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MEASURING GROUND MOVEMENT IN GEOTHERMAL AREAS OF IMPERIAL VALLEY, CALIFORNIA

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Significant ground movement may accompany the extraction of large quantities of fluids from the subsurface. In Imperial Valley, California, one of the potential hazards of geothermal development is the threat of both subsidence and horizontal movement of the land surface. Regional and local survey nets are being monitored to detect and measure possible ground movement caused by future geothermal developments. Precise measurement of surface and subsurface changes will be required to differentiate man-induced changes from natural processes in this tectonically active region.

I. INTRODUCTION

As with extractions and injections in oil-field and ground-water reservoirs, a direct relationship is expected in hot-water geothermal systems between pressure changes induced in the system and ground deformation that might result (Ref. 1). Experience in many areas of fluid-pressure change indicates that both vertical and horizontal components of deformation may occur as a result of either the compaction of surficial unconsolidated deposits or of deep-seated tectonic readjustments triggered by stress changes. Even subtle changes of stress at depth sometimes cause serious surface movements. Such problems undoubtedly will become more commonplace and severe as man's development of natural resources progresses.

Land subsidence, caused by the withdrawal of water, oil, and gas, has become common in the United States, affecting probably 10,000 mi^2 (25,900 km^2) of intensely developed land in five States (Ref. 2). Maximum subsidence is 29 feet (9 m) in the San Joaquin Valley and Long Beach areas of California, 13 feet (4 m) in the Santa Clara Valley of California, and is in excess of 8 feet (2.4 m) in the outskirts of Houston, Texas (Ref. 3). Horizontal ground movement exceeds 12 feet (3.7 m) in the Wilmington oil field of the Long Beach area, and, although largely unmeasured, it 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 caused by significant horizontal shifting of the ground. These features are attributed by the author to steep hydraulic gradients induced by pumping.

One of the potential hazards of geothermal production in Imperial Valley, either for power generation or 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 (Ref. 4), in 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 mi^2 (65 km^2), and the maximum subsidence rate is about 1.3 feet (0.4 m) per year. Total subsidence exceeds 10 feet (3 m), and, significantly, the area of maximum subsidence is outside the production field. Similar effects could occur in other "hot-water" geothermal fields. Periodic resurveys of bench marks throughout a production area and the surrounding region are needed to determine not only possible ground movement resulting from geothermal developments but also movement related to other geologic processes.

Imperial Valley is a "flat," arid area that is irrigated and intensively farmed with water from the Colorado River. It occupies part of a deep, sediment-filled structural trough on the border between the continental block of the western United States and the oceanic block of the eastern Pacific. A number of major and minor faults (Ref. 5, Fig. 3), largely masked by the alluvial deposits, traverse the structural trough. Currently this is 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. 1). Several of these anomalies already have been test-drilled and have active hot-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. 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 1 shows eight of the more prominent geothermal anomalies reported by the U. S. Bureau of Reclamation in 1971 (Ref. 6). Of these, the Buttes anomaly abutting Salton Sea southwest of Niland (Fig. 1) and the Heber anomalies 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 East Mesa anomaly 7 miles (11 km) southeast of Holtville, several deep test wells by the Bureau of Reclamation have produced hot water and steam and are presently undergoing further testing.

II. MONITORING PROGRAM

A. Vertical Control

Figure 1 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 increase, as geothermal production continues.

During the winter of 1971-1972, the first-order lines of Fig. 1 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 1971-1972 reference datum serves as a base from which subsequent elevation changes can be calculated. During the winter of 1973-1974, the first- and second-order networks were again surveyed to verify measurements of the 1971-1972 survey and detect changes that had occurred during the ensuing years. Figure 2 shows, in addition to the approximate location of the principal known faults traversing the region, the amount of vertical change along the first-order lines during the 2-year interval 1971-1972 to 1973-1974. In these computations, the bedrock tie west of El Centro was considered stable, and all other points in the net were considered floating. Interestingly, bench marks near Calexico and at the bedrock tie east of El Centro showed little or no change during this 2-year period. El Centro subsided roughly 0.6 inch (1.5 cm), and a general northward tilt of about 5 inches (13 cm) was measured in the 53 miles (85 km) from south to north in the valley. No explanation for this apparent northward regional tilt is attempted here; however, it is quite apparent that the modest activities in the three geothermal anomalies being tested had little or no effect. Results of the second-order leveling are not available for reporting here. As required by State and County ordinance, bench marks at each geothermal production site will be resurveyed periodically to reference ties of the first- and second-order nets to detect subsidence that may accompany geothermal production. Figure 3 shows the three locations where local level networks are being monitored by developers to determine if changes are occurring in areas of geothermal development.

