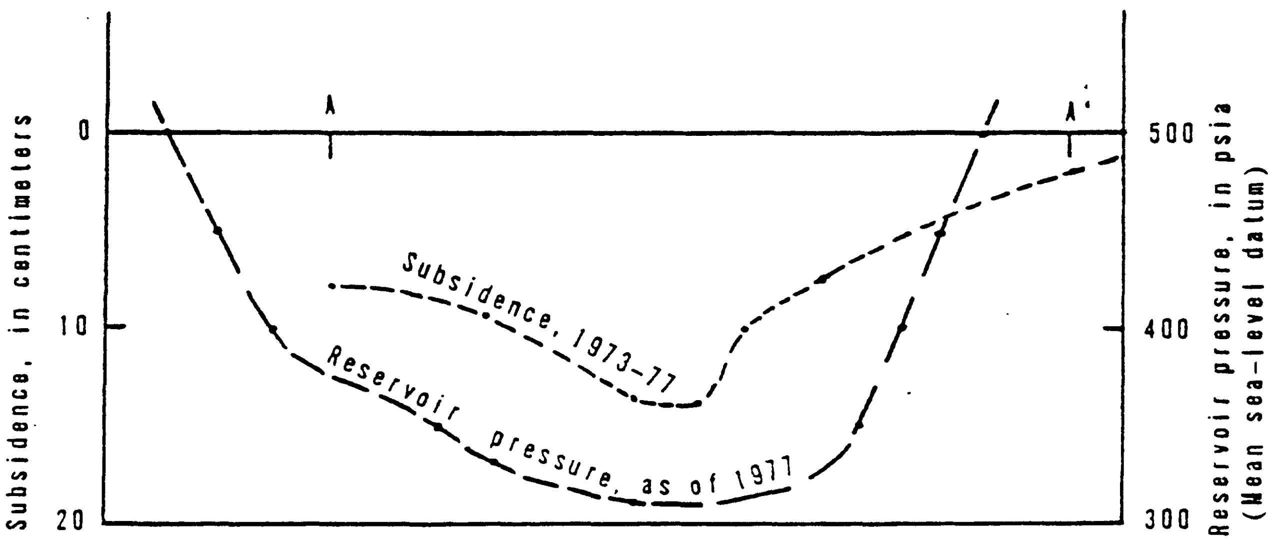

Figure 5.--Relation of subsidence to reservoir pressure along line A-A' (fig. 3). Pressure data from Lipman, Strobel, and Gulati, 1977, figure 7.

Figure 6 shows the measured vertical changes along a line of bench marks (ABCDE, fig. 1) southwesterly across the Mayacmas Mountains. In this graph, 1975 bench-mark elevations (precise first-order leveling along the entire route) are used as the horizontal base of reference, and 1973 and 1977 differences in elevations are shown. The locations of all bench marks are projected at right angles to the line of profile, and all elevation changes are calculated by holding the elevation of bench mark Y626, east of Lower Lake, stable during the $4\frac{1}{2}$-year period. The elevation of the terrain along the line of bench marks is also shown in figure 6.

Although there was considerable instability indicated in the leveling data from Lower Lake to Cobb, reaches E-D and D-C in figures 1 and 6, there were no accumulative changes in the 1973-77 data that suggested regional deformation. Elevation differences in this eastern part of the line indicated local changes due to frost action, bench-mark instability, or possibly to movement along numerous faults. From Cobb to Anderson Springs, reach C-B, apparent tilt is to the south or southeast, and occurs mainly within or close to the Collayomi fault zone. In the eastern half of reach B-A, apparent tilting is down to the northeast. Regional subsidence is indicated, during both the 1973-75 and the 1975-77 periods. Although some of this change may be due to bench-mark instability, there is strong evidence that the mountainous region between the Collayomi fault zone and the Mercuryville fault zone--the region overlying the dry steam part of the geothermal reservoir system--may be subsiding at rates of as much as 2 centimeters per year. Because this profile is 4 km or more distant from the present areas of steam production, the subsidence could be entirely natural tectonic movement unrelated to steam production. If it is related to production, it is highly pertinent to problems of reservoir depletion and ownership of subsurface fluids. Field data suggest that bench mark R1243--the assumed stable reference mark of figure 4--subsided 5.56 centimeters with respect to bench mark Y626 from 1973 to 1977.

