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NEW EVIDENCE OF THE CAUSATIVE RELATIONSHIP BETWEEN WELL INJECTION AND MICROSEISMICITY IN THE GEYSERS GEOTHERMAL FIELD

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ABSTRACT

A new analysis demonstrates a rough correlation between microseismicity with focal depths ≥ 2 km and injection in one well located in the southeastern portion of the Geysers geothermal field (in and near Unit 13), confirming what Stark (1990) has shown for the area to the northwest. The abrupt onset of microseismicity near well McKinley-5 early in 1980 follows the initiation of injection there by about three months. Until 1986, injection and numbers of earthquakes within 3000 feet of this well appear to be roughly correlated, with injection increases or decreases leading the rise or fall of microearthquake numbers. For the years after 1986, there seems to be no correlation between earthquake frequency and injection; this may be due to the overall decline of injection volumes in the well. A similar analysis was conducted for well Thorne-7, but no correlation is evident. However, after the start-up of injection in 1984, microseismicity near this well did become more continuous from month to month.

This article also presents a concise review of previous work on the subject of induced microseismicity in the Geysers geothermal field. It appears that both fluid injection and withdrawal trigger microseismicity, but that injection, on balance, triggers deeper events than does production. Causative mechanisms for triggering are also reviewed.

INTRODUCTION

The work of several researchers (especially that of Stark, 1990) has established that injection, as well as production, of geothermal fluids triggers large numbers of microearthquakes (defined as earthquakes of magnitude 3 or less) in The Geysers geothermal field (GGF). Some 300,000 microearthquakes took place during the period 1975-1992. Also, hundreds of small earthquakes with magnitudes from 3 to 4.2 appear to have been induced in the GGF. Figure 1 is a regional map showing epicenters of shocks with M ≥ 1.5 and regional faults with Quaternary, Holocene, and historic displacement.

This article reviews available seismicity data and previous work on induced seismicity in the GGF, and presents a new analysis demonstrating induced microseismicity in the southeastern part of the GGF. All data used are in the public domain. The new results offer further confirmation of the correlation between injection and microseismicity described by Stark (1990) for the central and northern parts of the GGF.

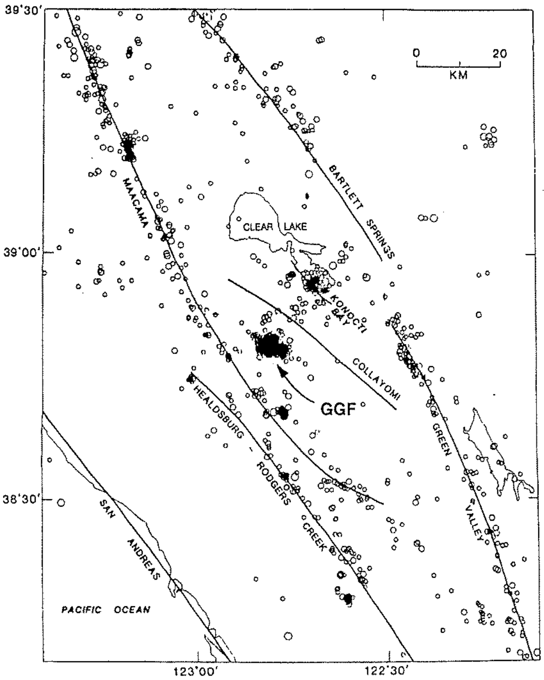

Figure 1: **Map showing regional faults and seismicity, Mc ≥ 1.5, March 1972-December 1981 (adapted from Eberhart-Phillips, 1988).**

SEISMICITY DATA

Seismicity associated with development of the GGF was not investigated until 1972 because seismographic networks did not have the capability to locate microearthquakes there before that time. Before 1972, the only seismographic network in the region was operated by the Seismographic Station of U.C. Berkeley, and the station nearest to the GGF was located at Calistoga, about 30 km to the south. The smallest earthquakes whose epicenters could be located in the area had magnitude of nearly 3. However, numerous unlocated epicenters of M ≥ 2 microearthquakes within 60 km of the Calistoga station were recorded at Calistoga between 1962 and 1977, and it is believed that many of the pre-1972 events, as well as later ones, had epicenters in the GGF. The rate of occurrence of shocks recorded at Calistoga during 1975-1977 was nearly twice that recorded during 1962-1963, and this has been related to increased power production in the GGF, as discussed below.