In order to monitor possible elevation changes occurring on the southern margin of Salton Sea, related to either tectonic readjustments or to geothermal production, two continuous stage recorders were installed at strategic locations to correlate fluctuations of the sea with two other stage gages of long record on the west shore of the sea. One of these new stage recorders is near the southern tip of the sea (Fig. 3), 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 less than a centimeter around the southern margin of the sea should be detectable with these recorders. Interpretation of the first year of correlative records from these recorders is in progress.

B. Horizontal Control

Two types of horizontal control nets 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 arrays of precise distance measurements in each of the areas of geothermal development to detect possible ground movement accompanying geothermal production.

Figure 4 shows the regional network being monitored by the Geological Survey, using geodolite equipment capable of accuracies of 1 unit in 10^7 units of distance. Late data suggest as much as 0.02 inch (5 mm/year) of right-lateral horizontal tectonic movement is occurring in the Obsidian Buttes area (Fig. 4) southwest of Niland, along what may be an extension of the Brawley fault. Interestingly, this indicated movement is in the general area where a number of recent geothermal test wells have been drilled and tested. The tectonic movement, however, predates the drilling of the wells.

Figure 5 shows the arrays of distance measurements being monitored in the Buttes area southwest of Niland to detect any horizontal movement. These local nets are being resurveyed by the Geological Survey using electronic distance-measuring equipment capable of accuracies of 2 units in 10^6 units of distance. Distance changes of only a few millimeters along these controlled lines can be detected. Because these distance measurements can be made so inexpensively, extra shots have been made in the event they are needed for future reference. Similar arrays are being monitored in the Heber and East Mesa areas; however, in these areas no elevated reference points are available and long line-of-sight controls are more difficult. Control lines extend not only across geothermal areas where geothermal changes are anticipated, but also across structural zones where tectonic movement might occur.

III. SURFACE AND SUBSURFACE INSTRUMENTATION

Consider for a moment a geothermal area in which thermal fluids are extracted at depth at one location, and these and other fluids are injected nearby to minimize formation-pressure declines and subsidence (Fig. 6). Extractions cause a drop in formation pressures, compaction, and subsidence. Injections cause a pressure buildup, expansion, and rebound. These vertical changes, y_1 and y_2 in Fig. 6, are significant in understanding the mechanics of the geothermal system. In addition, steep pressure gradients may develop between the two wells, and possibly horizontal ground movement as represented by the lower arrows in Fig. 6. To monitor possible horizontal movement, precise distance measurements, x_1 and x_2, x_3 and x_4 in Fig. 6, are needed between the extraction and injection wells. Compression would be greatest near the extracting well, and horizontal tension would tend to develop near the injection well. This type of horizontal movement, with significant compression in the area of fluid-pressure decline and tension around the perimeter, has been observed in numerous stressed subsurface reservoirs.

If the land surface tilts, as shown in Fig. 6, the tilt should be at a maximum somewhere midway between the centers of extraction and the injection, and could be recorded by a tiltmeter at this midpoint. We have reason to believe, however, that in many instances the land surface does not deform as a stressed beam. Rather, shear seems to develop along near-vertical planes, with individual blocks between the shear planes moving vertically up or down (Fig. 6). We are installing tiltmeters at a few sites to determine what type of surface deformation actually occurs. Also, at several locations where shallow ground water is being pumped in the vicinity of deep geothermal wells (see Fig. 6, right), extensometers are being installed to differentiate deep compaction caused by deep geothermal extractions from relatively shallow compaction due to ground-water production. Without some method of differentiating these two processes, geothermal developments can be unjustly blamed for subsidence caused by ground-water pumping.

At East Mesa, 17 miles (27 km) east of El Centro (Fig. 1), where the U. S. Bureau of Reclamation is experimenting with deep extractions and injections in the geothermal reservoir, tiltmeters and extensometers are being installed on an experimental basis, as shown in Fig. 7. Two sensitive tiltmeters, installed in 10-foot (3-m) pits to minimize thermal problems, are being positioned between the four extraction wells and the one injection well. Also, two mid-depth extensometers are being positioned between the area of geothermal development and nearby farmlands to monitor changes in water levels and compaction in the upper 1150 and 1400 feet (350 and 430 m), respectively, of alluvial deposits. Already in this area, even before significant geothermal developments have begun, numerous complaints from nearby ranchers have charged that geothermal drilling has had adverse effects on their water wells.