Horizontal Changes

Two types of horizontal ground movement were anticipated during the layout of the control net--(a) slow right-lateral tectonic creep, principally along major fault zones, and (b) radial inward horizontal compression of the geothermal production area. Control lines (fig. 2) were laid out to accommodate the monitoring of both processes. Survey data of 1972-77 indicate that both types of movement are continuing in The Geysers-Clear Lake region. Because many of the control lines had only one or two sets of measurements, the generalized rates of movement summarized in figures 7 and 8 are based on the measured changes along about 30 lines with sufficient record to indicate trends.

Figure 7 shows the structural setting of The Geysers geothermal production area, and a generalization of the rates of change of horizontal distance detected by the 1972-77 surveys. Two types of changes are presented in the interpretive data--(a) average rates of horizontal shortening or lengthening of long lines spanning the major fault zones outside the geothermal production area, and (b) generalized movement vectors suggesting the direction and rate of local compression in the production area. All rates of change are in millimeters per year and all are based on more than one set of measured changes.

Measured rates of change on all except three lines of figure 7 suggest right-lateral movement on the principal fault zones. The exceptions are the -2, -4, and -4 lines that cross the Mercuryville fault zone. Rates of change shown are 9 millimeters per year or less, but in each instance register only a component of the actual movement along the various fault zones. North and west of the steam production areas, calculated rates of movement along northwest-trending fault planes, resolved from the data of figure 7, exceed 1.2 centimeters per year during the 5-year period. Repeated measurements along 3 other lines (fig. 7) spanning the Mercuryville and Maacama fault zones, were not consistent--all showed regional shortening but erratic rates. These rates are considered questionable pending future surveys.

A few lines of the control net are alined directly across the steam production area but would include at least a component of right-lateral tectonic change that might occur in the Big Sulphur Creek fault zone (fig. 7).

The generalized local vectors of horizontal movement in the production area are resolved from measured changes along local control lines after removal of apparent regional tectonic changes. These vectors denote calculated rates of relative movement within the production area and are not changes in lengths of survey lines. The rates of horizontal movement in the production area, in all instances in a direction toward the center of fluid withdrawal, range from about 15 millimeters per year in areas of heaviest fluid production to about 4 millimeters per year in the peripheral area.

Of particular interest are the abrupt changes in rate of movement, and sometimes reversal in direction of ground movement, in areas of new steam production (fig. 8). Survey lines spanning the well field supplying steam to power plant 11 (upper two graphs) showed marked changes in rate soon after steam production began in 1975. Lines crossing the older producing areas (lower two graphs) show double the rates of horizontal compression and much more uniform changes. As with vertical compression of the geothermal reservoir system, surface measurements to date suggest that the horizontal compression of the deep reservoir system is directly related to fluid-pressure changes--changing rapidly soon after the effects of new steam production are felt, and gradually establishing more or less steady-state rates of compression as the rate of pressure decline stabilizes.