By 1972, the highly sensitive seismographic network operated by the U.S. Geological Survey in northern California (CALNET) was routinely providing hypocentral locations (epicenters and focal depths) of many (but not all) shocks with Mc ≥ 1 in the GGF (Bufe and Ludwin, 1980). In 1975, CALNET's capability in the GGF was greatly increased by the addition of four new stations located at the periphery of the field. With this enhancement CALNET (and the computer system used to process its data) began to provide hypocentral locations of all shocks with M ≥ 1.2 (Oppenheimer, 1986). Since 1975, CALNET hypocentral coordinates have typically had a horizontal precision of around 0.4 km (1,300 feet) and a vertical precision of 0.6 km (2,100 feet). Figure 1 shows earthquakes with M ≥ 1.5 in the GGF and Clear Lake Basin, as well as surrounding region, and reveals dense clusters of microseismicity in these two regions.

Plots of GGF epicenters for the three periods 1976-1980, 1981-1985 and 1986-1990 (David Oppenheimer, personal communication, March 1993) were examined and very clearly show the southeastward development of seismicity in response to progressive step-out of geothermal exploitation in the same direction. Figure 2 is a histogram (also provided by Oppenheimer) showing annual numbers of shocks in the GGF from 1975 to 1991. It reveals a major increase in seismicity from 1975 to 1983, accompanying the large increase in steam production in the GGF.

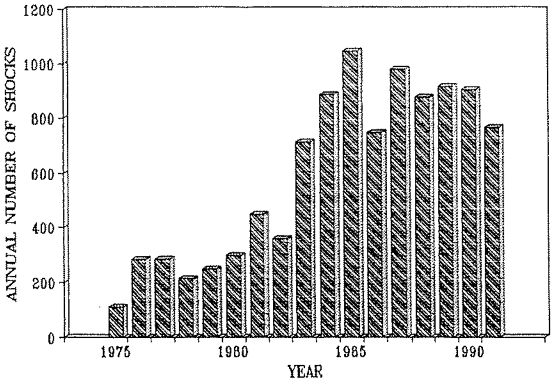

Figure 2: **Histogram showing annual numbers of shocks with Mc ≥ 1.4 occurring in the GGF, 1975-1991 (data from USGS).**

Since 1972, only four earthquakes have had M ≥ 4.0 (up to 4.4); these occurred in the years 1982, 1984, 1990, and 1992. The two largest shocks on record for the GGF had M 4.2 (8/18/90) and M 4.4 (9/19/92).

PREVIOUS INVESTIGATIONS OF INDUCED SEISMICITY

Bufe and Ludwin (1980) were the first researchers to investigate features of seismicity in the GGF over a long period of time (the eight-year period from January 1972 to April 1980). Their work related hypocenter locations of thousands of shocks to locations of production and injection wells and examined temporal variations and spatial clustering of seismicity, relating these to the onset of production serving two power plants.

Their study reached several important and fundamental conclusions, as follows: 1) two clusters of seismicity persisted through the period 1975-1980 and coincided with the most heavily exploited area of the steam field; 2) focal depths ranged from near-surface to 5 km (16,000 feet); and 3) steam production and seismicity are spatially correlated. The two largest earthquakes between May 1975 and December 1978 had magnitude (M) 3.8 (12/22/76) and 3.5 (9/22/77). These were centered near the two injection wells (DX-7 and LF-3) most distant from production wells, suggesting a link between fluid injection and larger shocks. Initiation of steam production for Unit 15 in June 1979 was attended by an increase in seismicity within two weeks; this appeared in a tight cluster about 0.5 km north of injection well PEC A-6. Between 1972 and 1977, the size of the largest annual shocks increased from M 3.1 to M 3.8, paralleling the increase of steam production. In addition, the largest shocks tended to occur between October and January, as contrasted with the biannual maxima of daily numbers of shocks which occurred in January-February and July-August. The late fall-early winter occurrence of larger shocks may be related to the seasonal increase in mean sky cover and monthly precipitation, which causes an increase in the volume of steam condensed and injected. Fault-plane solutions indicated the occurrence of strike-slip, normal, and thrust faulting, with strike-slip predominant, revealing great heterogeneity in the local stress field. However, maximum and minimum horizontal compressive stress orientations averaged NNE and WNW, respectively, in accord with the regional stress pattern.

