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MONITORING GROUND MOVEMENT IN GEOTHERMAL AREAS [1]

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ABSTRACT

One of the potential hazards of geothermal production, either for power generation or for water or mineral supply, is the threat of associated land subsidence and ground movement. As with oil-field and ground-water extractions, a direct relationship is expected between pressure changes induced in the hydrologic system and ground deformation that might result.

Two geothermal areas in California are presently being monitored for possible ground movement, caused either directly by the fluid withdrawal, or indirectly by other geologic processes triggered by the withdrawals. Rocks in The Geysers area are largely consolidated, and the geothermal field a dry-steam system; thus, little or no land-surface change is expected as geothermal steam production continues. Landslides and tectonism are active in The Geysers area, however. Steam production in Imperial Valley is from weakly metamorphosed rocks overlain by unconsolidated sediments, and will be accompanied by large extractions of geothermal waters. Subsidence, horizontal ground movement, and serious encroachment on the ground-water regime are definite hazards in Imperial Valley unless adequate precautions are taken.

Horizontal and vertical survey nets are presently being monitored by the U.S. Geological Survey and other agencies to detect possible ground movement in areas of geothermal production. To differentiate changes caused by geothermal extractions from those due to other causes is one of the challenges of this research program.

INTRODUCTION

Significant ground movement frequently accompanies the extraction of large quantities of fluids from the subsurface. Experience in many areas of fluid-pressure decline indicates that movement may include both vertical and horizontal components of deformation, and result from

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either the compaction of surficial unconsolidated deposits or from deep-seated tectonic readjustments triggered by the withdrawals. Even subtle changes of stress at depth sometimes cause serious surface movements, and indicate the type of problems that undoubtedly will become more commonplace and severe as man's exploitation of natural resources progresses.

Land subsidence, caused by the withdrawal of water, oil, and gas has become relatively common in the United States (Poland and Davis, 1969), affecting probably 10,000 square miles of intensely developed land in five States. Maximum subsidence is 29 feet in the San Joaquin Valley and Long Beach area of California, 13 feet in Santa Clara Valley of California, and is in excess of 8 feet in the outskirts of Houston, Texas. Horizontal ground movement exceeds 12 feet in the Wilmington oil field of the Long Beach area, and although largely unmeasured, probably continues in numerous heavily pumped ground-water basins of the west. Extensive earth fissures and cracks forming on the margins of numerous heavily pumped basins, principally in Arizona, and presently threatening land use in several areas, are attributed by the author to steep hydraulic gradients induced by pumping.

One of the potential hazards of geothermal production, either for power generation of for water or mineral supply, is the threat of land subsidence and lateral ground movement that might result. Where large quantities of geothermal water are extracted or steep pressure gradients are induced in the hydrologic system, significant deformation of the land surface may occur. At Wairakei, New Zealand (Hatton, 1970), one geothermal field where large quantities of fluids have been produced, both horizontal and vertical ground movement has been measured. Subsidence affects more than 25 square miles, with a maximum subsidence rate of about 1.3 feet per year. Total subsidence exceeds 10 feet, and of particular significance, the area of maximum subsidence is outside the production field. Similar effects could occur in other geothermal fields. Periodic resurveys of bench marks throughout the production area determine not only possible ground movement resulting from geothermal developments but also movement related to other geologic processes.

MONITORING PROGRAM

Geothermal systems are of two contrasting types--hot water and dry steam (White, Muffler, and Truesdell, 1971). Most known geothermal areas are of the hot-water type, in which large volumes of water are produced with the steam, and there is a direct intertie with the hydrologic system. Few areas are of the dry-steam or vapor-dominated type which may be completely separated from the hydrologic regime. Both types are characterized by active faulting, frequent earthquakes, and relatively young geologic structures.