IV. CONCLUSIONS

As in three other geothermal resource areas of the west, regional and local networks of vertical and horizontal surveys have been established in Imperial Valley to monitor ground movement that might accompany geothermal developments. Periodic resurveys of these nets will be the basis for calculating vertical and horizontal changes that occur between surveys. Also, recording tiltmeters, extensometers, and stage gages on Salton Sea are being maintained to detect changes as they occur. Various Federal, State, and local agencies are involved in this monitoring program.

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. In most instances, several years of records will be required before geothermal effects can be determined and firm conclusions reached.

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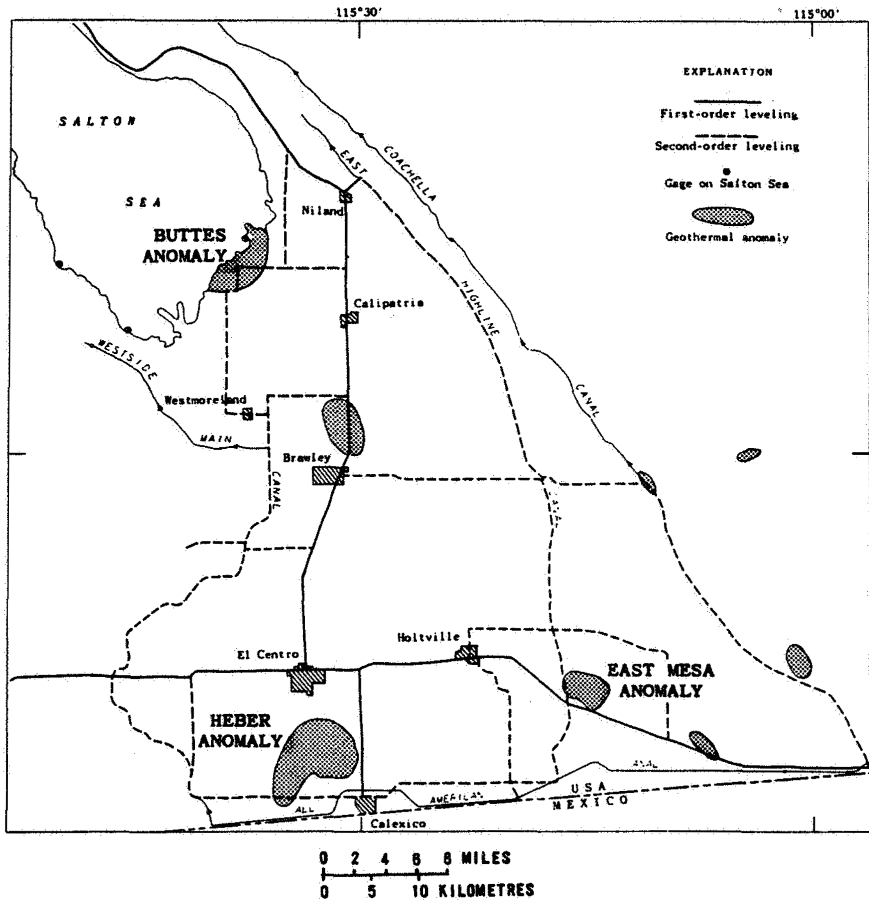

Fig. 1. Location of geothermal anomalies and network of leveling, Imperial Valley, California