Figure 8

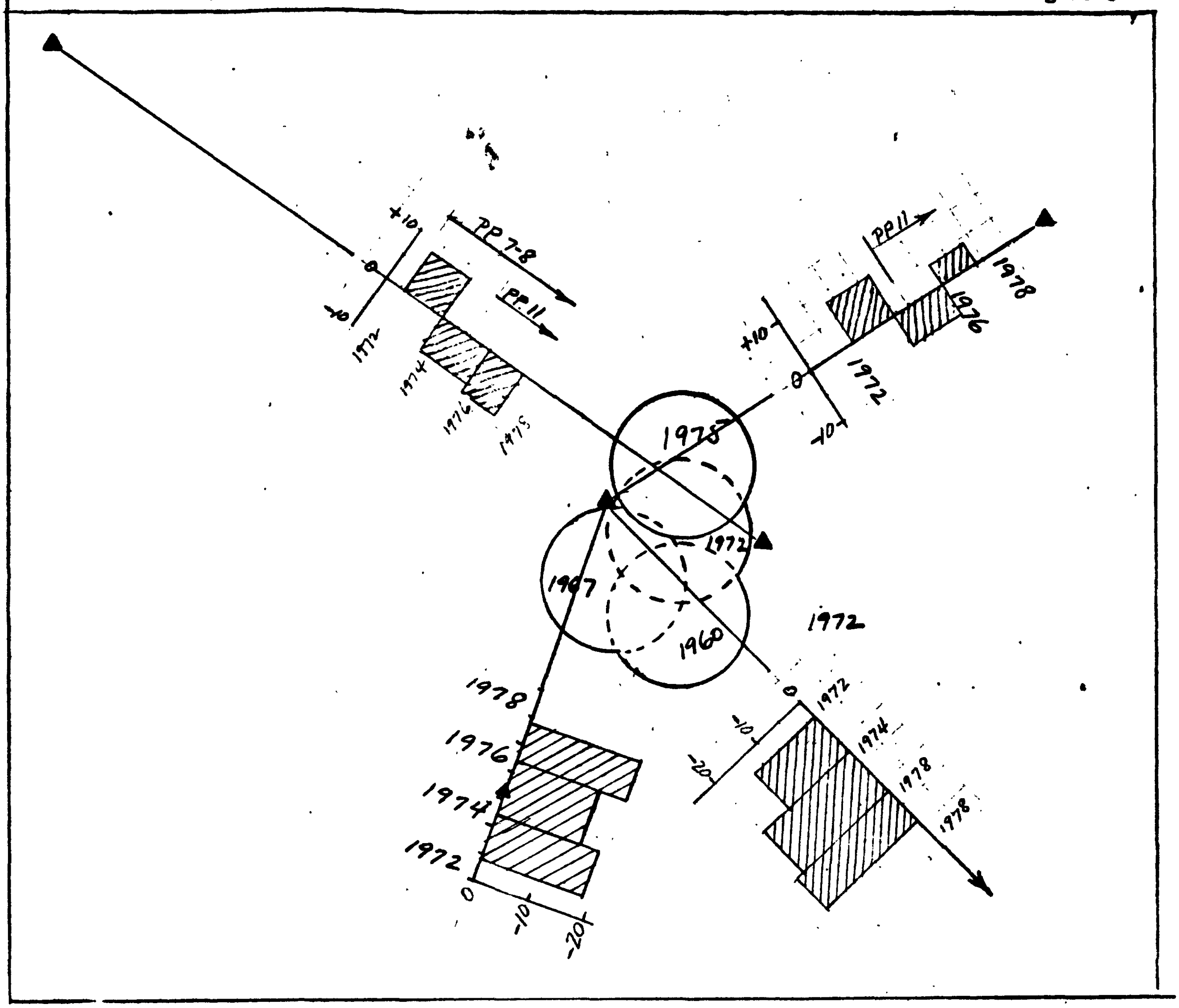

Figure 8.--Changing rates of ground movement on lines spanning the geothermal production area, Rates are in millimeters per year; lengthening (+) above line, shortening (—) below line

CONCLUSIONS

Two types of surface ground movement are occurring in The Geysers-Clear Lake area--(a) regional tectonism of natural origin, with right-lateral creep along the principal fault zones and regional subsidence between the Collayomi and Mercuryville fault zones, and (b) local subsidence and horizontal compression of man-made origin in the steam production area. Regional changes are at rates of a few millimeters per year; local movements are at rates of a few centimeters per year. Measured surface effects over comparatively short periods suggest that the deep geothermal reservoir is being compressed both vertically and horizontally as fluid pressures within it are drawn down by production.

Of particular interest, and quite unexpected in view of similar studies in other areas, are the abrupt changes in rate of both vertical and horizontal surface deformation in areas of new production. Surface changes suggest that both the vertical and the horizontal compression of the geothermal reservoir are most rapid soon after new or increased steam production. Within months after the inception of steam production or after an increase in rate of production, deformation rates tend to stabilize. These deformation-rate changes are most noticeable on horizontal lines spanning the production area for power plant 11 (fig. 8), which began production several years after monitoring networks were established.

Because the depth of production wells and the areal distribution of wells supplying a particular power plant are of the same order of magnitude, the vertical and horizontal dimensions of the geothermal reservoir system affected by fluid withdrawals for this power plant are about the same. It is expected, therefore, that the rates of vertical and horizontal surface deformation for a given stress change would also be of the same general order of magnitude for reservoir systems at shallow depth. Because the measured rates of horizontal and vertical deformation over the steam-production area are about the same, it appears that both the horizontal and vertical stresses induced by steam production, and also the rock compressibilities of the reservoir system are about the same in the horizontal and vertical directions.

Interpretation of the regional tectonic strain rates may be complicated by the possibly episodic nature of local strain over geologically short periods. Longer periods of monitoring and more detailed nets (figs. 1 and 2) should make it possible in the future to assign movement to specific fault zones, and to assign increments of tilting to specific fault blocks. Such data will be important in assessing the seismic risk potential in the region.

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