In 1984, Eberhart-Phillips and Oppenheimer published a important paper concerning induced seismicity at the GGF. Their conclusions were based on data for 7,215 relocated earthquakes recorded during the period from May 1975 to February 1982. Their conclusions were similar to those of Bufe and Ludwin (1980), but new findings included the following. Clustering of microseismicity near production wells is even more apparent than in earlier studies and aseismic areas within the GGF correlate with the local absence of geothermal production. All hypocenter clusters lie within or below production areas, but not all wells have nearby clusters. Earthquakes are deepest in the areas of oldest production. The sharp southwestern boundary of seismicity appears to be structurally controlled by the northeast-dipping Mercuryville thrust fault. Statistical cross-correlations between monthly numbers of shocks and monthly volumes of steam produced and fluid injected for several wells show no consistent correlation between injection and seismicity, nor between steam withdrawal and seismicity for wells in production longer than seven years.

However, the correlograms for injection and seismicity for seven wells have been reviewed by this writer, and it is concluded that significant correlation exists between injection and seismicity for three of the injectors (DX8, HJ9, and GDC53-13). The fact that the other four injectors do not show such correlation may be an artifact of the spatial volumes used to select shocks for correlation (vertical cylinders centered on wellheads with a radius of 1 km). According to Stark (1990), it appears that the clustering of shocks near injection wells is evident only for depths greater than around 2 km.

Stark (1990), of Unocal Geothermal Division, published an article demonstrating that injection causes the deeper induced earthquakes observed in Unocal's portion of the GGF; he principally utilized data obtained with Unocal's seismographic network at the GGF. Earthquake clusters associated with injection wells form a rough three-dimensional image of injected liquid. He shows that the spatial correlation is obvious only in seismicity deeper than about 4,000 feet below sea level. Temporal correlation between the onset of injection and seismicity is generally clear and has been observed in about ten cases, for several injection wells. Some seismicity clusters extend rather far, as much as 4,000 feet, from injection wells. Isotopic analysis shows that the flashed injectate is "heavier" than the native steam/water and that steam wells producing a significant percentage of "heavy" steam coincide with these extended earthquake clusters. Also, some of these clusters are found in zones where reservoir pressure is higher than in the nearby injectors. Stark concluded that this seismicity occurs where injected water flows as a liquid driven by gravity or hydraulic pressure. He noted that not all injection is accompanied by seismicity, and that some seismicity, especially the shallower portion, appears to be more closely related to steam production.

INDUCED SEISMICITY IN THE SOUTHEASTERN GGF

Epicenters of 1,048 microearthquakes (all magnitudes) with focal depths greater than 2 km in the southern GGF are shown in Figure 3 (data provided by David Oppenheimer, personal communication, March 1993); also shown are the traces of the eight injection wells known to exist in the area shown (data provided by Ali Khan, California Division of Oil and Gas (CDOG), personal communication, March 1993). It can be seen that there are just two dense clusters of epicenters: one in the central portion of the map, extending from the north-central part of Unit 13 to the southern end of West Ford Flat; the other one is located in the northwest corner of the map area. This second cluster is within the area investigated by Stark (1990), which extended south into Unit 18; however, only a handful of shocks occurred there during the period covered by his work (November 1988 to August 1989).

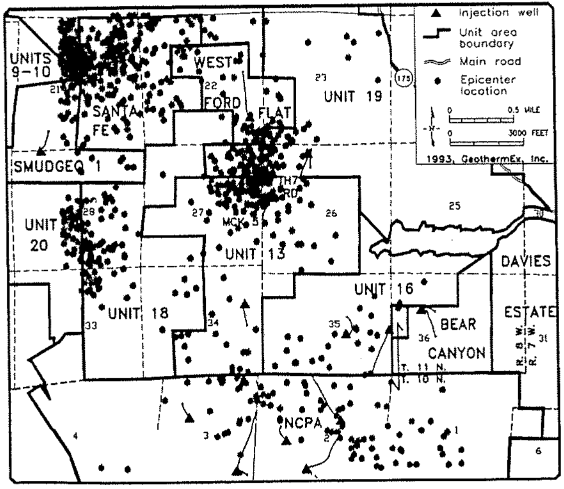

Figure 3: Map showing epicenters of earthquakes M ≥ 0.7 and depth greater than 2 km in the southern GGF, 1975-1992 (data from USGS).

