GEOTHERMAL INDUCED SEISMICITY - BANE OR BLESSING?

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Abstract

Production of steam or hot water from a geothermal reservoir and disposal of geothermal fluids by injection can be expected to disrupt hydrologic and tectonic equilibria in and around the reservoir, possibly producing instabilities leading to increased seismicity. As in well-documented cases of seismicity associated with reservoir impoundment (earthquakes as large as magnitude 6.5) or fluid injection (events as large as magnitude 5), the mechanisms of earthquakes induced by geothermal production and injection seem to reflect the regional tectonic stress orientation. Most probably the events are triggered by reduction in effective normal stress brought about by non-uniform pore pressure changes and thermal cooling. Although earthquakes induced by geothermal operations may very likely result in enhanced local seismicity and possibly damaging earthquakes, concern over this possible increase in seismicity has not been a barrier to geothermal development. At the world's largest geothermal development, The Geysers, thousands of earthquakes have been detected and located by the U.S. Geological Survey/Department of Energy network. The larger (magnitude 2.0 to 3.8) of these events are felt on a weekly basis, and some are disruptive in that temporary plant shutdowns result from the response of machinery-protective devices the earthquake-induced vibration. The largest events to date have occurred at injection wells.

On the positive side, earthquakes induced by cooling or fluid pressure changes provide unique information on the location of fracture zones within the reservoir by mapping the paths of fluids being withdrawn or injected. This information can be invaluable for geothermal reservoir definition and operations management.

Induced seismicity may also generate new fractures in the rock and serve to maintain existing fracture permeability in the presence of cementation and compaction processes which decrease permeability in the reservoir.

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Introduction

When man modifies the hydrologic regime by fluid withdrawal or injection, he runs the risk of releasing stored elastic shear strain, often in the form of earthquakes. This phenomenon of induced seismicity has been demonstrated in the case of reservoir impoundment resulting from construction of dams (Gupta and Rastogi, 1976) and in the case of fluid injection in boreholes (Healy and others, 1968). The largest induced earthquakes to date have had magnitudes near 6.5, but there is no reason to believe that larger earthquakes could not be triggered. The principal factor in triggering earthquakes is believed to be increased fluid pressure which reduces the effective normal stress on faults. This is the stress which inhibits fault movement. The same effect can be achieved by thermal cooling (Denlinger and Bufe, 1981).

Since techniques for extraction of geothermal heat generally involve both fluid withdrawal and injection, geothermal operations can be expected to trigger earthquakes in regions of stored elastic shear strain. Most hydrothermal regions are tectonically active; thus one might expect induced seismicity to result from geothermal production activities in these regions. Hot dry rock sites may or may not be in tectonically active regions, but the high fluid pressures required to hold fractures open can be expected to release shear stresses which might exist across other preexisting fractures, and induced seismicity is likely.

To date earthquakes triggered by geothermal production activities have been too small to result in property damage or loss of life, and thus have not posed a barrier to geothermal development. Geothermal induced seismicity has not been considered a high priority environmental concern by the Interagency Geothermal Coordinating Committee (IGCC).

Steam production and condensate injection at The Geysers

The only large-scale geothermal power development in the United States is at The Geysers steam field in northern California. Power production at The Geysers reached 900 megawatts with the addition of Plant No. 14 this year. When the plants are operating at full capacity, over 6 million kilograms of steam are removed and nearly 2 million kilograms of condensate injected each hour. Although the mass of water injected is less than that withdrawn, the rate of fluid injection is nevertheless great and is, we believe, responsible for triggering the larger earthquakes at The Geysers.

The rate of fluid injection at The Geysers complements the rate of evaporation, which is higher (80% of produced steam) during the dry, sunny months than during the rainy, overcast winter period (60%). Significantly, most of the larger ($M \geq 2.5$) earthquakes at The Geysers occur during the rainy season when injection rates are highest.

Injection wells are in several instances distant enough from producing wells to permit isolation of the effects of fluid injection on earthquake activity. The two largest earthquakes to occur at The

Geysers (December 22, 1976, magnitude 3.5; September 22, 1977, magnitude 3.8) were located within a few hundred meters of isolated injection wells (DX-7 and LF-3, respectively) outside the regions of steam extraction.

