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MONITORING NATURAL SUBSIDENCE AND SEISMICITY IN THE IMPERIAL VALLEY AS A BASIS FOR EVALUATING POTENTIAL IMPACTS OF GEOTHERMAL PRODUCTION

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INTRODUCTION

The Imperial Valley Environmental Project (IVEP) is being carried out by LLL for the U. S. Department of Energy. Objectives of the project are to identify the key environmental issues about geothermal energy development in the Imperial Valley, to assemble and evaluate available information about these issues, and to develop the additional information necessary for complete environmental assessments. The process is designed to ensure environmentally acceptable development. The IVEP studies cover many technical areas, including air, water and ecosystem quality and socio-economic effects; this paper reports the results of work done on potential geologic effects of geothermal development.

The key geological issues in the Imperial Valley are the potential for significant subsidence and seismicity which could be induced by geothermal production. Reduction of reservoir pressure by production will cause compaction of the reservoir; the fraction of this that will affect the surface as subsidence is a complex function of rock strength and thickness of the rocks overlying the reservoir. There is considerable uncertainty about the amount of subsidence which might be expected, because at this time models cannot accurately predict it. The reason is that the relationship between rock properties measured in the laboratory and long-term subsidence is not clearly understood; however, an upper bound can be estimated. Injection of spent fluid has been used successfully in other areas to control reservoir pressure drop, and thus compaction and subsidence. Low pressure injection in California is not known to have caused any induced seismicity, and it is planned to use low pressures in the Imperial Valley. However, high pressure injection in Colorado has induced seismic activity at the point of injection. While the injection pressures necessary in the Imperial Valley are much lower than those in Colorado, the possibility of induced seismicity cannot be dismissed.

The detection of such earth movements in the presence of a high level of natural subsidence and a degree of earthquake activity among the highest in North America requires careful documentation of existing levels of such activity and continued monitoring for any anomalous response to geothermal development. Clearly, our major technical problem is to develop techniques to distinguish between natural and induced activity.

Because relatively sparse detection networks were already in place, our program has involved extensive cooperation with other agencies - Federal, California, and local - as well as the geothermal developers. In both subsidence and seismicity studies, our projects augment the existing network to obtain additional information in critical areas; thus, we added local subsidence detection networks to the regional networks, and augmented the U. S. Geological Survey seismograph network to increase sensitivity to small earthquakes near the Salton Sea. We believe the program has substantial mutual benefits.

A long time is necessary for collection of adequate geologic baseline data. Therefore, we believe that it is especially important to continue these monitoring programs. Although most field activities in the IVEP have terminated, we plan to continue seismic and local subsidence monitoring through 1979, and negotiations are underway to transfer these activities to other agencies after that time.

SUBSIDENCE STUDIES

Regional subsidence detection The possibility that significant subsidence might be induced by geothermal production was recognized as a potential problem early in the 1970s. Agriculture there depends upon a complex system of irrigation canals and drains, constructed on the flat Valley floor which slopes gently to the north. This system could be damaged by subsidence. The Imperial County Department of

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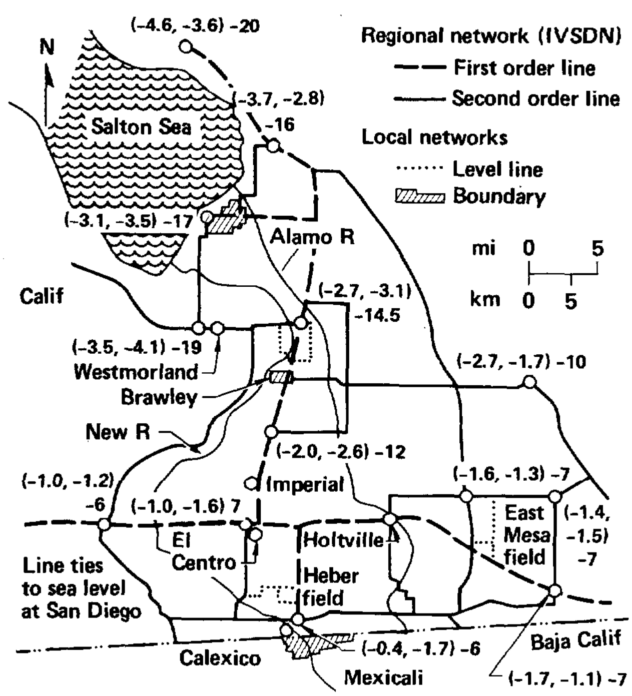

Figure 1. Imperial Valley Subsidence Detection Network and local networks. At each point, first number is the rate of subsidence (cm/yr) 1972-74; the second, the rate of subsidence (cm/yr) 1974-77. The third number is total subsidence for 1972-77. Free adjustment data by Reese (1977).