We focus our attention on the central epicenter cluster, which contains well over 230 events at focal depths ≥ 2 km. This is flanked by two injection wells: TH-7RD (Thorne 7 redrill), on the east, and MCK-5 (McKinley 5), on the south. Monthly injection data were made available for both of these injection wells (Ali Khan, CDOG, personal communication, March 1993; Joe Beale, Calpine, personal communication, May 1993). The CDOG data were checked against the Calpine data (after conversion of the latter from barrels to metric tons), and it appeared that the injection volumes given by CDOG for TH-7RD were much too small; thus, the Calpine data were utilized (Joe Beale, personal communication, May 1993) for TH-7RD. Beale also pointed out that wells MCK-5 and TH-7RD together have performed all injection within Unit 13.

Figure 4 compares monthly counts of earthquakes within the central epicenter cluster (depth ≥ 2 km), to a distance of 3,000 feet from MCK-5, with monthly fluid mass injected in well MCK-5. The entire history of injection in MCK-5 is shown, beginning early in 1980 and running through 1992. A rough correlation between injection and seismicity may be seen for the period 1980 to 1984. The U.S.G.S. seismic database, which includes events from 1974 onwards, shows no events occurring in this area prior to 1980. The abrupt onset of injection in early 1980 was followed by the initiation of seismicity within three months; injection was variable but had a relatively high average through 1983, and was accompanied by low to moderate seismicity. The three-month cessation of injection in MCK-5 early in 1984, followed by an abrupt resumption, appears to immediately precede the largest monthly number of shocks (10) in the search area. In late 1984 to early 1985, average monthly injection declined, but seismicity continued at a moderate rate into early 1986, and then ceased until late in 1987. This 1-1/2-year-long cessation of seismicity may possibly have been the result of declining injection. Since 1988, the low level of continuing seismicity has exhibited no correlation with injection, but that might be explained by the fact that injection was occurring only in

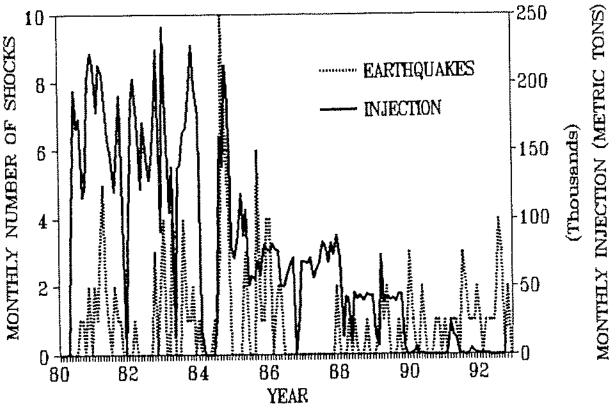

Figure 4: Comparison of monthly injection in well MCK-5 and earthquake frequency within 3,000 feet of the well (all reported shocks, depths ≥ 2 km)

relatively small amounts (from zero to less than 50,000 metric tons per month).

Figure 5 compares injection in well TH-7RD with seismicity (focal depths ≥ 2 km) up to 2000 feet to its west, and no correlation is evident. However, one may see that after the beginning of injection late in 1984, the rate of occurrence of microearthquakes became more continuous than it had been previously, and it is possible that these are related occurrences.