The following five types of ground movement might occur conjunctively in a producing geothermal area, either caused by or unrelated to geothermal developments:

a. Subsidence or rebound of the land surface, due to fluid-pressure changes.
b. Lateral ground movement, due to induced fluid gradients.
c. Vertical ground movement, due to thermal expansion or compaction of the rocks.
d. Tectonic faulting or folding.
e. Landslides and mass wasting, particularly in areas of steep terrain, unstable bedrock, and heavy rainfall.

Only a precise long-term monitoring program can hope to differentiate among these types of ground movement.

Figure 1 shows the two principal geothermal areas in California being monitored--The Geysers, a dry-steam area north of San Francisco, and Imperial Valley, southeast of Los Angeles, where eight known geothermal anomalies all suggest hot-water conditions.

GEYSERS AREA

The Geysers geothermal area is about 75 air miles due north of San Francisco, in the northeast corner of Sonoma County, California. Situated in the northwest-trending Mayacmas Mountains (fig. 2) of the northern Coast Ranges, the area is characterized by rugged topography with about 2,500-foot relief and by highly folded, fractured, and sheared rocks of the Franciscan Formation of Late Jurassic and Cretaceous age.

Drilling for geothermal steam began in the 1920's and was resumed in the mid-1950's. Geothermal power generation became a reality in 1960, and by fall 1973, 400 megawatts of power will be on line. The Geysers will be in fall of 1975 the largest source of geothermal power in the world.

Being a vapor-dominated resource area, little water is produced at The Geysers. All of the production is dry steam, and bottom-hole pressures are about 30 times atmospheric. Therefore, little or no measurable subsidence is expected due to geothermal production. Three other types of movement of considerable interest are presently under surveillance at The Geysers:

a. Landslides and down-slope creep which affect most of the steep slopes of the area,
b. regional and local tectonism, and
c. temperature changes which are probably affecting all the rocks in the production area.

Any possible surface movement caused by geothermal fluid withdrawal will be masked by the greater changes of these other processes.

Horizontal control.--Two networks of horizontal control are monitoring horizontal changes in The Geysers. The first is a highly precise regional network shown in figure 2, designed to detect any regional movement that might take place. The second is a local