Public Works and the Imperial Irrigation District were joined by the California Division of Oil and Gas and the U. S. Geological Survey in forming the Imperial Valley Subsidence Detection Committee, which sponsored the construction of a network of precisely leveled benchmarks (Figure 1). The network was surveyed first in 1971-72, and resurveyed in 1973-74. Between these levelings, substantial downward movement of the Valley floor relative to the mountains to the west had occurred (Lofgren, 1974).

One of our first objectives in the IVEP was to negotiate a resurvey of the network. A cooperative effort resulted in releveling, which took place in the winter of 1976-77. Results from a free adjustment of all three surveys by the National Geodetic Survey were reported by Reese (1977), and some key points are shown on Figure 1. An intensive data analysis is underway, but detailed results are not yet available. The region is subsiding relative to the mountains to the west, and the downward movement is greater to the north and to the east in the Imperial Valley. The rate of subsidence is not uniform over time. No discernible effects of these movements have been noted on surface structures in the Valley during the period of measurements.

Because of the resurveys, baseline data about natural regional land surface movement has been acquired during a period when only very small-scale geothermal test activities were taking place. Future resurveys will allow documentation of any motion in the Valley, both that due to natural causes and any induced movement.

Local subsidence detection networks Local subsidence detection networks are an important part of subsidence studies in the Imperial Valley. We believe that local differential subsidence - a "dimple" - which might be induced by geothermal production is potentially more of a problem than regional movement; local networks which can detect such motion are very important. Data obtained from repeated levelings of these local networks before geothermal production begins will be used to establish patterns of local movement. These patterns will be invaluable in determining whether any apparently anomalous activity is natural or induced.

We have constructed three local subsidence detection networks, one each at the Salton Sea field, North Brawley field, and Heber field. The Bureau of Reclamation has constructed a similar network at the East Mesa field. The networks at North Brawley, Heber and East Mesa are designed as frameworks to which local levelings of wells can be tied. At the Salton Sea field, we constructed a tightly controlled network to observe small-scale land surface movement. This network, designed by Harold Ganow and the authors, consists of a grid of benchmarks on half-mile centers over the portion of the field with current activity. The network was constructed in May, 1976, by Imperial County and releveled in May, 1977 by the National Geodetic Survey. Data from both surveys were adjusted relative to an anchor point within the grid by the National Geodetic Survey (Reese, 1977), as shown in Figure 2. Up to 40 mm of relative movement occurred during this one-year period. The data show a pattern: a southwesterly-trending swale just east of Obsidian Butte is bordered east to west by rises. Three earthquake swarms occurred here during November and December, 1976 (see Figure 3), midway in time between the two levelings. We are determining the relationship between these swarms and the observed land surface movement. The network will be surveyed again next winter to obtain additional information.

Sensitivity to subsidence At present, subsidence predictions cannot be made accurately because the relationship between rock properties measured in the laboratory and long-term subsidence is not clearly understood. Measurements of porosity *in situ* may be used to estimate the maximum possible subsidence (Schatz and others, 1978). We are studying the geothermal fields in the Imperial Valley to estimate the significance of effects which might reasonably be expected, and the costs of re-

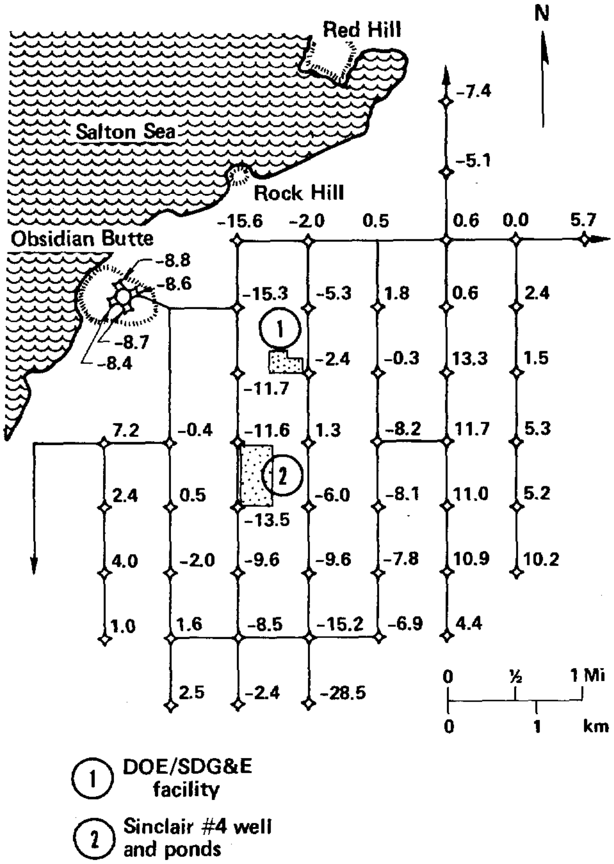

Figure 2. Local network, Salton Sea Geothermal Field. Vertical movement (in mm) during one-year period, May 1976-May 1977. Data from Reese (1977).

pairing such damage. Each of the areas is unique, with differing placement of such surface features as irrigation canals, field tiling, and drains, as well as differing topography, so that the potential for damage and the cost of repairs must be assessed on a site-specific basis.