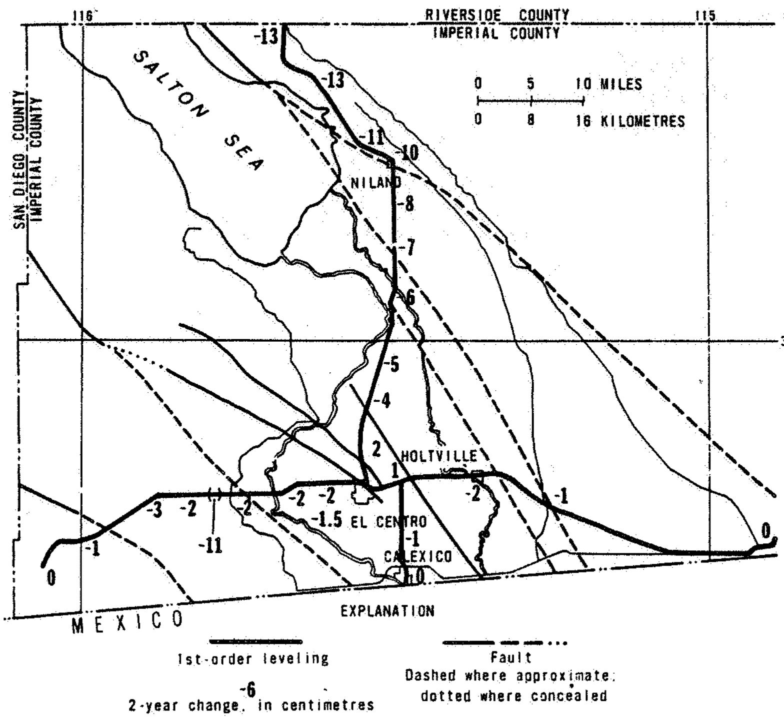

Fig. 2. Network of first-order vertical control and 2-year change in elevation

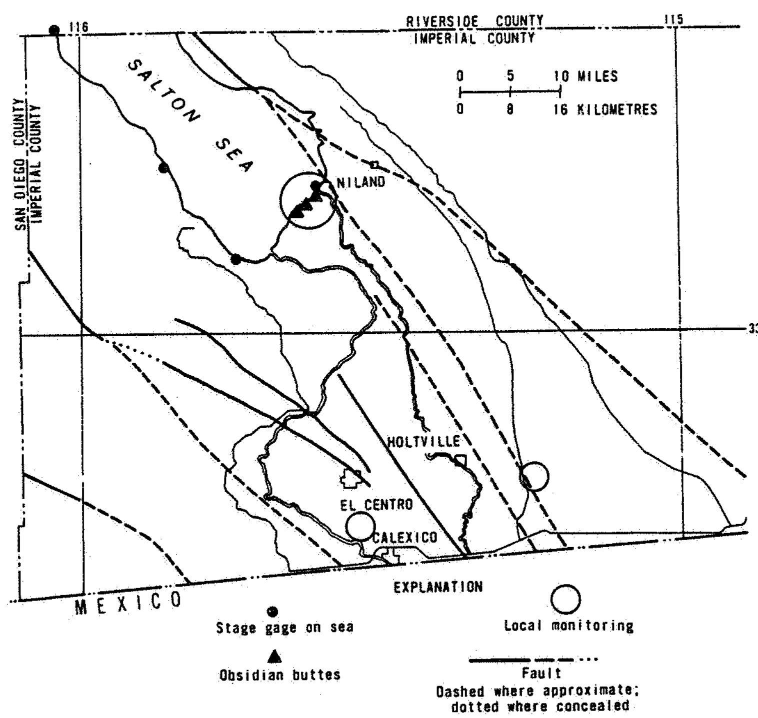

Fig. 3. Geothermal areas of local vertical and horizontal control monitoring