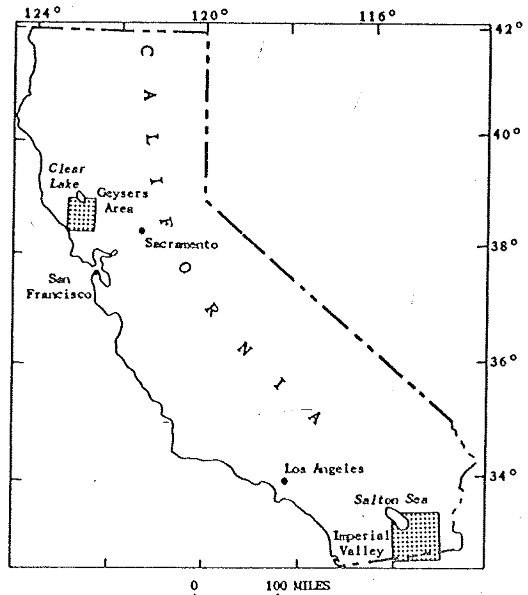

FIGURE 1.—Principal areas of geothermal monitoring in California

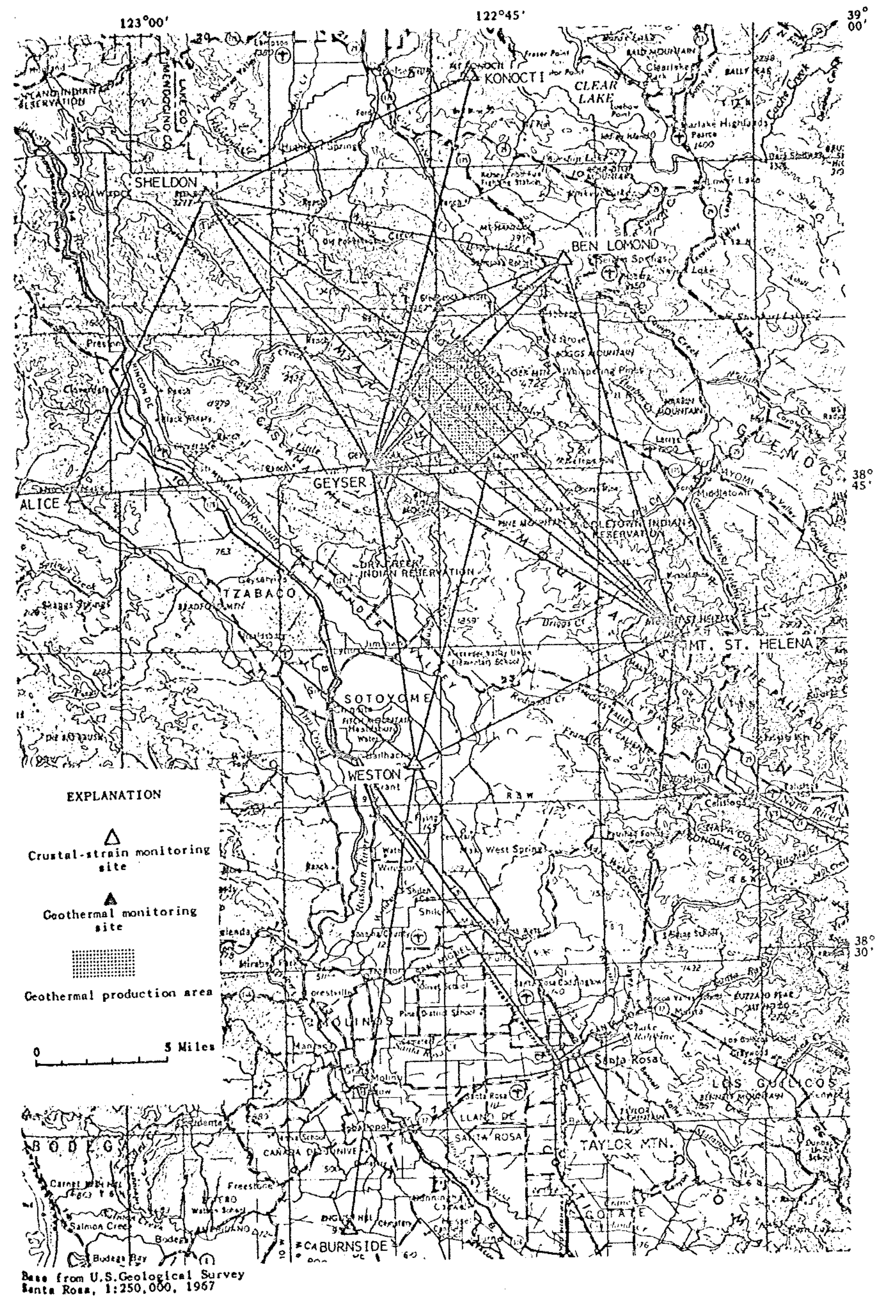

FIGURE 2.—Regional horizontal control, The Geysers area, California.

network, tied to control points of the regional net, to measure movement that might occur between points within the production area. Both surveys use line-of-sight electronic distance-measuring equipment. The regional network, maintaining accuracies of about 1 unit in 10^7 units, was established in 1972 and is scheduled for resurvey in the fall of 1973. The local net, with accuracies of about 1 unit in 10^5 units or roughly 0.05 foot per mile, is used to measure movement over shorter distances and is being resurveyed several times per year.

Owing to the rugged terrain, numerous steep-angled line-of-sight measurements can be made with the distance meter from permanent bedrock outcrops to secondary bench marks across the canyons. Both horizontal and vertical components of movement can be calculated from the slope-distance measurement. Because of the nature of the electronic survey equipment, however, calculated horizontal components of the measured slope distance are much more accurate than the calculated vertical components.