STUDIES OF SEISMICITY

The Imperial Valley is one of the most earthquake-prone areas in North America, with many active faults having both strike-slip and vertical motion. There are also recent volcanoes, associated with geothermal areas, which are likely to have abnormal types and levels of seismic activity.

Because it is possible that geothermal production could induce seismic activity as a result of producing and injecting geothermal fluid, it is important to document the natural seismic activity to establish a baseline against which to compare future seismic activity levels. Because the level of natural seismicity was known to be high and variable in the region, it was recognized that subsequent to geothermal development it would be a major technical problem to distinguish between natural and induced seismic activity.

In 1973, the USGS extended their regional seismographic network into southeastern California to obtain data about the San Andreas fault system. This resulted in a major improvement in the accuracy of earthquake detection and location in the Imperial Valley region. However, the sensitivity of the network in the vicinity of the Salton Sea geothermal field was not sufficient to detect and locate small earthquakes accurately. One of our major objectives in the IVEP, therefore, was to improve coverage in this locality, and we contracted with the USGS to install additional stations.

In November, 1976, the six stations shown in Figure 3 were installed; they had an immediate test. A series of three closely-spaced earthquake swarms occurred in the midst of the new array of stations during November and December 1976; Figure 3 shows the distribution of the epicenters of these events. Because of the added sensitivity, excellent resolution of location and distribution over time of the swarm events was possible. Thus, in a recent report, Fuis and Schnapp (1977) interpret the distribution of events to determine the sequence of events to suggest a north-northwest-migrating displacement on the Brawley fault that triggered displacements on related structures. In other new work, assisted in part by the new stations, Johnson (1977) interprets seismic data to state that most earthquake sequences associated with the Brawley and Imperial faults can be classified as swarms.

This information helps to make it clear that the distribution over time of earthquakes in the Imperial Valley is extremely variable, and that swarms of earthquakes, mostly associated with the Brawley and Imperial faults, are quite common in the Valley. Without this knowledge, one might expect that earthquakes would occur in a relatively uniform sequence best described by a Poisson distribution; if a swarm occurred near a geothermal facility, the increased earthquake rate would suggest a causal relationship between geothermal activity and the swarm. Because swarms of earthquakes are common in the Valley, clearly an increase in earthquake rate is insufficient in itself to indicate a causal relationship.

Another technique which promises to be useful is determination of the depth of focus of earthquakes. Johnson and Hadley (1975) present data from the Brawley swarm of January, 1975 which indicate that virtually all the events of that swarm occurred at focal depths greater than about 4 km. Because geothermal fluid is produced and injected at depths in the range of 1-2 kms, one would expect that most events which might occur as a result of these processes would be centered at about these depths. At present, the sensitivity of the network is insufficient to give such close resolution with confidence in

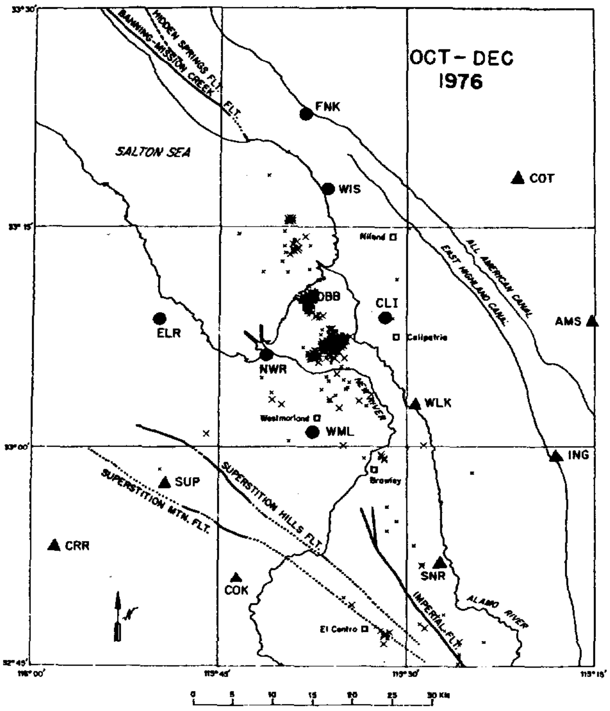

Figure 3. Location of earthquake epicenters in the Imperial Valley for the period Oct. 1, 1976 to Dec. 31, 1976. Solid triangles are seismograph stations in the USGS network installed in 1973. Solid circles are stations added in Nov. 1976. From Schnapp and Fuis (1977).

all cases. Calibration of the network is scheduled for spring of 1978 and will improve the velocity model; further improvement can be expected with installation of a 3-component seismograph at one or more of the stations of the network.

We believe that continued seismic monitoring in the Imperial Valley, accompanied by continuing research, will provide sufficient information to distinguish between natural and induced events with reasonable certainty.

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