Maximum injection rates in single wells at The Geysers are on the order of 300,000 kg/hr. The table below compares this rate with injection rates at other sites of geothermal interest or where induced seismicity has occurred.

Table 1

Site	Maximum Sustained Injection Rate (kg/hr)
The Geysers (field)	2×10^6
The Geysers (single well)	3×10^5
Larderello, Italy (field)	1×10^5
Larderello (Sasso 22, water loss rate during drilling at depth of 4 km)	1×10^5
Fenton Hill (LASL)	1×10^5
Rocky Mountain Arsenal (single well)	8×10^4
Rangeley Oil Field, Colo. (field)	2×10^6

From Table 1 it is apparent that the fluid injection program at The Geysers is massive. Although the injection pressures are subhydrostatic, the pressure gradients between injection wells and production wells are large, as the reservoir is severely underpressured. The temperature contrast between the injected condensate and the reservoir rock is also large and thermal stresses must be high in the vicinity of the injection wells.

Because The Geysers is a steam field, one might expect that problems such as subsidence normally associated with withdrawal of oil or water would not occur here. However, Lofgren's (1980) data indicated a subsidence rate of 3 cm/year over the production zone. The combined effects of steam withdrawal and condensate injection have resulted in a consistently high level of shallow (0 to 4 km) earthquake activity at The Geysers, and perhaps the greatest frequency of felt events in the United States. The Pacific Gas and Electric Company, operator of the power plants at The Geysers, reports that earthquakes are felt weekly and some are intense enough to temporarily shut down power plants.

Characterization of induced seismicity at The Geysers

Since 1975 the U.S. Geological Survey has operated a network of seismographs in The Geysers-Clear Lake region. The present configuration of the network is shown in Figure 1. Marks and others (1978) have documented the existence of two clusters of earthquake activity at The Geysers. These clusters are spatially correlated with two separate zones of decreased fluid pressure resulting from steam production described by Lipman and others (1977). Marks and others (1978) also examined pre-1975 earthquake data and conclude that the seismicity level at The Geysers has increased since production began. The earthquakes at The Geysers resemble those in the surrounding region with regard to focal mechanism (Bufe and