Vertical control.--Figure 3 shows the extent of first- and second-order level lines in The Geysers area as of May 1973, and also an 18-mile loop of new leveling in the geothermal production area to be established in 1973 as a part of this monitoring program. All surveying is by the National Geodetic Survey (formerly U.S. Coast and Geodetic Survey). During 1973, the loop in the production area and the tie to the first-order regional network at Lower Lake are being leveled to first-order accuracy by the National Geodetic Survey. Bench marks in the geothermal production area are closely spaced, and wherever possible have been established on bedrock outcrops and heavy structures. Periodic releveling of these bench marks will monitor regional and local changes that might take place.

Numerous secondary bench marks are being established throughout the production area wherever significant movement, principally downslope creep, is expected. Frequent resurveys of these bench marks will detect differential movement as it occurs.

IMPERIAL VALLEY

In sharp contrast with The Geysers area, Imperial Valley is a flat, intensely farmed, arid agricultural area. Located about 150 miles southeast of Los Angeles (fig. 1), Imperial Valley occupies part of a deep, sediment-filled structural trough on the border between the continental block of western United States and the oceanic block of the eastern Pacific. A number of major and minor faults (Dutcher, Hardt, and Moyle, 1972, fig. 3), largely masked by the young alluvial deposits of the valley, traverse the structural trough, making this one of the most tectonically active areas of the country.

Thermal gradients are unusually high throughout much of Imperial Valley; however, eight known areas of anomalously high temperatures appear especially favorable for geothermal production (fig. 4). Several of these anomalies already have been test-drilled and have active hot-