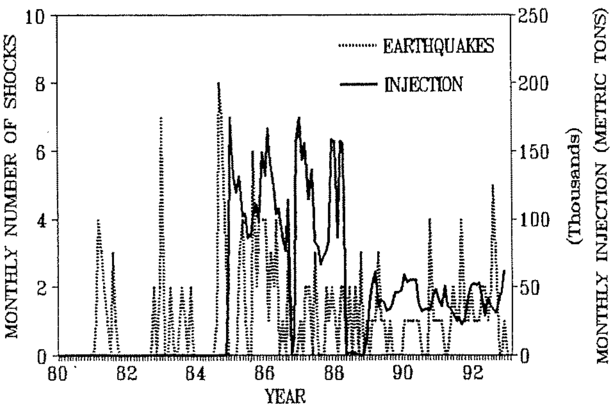

Figure 5: **Comparison of monthly injection in well TH-7RD and earthquake frequency within 3,000 feet of the well (all reported shocks, depths ≥ 2 km)**

Another injection well, 958-6, is located in the southeastern corner of Unit 16. Although large volumes have been injected into this well in every month (150,000 to more than 200,000 metric tons per month) since mid-1986, only weak clustering of seismicity can be seen near it (Figure 3). However, it seems that seismicity in this area began to increase early in 1993 (Joe Beale, Calpine, personal communication, May 1993).

Enedy and others (1993) documented the occurrence of microseismicity within NCPA's operating area in the southeastern GGF for the first six months of 1992. They noted the general spatial correlation of microseismicity with locations of five NCPA injection wells, and that hypocenters are rarely deeper than the bottom of the wells' injection intervals. They interpreted this to mean that injectate is not migrating to greater depths within the reservoir.

CAUSATIVE MECHANISMS

Causative mechanisms, that is, rock mechanical principles, for seismicity induced by fluid injection are discussed briefly here. If fluid is injected into reservoir rocks at a pressure that locally exceeds ambient fluid pressure, the increase of pore pressure causes a decrease of effective normal stress across fractures. According to the well known Hubbert-Rubey theory, this phenomenon may cause brittle failure along fractures which are already stressed close to failure; a brittle-failure event radiates elastic waves (an earthquake). While several investigators have considered this process as possible in the GGF, some have doubted that injection would actually lead to local increase of pore pressure. Denlinger and Bufe (1982) point out that reinjected condensate flows into the reservoir under its own weight and that production well pressures in the permeable fracture systems are some 50 to 200 bars (atmospheres) lower than the hydrostat (pressure based upon a column of water standing to surface elevation). Stark (1990) counters this argument, noting that there is hydrostatic overpressure at the bottom of an injection well, because water therein typically stands hundreds to thousands of feet above total depth. For this reason, the overpressure due to injection may easily amount to tens of bars (100s of psia).

Another means by which injection may induce brittle failure is by cooling of rock adjacent to fractures, which reduces the normal stress across them; again, the Hubbert-Rubey theory applies. Finally, the mass loading of injectate may increase the vertical stress, and hence the shear stress across dipping fractures, in underlying rocks.

Withdrawal of reservoir steam and accompanying volumetric contraction (due to temperature and pressure declines) can induce brittle failure by means of two principal mechanisms: (1) it may reduce normal stress across fractures; or (2) it may increase shear strength by closing of fractures. The first mechanism relies yet again on the Hubbert-Rubey theory, while the second presumes that, in their virgin state, reservoir rocks were too weak to sustain brittle fracture, and deformation then occurred only aseismically, by creep. Volume decrease may also produce local, indeterminate stress perturbations which locally trigger brittle fracture. Increase of shear strength of reservoir rocks may also result from mineral deposition in fractures, due to phase separation of the fluid as it is withdrawn. Analysis of geodetic and gravity data has shown significant land subsidence and contraction of reservoir rocks, that is, overall volumetric contraction, at the GGF (Denlinger and others, 1981; Oppenheimer, 1986).

CONCLUSIONS

Available data and previous investigations demonstrate that induced seismicity at the GGF is caused both by production and injection of geothermal fluid, which perturb the natural stress regime and/or rock strength, triggering numerous microearthquakes. Production appears to be the primary cause of shallow seismicity (above a depth of around 2 km), while injection appear as the prime cause of deeper shocks. On the whole, seismicity of the GGF has fault mechanics very similar to that of the entire region, extending throughout the northern Coast Ranges.

New analyses of the relationship between microseismicity and fluid injection in the southeastern Geysers geothermal field (GGF) presented herein suggest that injection triggers nearby microseismicity. The work of Enedy and others (1993) corroborates this interpretation. The fact that relatively little seismicity appeared through 1992 in the GGF to the southeast of Unit 13 may be due to the relative immaturity of development in this part of the field.

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