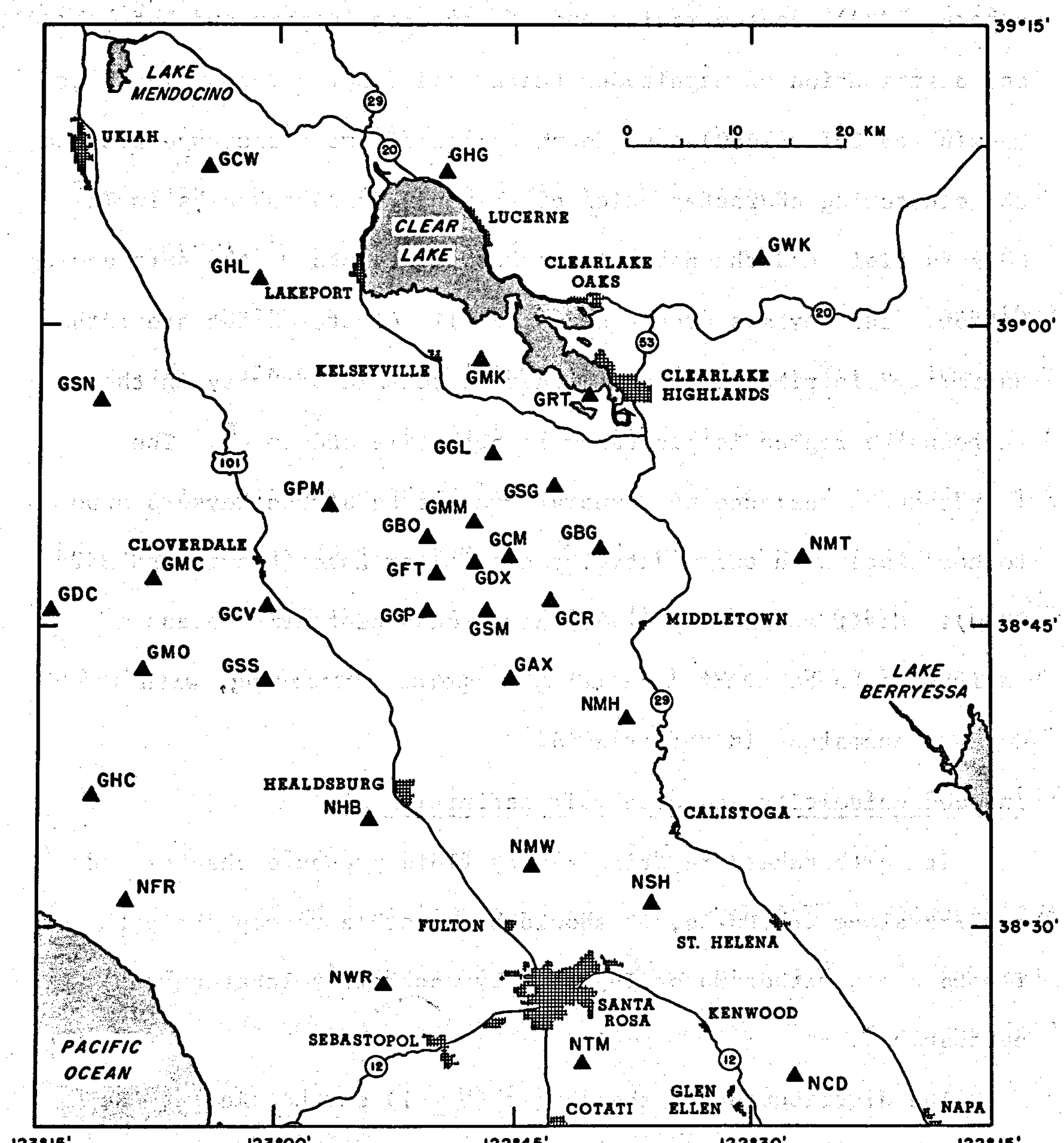

Fig. 1. Seismographic stations operated by USGS in and around the Geysers KGRA known geothermal resource area. Data are telemetered to Menlo Park for analysis. Stations GDX, GBO, GMM, GFT, GSM, GCR, GCM are in the steam production area at The Geysers.

others, 1980), source radius and stress drop (Peppin and Bufe, 1980), and distribution of magnitudes (Marks and others, 1978). However Ludwin and Bufe (1980) have found a significant difference between the clustering characteristics of the induced earthquakes in The Geysers field and the naturally occurring events in the surrounding region. The Geysers events are spatially clustered but are rather uniformly distributed in time, whereas seismic activity in the surrounding region is clustered in both time and space. The infrequent occurrence of temporal clustering at The Geysers appears to correlate with swarm activity near Clear Lake (Ludwin and Bufe, 1980). Cavit and Hadley (1980) have found geothermal areas in California to be characterized by temporal clustering, with The Geysers anomalous in this regard.

Induced seismicity and reservoir definition

If earthquakes are triggered by fluid pressure changes and cooling along fractures, it should be possible to map the paths of fluids being withdrawn or injected by accurately locating the earthquakes.

The distribution of the larger ($M \geq 1$) earthquakes at The Geysers from June 1975 to June 1980 is shown in Figure 2. Figure 2A shows the shallow activity in the field, while Figure 2B shows events below a depth of 2 km. The shallow earthquakes are concentrated in the zones of maximum pressure decline (Lipman and others, 1977) in the shallow reservoir. The deeper events of Figure 2B follow quite a different pattern, possibly defining the reservoir at depth.