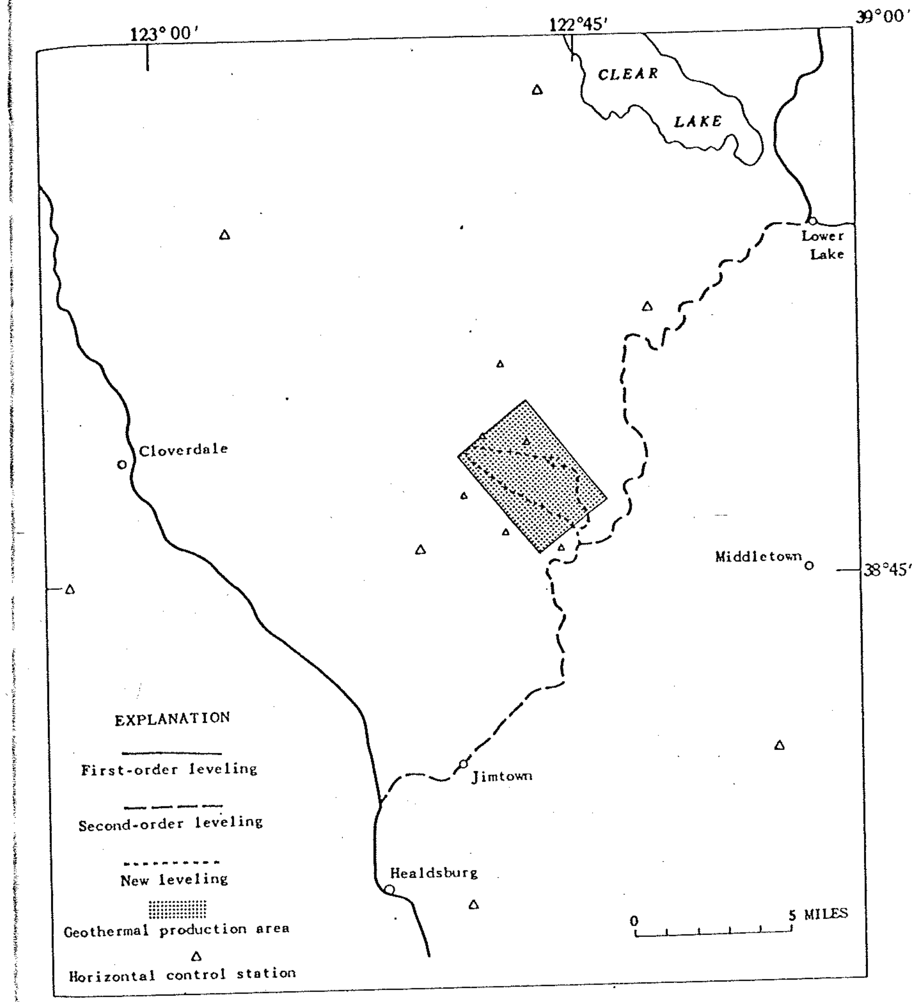

FIGURE 3.—Regional vertical control, The Geysers area, California

water (which flashes to steam) wells ready for production; others are scheduled for test drilling in the near future. Wherever deep wells have been tested, hot-water geothermal conditions have been observed rather than dry steam as at The Geysers. This suggests that as geothermal development progresses, not only will large quantities of thermal waters be produced, but also production will have an intimate effect on the hydrologic regime of the overlying ground-water reservoir. The possibilities of land subsidence, lateral deformation, and infringements on existing water rights, therefore, are very real in Imperial Valley.

Figure 4 shows eight of the more prominent geothermal anomalies reported by the U.S. Bureau of Reclamation in 1971 (U.S. Bur. Reclamation, 1971). Of these, the fields (1) abutting Salton Sea southwest of Niland and (2) due south of El Centro, have received the most attention by industry, and have production wells awaiting pilot-testing. Also, near the center of the anomaly 7 miles southeast of Holtville, a deep test well by the Bureau of Reclamation has produced hot water and steam and is presently undergoing further testing.

Horizontal control.--Two types of horizontal control are currently being monitored in Imperial Valley; first, a highly precise regional trilateration network spanning the structural trough to measure regional tectonic movement, and second, local radial networks from production centers in each of the areas of prospective geothermal development to detect possible local ground movement that might accompany geothermal production. The regional network is being monitored by the Geological Survey, using geodolite equipment capable of an accuracy of 1 unit in 10^7 units, and is scheduled for resurveying in the fall of 1973. Local nets at each production site are being resurveyed periodically by the Survey using distance-measuring capability of 1 unit in 10^5 units.

As presently planned, considerable geothermal or supplemental water will be reinjected into the geothermal reservoir to maintain formation pressures to minimize problems of subsidence. Reinjection would tend to maximize fluid gradients between the point of extraction and the point of injection, which in turn would cause stresses in the direction of the gradient. Possible ground movement from the injection well and toward the extraction wells during the initial stages of development is being monitored at the three locations listed above.

Vertical control.--Figure 4 shows the network of leveling established to measure possible vertical changes that might accompany geothermal development in Imperial Valley. The lines of first-order leveling running east, north, and west from El Centro had been surveyed several times prior to 1971, and indicated considerable tectonic movement was occurring in this portion of the structural trough. Tectonism will undoubtedly continue, and may possibly increase, as geothermal production continues.