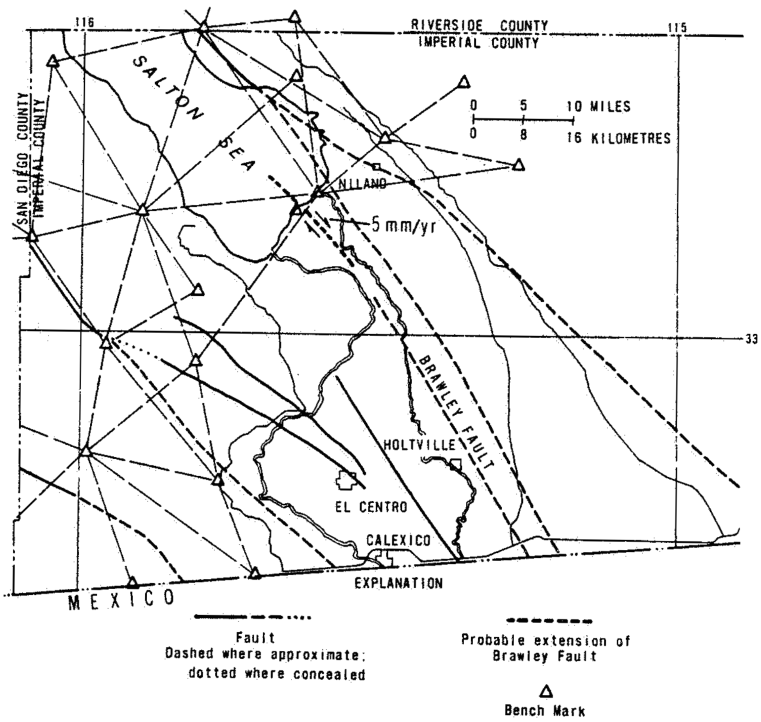

Fig. 4. Regional network of horizontal control

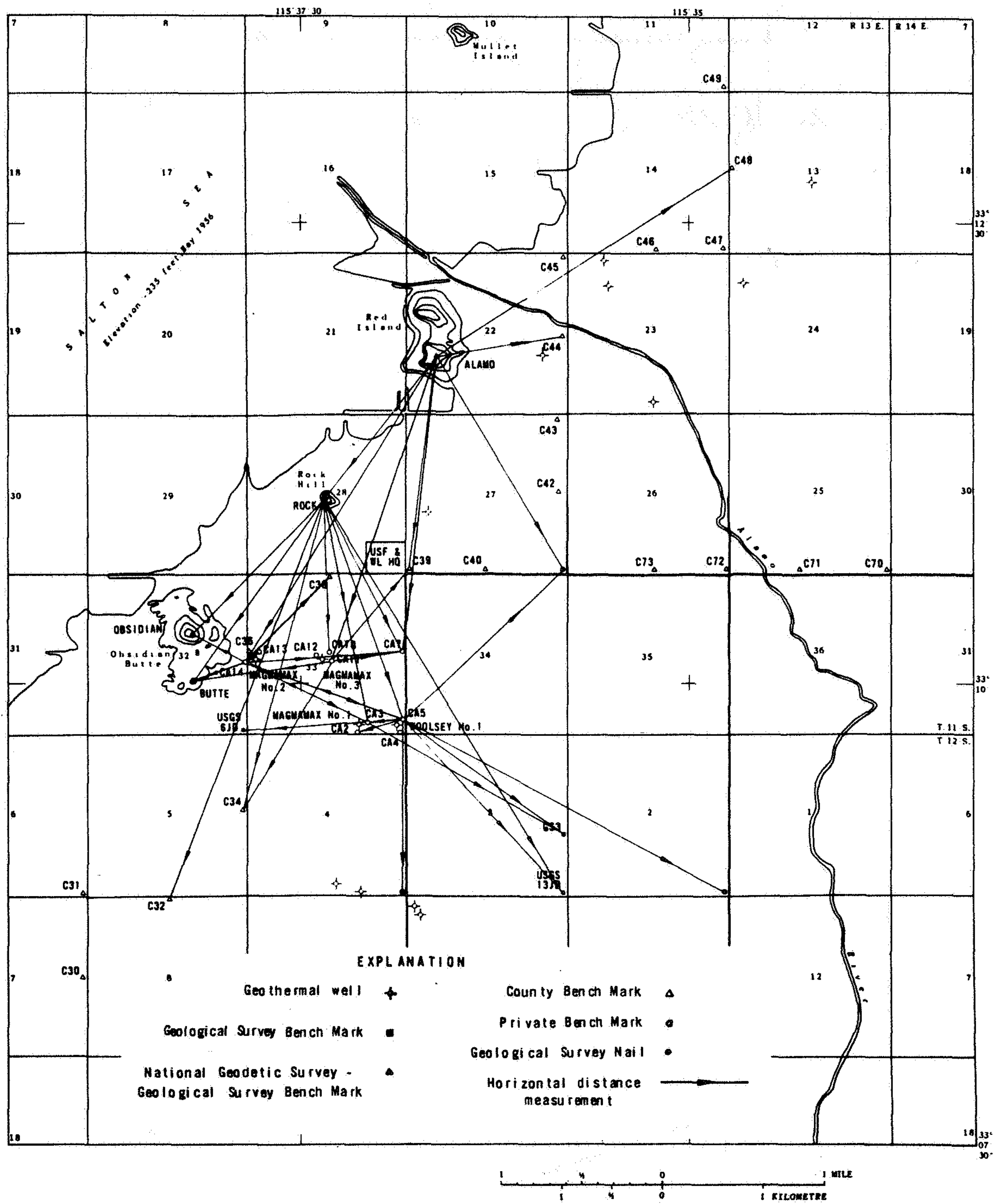

Fig. 5. Network of horizontal control in Buttes area