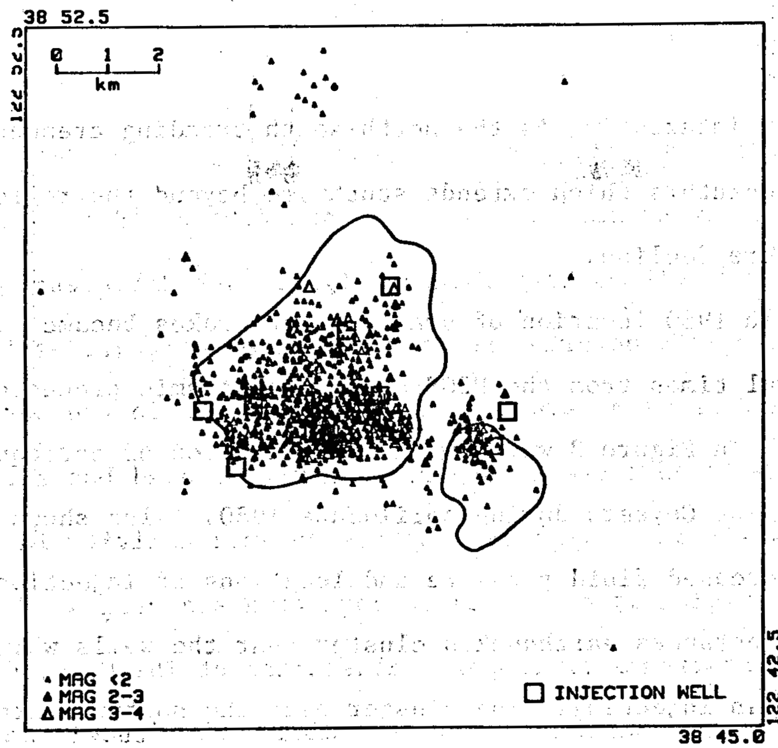

Fig. 2A. Distribution of larger (M ≥ 1) shallow (depth less than 2 km) earthquakes at The Geysers. Wells presently and previously used as injectors are also shown. The zones of fluid pressure decrease associated with steam production are outlined by the 500 psi isobar of Lipman and others (1977).

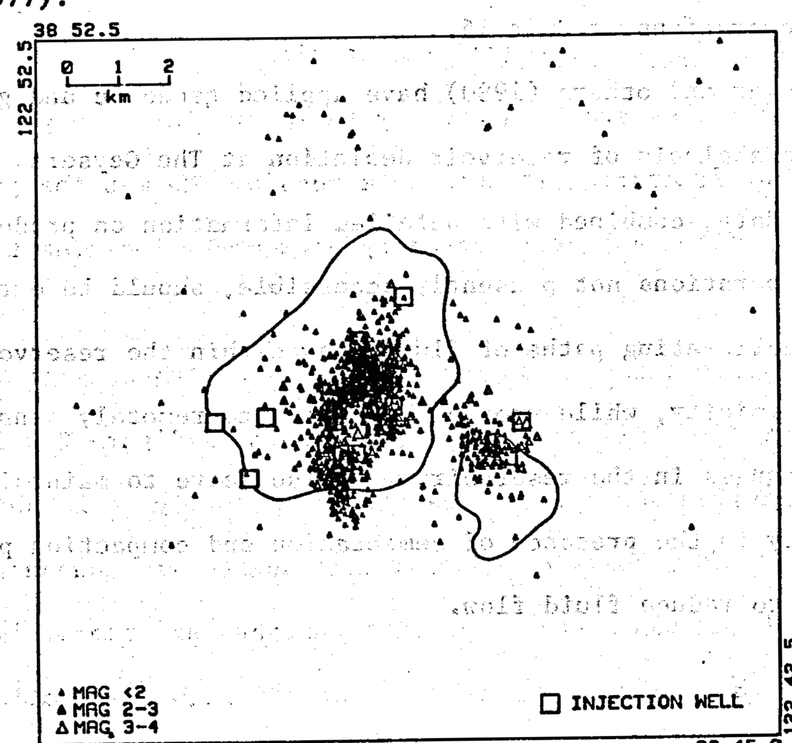

Fig. 2B. Distribution of larger (M ≥ 1), deeper (depth range 2 to 5 km) earthquakes at The Geysers. Injection wells are also shown. The zones of fluid pressure decrease associated with steam production are outlined by the 500 psi isobar of Lipman and others (1977).