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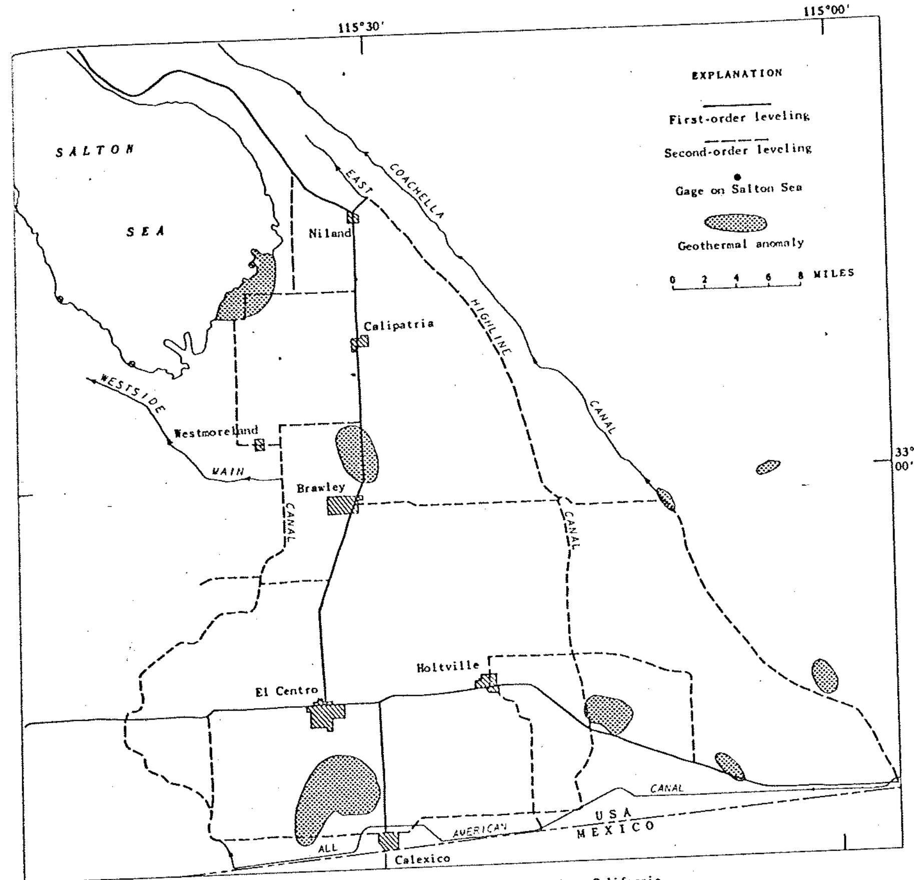

FIGURE 4.—Network of leveling in Imperial Valley, California

In the fall of 1971, the first-order lines of figure 4 were again leveled by the National Geodetic Survey, and also, the second-order lines were established and surveyed by other agencies under direction of the National Geodetic Survey. This 1971 reference datum serves as a base from which subsequent elevation changes can be calculated. Releveling of this entire network, including both first- and second-order lines, is scheduled for late fall, 1973. As required by law, bench marks at each geothermal production site will be periodically resurveyed to reference ties of the first- and second-order net to detect subsidence that may accompany geothermal production.

In order to monitor possible elevation changes occurring on the southern margin of Salton Sea, related either to tectonic readjustments or geothermal production, two newly installed continuous stage recorders are now being used to correlate fluctuations of the sea with two other stage gages on the west shore of the Sea. One of these new stage recorders is near the southern tip of the Sea (fig. 4), the other within the geothermal anomaly southwest of Niland. Each of the stage gages is being tied into the valleywide network of vertical control. Differential elevation changes of even a few hundredths of a foot around the southern margin of the Sea should be detectable with these recorders.

CONCLUSIONS

Two important geothermal resource areas--The Geysers, a vapor-dominated geothermal system in northern California, and Imperial Valley, comprising scattered water-dominated geothermal anomalies in southern California, are being monitored for possible subsidence and lateral surface deformation. Surface changes may be caused by geothermal extractions, fluid injections, induced hydraulic gradients, thermal changes, landslides, and tectonism. To differentiate ground movement caused by geothermal extractions from changes due to other geologic processes is one of the principal challenges of this research project.

Regional and local networks of horizontal and vertical control have been established at The Geysers and at several of the geothermal anomalies of Imperial Valley. Periodic resurveys of these nets will be the basis for calculating ground deformation that might accompany geothermal extractions. Various Federal, State, and local agencies are involved in this monitoring program.

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