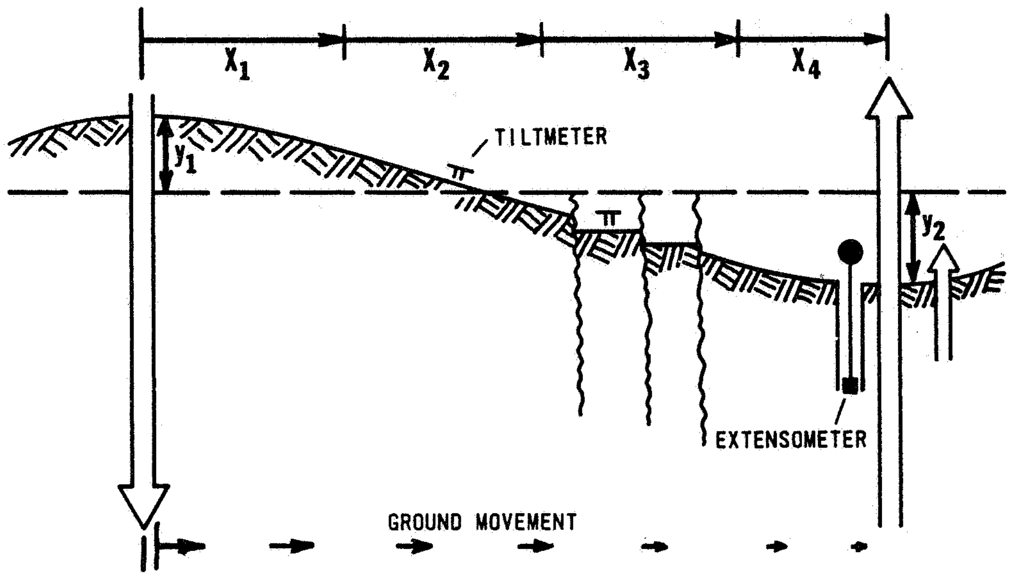

Fig. 6. Surface deformation in an extract-injection area

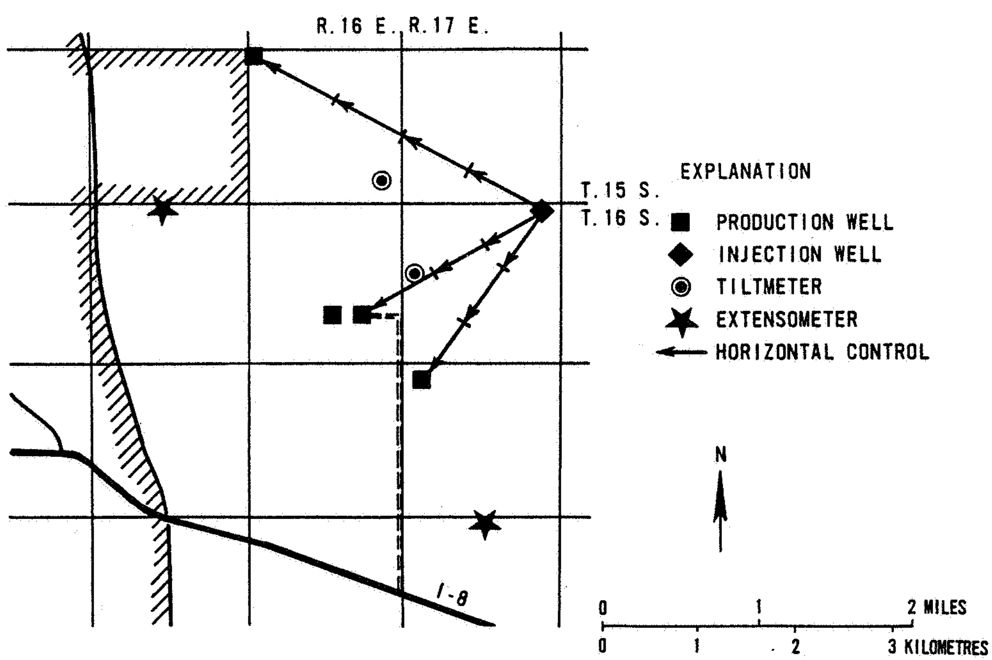

Fig. 7. Instrumentation installed at East Mesa geothermal area