Particularly interesting is the north-south trending crescent-shaped zone of hypocenters which extends southward beyond the region of known pressure decline.

Early in 1980 location of smaller earthquakes became feasible using arrival times from the USGS automatic seismic processor in Menlo Park. In Figure 3 we show the distribution of earthquakes ($M \geq 0.5$) at The Geysers during April-June 1980. Also shown are the zones of decreased fluid pressure and locations of injection wells. In several instances earthquakes cluster near the wells which most recently began injecting. The cluster near the southwesternmost injection well is new and lies outside the zone of previous seismicity, although within the boundaries of the pressure sink. This new cluster is believed to be the result of production and injection operations at Unit 15.

Denlinger and others (1980) have applied geodetic and gravity data to the analysis of reservoir depletion at The Geysers. Earthquake data, combined with detailed information on production and injection operations not presently accessible, should be extremely useful in delineating paths of fluid flow within the reservoir. Induced seismicity, while providing a means to remotely sense physical changes in the reservoir, may also serve to maintain permeability in the presence of cementation and compaction processes which tend to reduce fluid flow.

Acknowledgment

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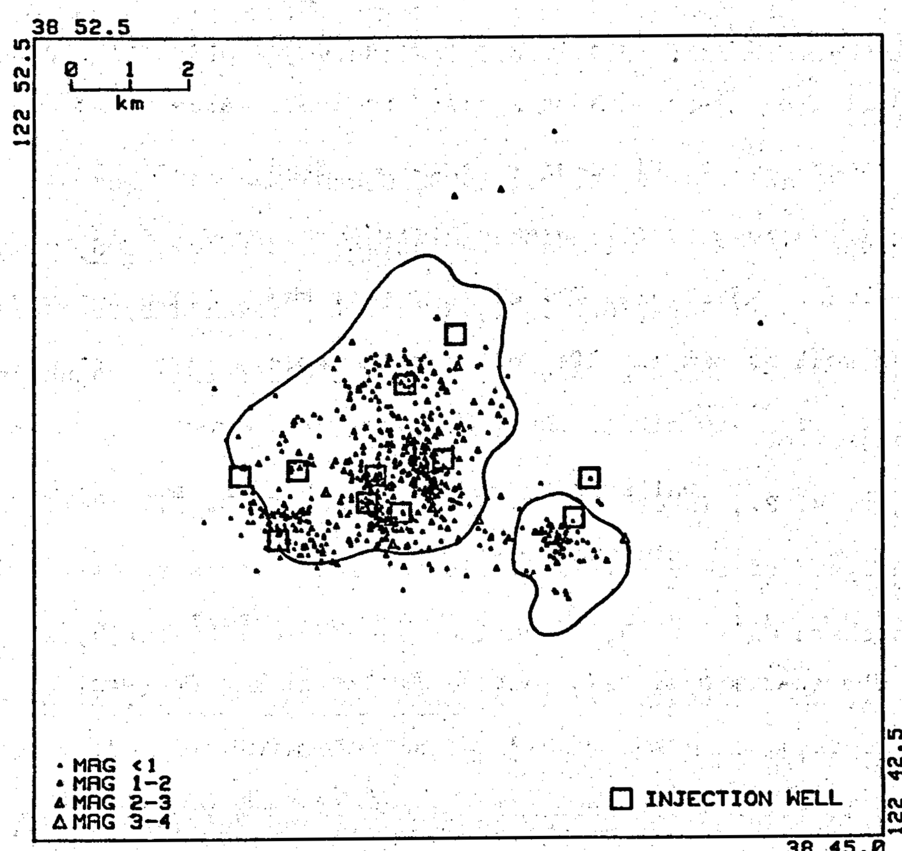

Fig. 3. Distribution of earthquakes (M $\geq$ 0), at The Geysers, April-June 1980. Locations are based on arrivals picked automatically by USGS real-time seismic processor. During this period injection had been suspended at the northernmost injection well and the easternmost injection well. The zones of fluid pressure decrease associated with steam production are outlined by the 500 psi isobar of Lipman and others (1977).

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