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Microearthquakes in the Southeast Geysers Before and After SEGEP Injection

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ABSTRACT

Microearthquake (MEQ) activity in the southeastern portion of The Geysers geothermal field was monitored before and after the November 1997 start-up of the Southeast Geysers Effluent Pipeline (SEGEP), covering the time interval January 1995 through February 1999. SEGEP has more than doubled Southeast Geysers injection rates, significantly mitigating steam production decline. Injection-induced seismicity was observed both before and after the SEGEP startup. For MEQ's of magnitude (M) ≤ 2.0 the rate of occurrence, as measured by a shift in b-slope, increased by about 40% after SEGEP start-up. For $M > 2.0$ there was no discernable change in activity, with about 4 events per year recorded both before and after SEGEP. The largest events recorded, $M = 2.6$ and 2.4, occurred over a year prior to SEGEP. The absence of a correlation in the $M \geq 2.0$ range is consistent with previous analyses of injection-induced seismicity both at The Geysers and at Larderello field, Italy. These observations suggest a magnitude ceiling for injection-induced seismicity at both steamfields.

Introduction

In November 1997 the Southeast Geysers Effluent Pipeline (SEGEP) commenced operation, importing a mixture of lake water and treated waste water for the purpose of mitigating production decline through increased water injection. A 21-station seismic network, in operation since 1989, monitored microearthquake (MEQ) activity before and after the start-up of SEGEP, providing a unique opportunity to observe the seismic response to a major increase in injection.

At The Geysers geothermal field, induced seismicity has been studied since the early 1970's, and a number of production-related and injection-related triggering mechanisms have been proposed. Hamilton and Muffler (1972) were among the first to study Geysers MEQ's, at a time when installed generating capacity was 82 MW. Deploying a local seven-station array for three weeks in 1971, they recorded 53 events. All but one had magnitudes (M) estimated at less than 0.0. The events were clustered around the production and injection wells.

By 1982, production capacity in The Geysers had expanded to over 1000 MW, fed by steam produced from a greatly expanded area of steam wells. Eberhart-Phillips and Oppenheimer (1984) documented a dramatic increase in seismicity since the early years of production, and showed that, in general, MEQ activity began in newly producing areas of the steamfield within a few months of start-up of the associated power plant. Marks *et al.*, (1978) suggested that the frequency of MEQ events of $M > 2.0$ had also increased.

Oppenheimer (1986) analyzed the stress field determined from the MEQ data, concluding that below a depth of 1 km the steamfield area was undergoing extension perpendicular to a NNE axis with an azimuth of 15°. He noted that this direction was consistent with the regional tectonic stress field, implying that stresses developed in the steam reservoir are small relative to the magnitude of the regional stress field. Oppenheimer also noted a tendency for seismicity to propagate downward over time.

Two likely mechanisms of induced seismicity were suggested by Oppenheimer: 1) conversion from aseismic slip (i.e. creep) to seismic slip caused by rock embrittlement due to mineralization (proposed by Allis, 1982), and 2) increased shear stresses due to reservoir contraction, either as a result of decreased pore pressure or thermal contraction due to cooling. The Hubbert and Rubey (1959) mechanism of injection-induced seismicity, which depends on increasing pore pressures, and hence decreasing effective normal stress, was discounted for The Geysers by Eberhart-Phillips and Oppenheimer (1984). They considered it unlikely that sufficient fluid pressure was generated, because the injection wells accept water without pumping, under partial vacuum. Stark (1991) presented temporal and spatial correlations supporting injection-induced seismicity at relatively deep levels (>7000') beneath the field, suggesting that as many as half of the events in the field might be induced by injection. He suggested that the Hubbert-Rubey mechanism might apply, because even under partial vacuum injection conditions, Geysers injection wells develop a stable water level above the bottom of the well bore, creating hydraulic head at least to the bottom of the wellbore. Moreover, water breakthrough from injection to production wells is occasionally observed, establishing that some fractures become water-filled and that formation hydraulic pressures could be increased due to injection wells. Alternatively, in a proposed mechanism similar to the Hubbert-Rubey, cooling of fracture surfaces exposed to injected water could expand the fracture apertures, thereby reducing normal stress across the fractures and triggering MEQ's. This alternative mechanism was later quantified by Mossop and Segall (1997), who calculated that it could be the dominant mechanism of injection-induced seismicity fieldwide. In the highly fractured and tectonically stressed Geysers region, even small injection-related stress changes, of any origin, might be sufficient to "nudge" an existing fracture or fault to the failure threshold.

Regardless of the mechanism, Barker *et al.*, (1995) presented evidence that the spatial and temporal correlations between injection and MEQ's degrade markedly for events of magnitude > 2.0, suggesting a possible magnitude limit for injection-induced MEQ's. Similar evidence had been presented by Batini *et al* (1985) for injection-induced seismicity at the Larderello steamfield in Italy.

In 1987 steam production in The Geysers peaked and has subsequently declined. During the last decade, Geysers steamfield operators have implemented the strategic use of injection to sustain reservoir pressure and steam flow (Enedy, *et al.*, 1991; Goyal and Box, 1992; Beall, 1993). This endeavor is particularly important because The Geysers is a vapor dominated field and, as a consequence of evaporative losses in the cooling towers, only about 25% of the produced mass of steam is available (as power plant condensate) for injection. The effort to obtain more water for injection culminated in 1997 with the start-up of SEGEP. A mixture of wastewater and lake water is transported 29 miles from the community of Clear Lake to The Geysers. Since November 1997, SEGEP has, with few interruptions, more than doubled the rate of injection in The Southeast Geysers from approximately 1.6 to 3.6 billion pounds per month (12-month averages) (Figure 8, page 256). This has led to significant mitigation of steam production decline.

Because of the documented history of injection-induced MEQ's, there is concern as to whether this increase in injection could cause larger, possibly damaging earthquakes. The current study examines the seismic activity of the Southeast Geysers area over a period extending from 34 months prior, to 16 months after, the initiation of continuous, high rate SEGEP injection (approximately November 1, 1997).

Seismic Array

In 1988 Unocal expanded its triggered, telemetered seismic monitoring array, operated since 1985, to a 21-station fieldwide array. The expanded array includes six stations within the Southeast Geysers, with an average spacing of about 1.5 miles (Figures 3 and 4). All events recorded are normally auto-located using computer-generated picks of P wave arrivals. For events originating in the Southeast Geysers area, P and S arrivals are hand picked to maximize hypocentral precision. On the average, locations are accurate to within about 500 feet horizontally and 1000 feet vertically. Coda magnitudes are estimated using the empirically-derived formula $M = 2.0 * \log D - 0.87$, where D is the measured coda duration in seconds (Lee and Stewart, 1981).

During the period January 1995 through October 1997, Southeast Geysers injection and production rates were fairly stable, except for normal seasonal fluctuations (Figure 7, Page 256). Consequently this time period was chosen to represent pre-SEGEP seismicity. For the post-SEGEP time period, the cutoff month of February 1999 was determined by the most recent MEQ data available.

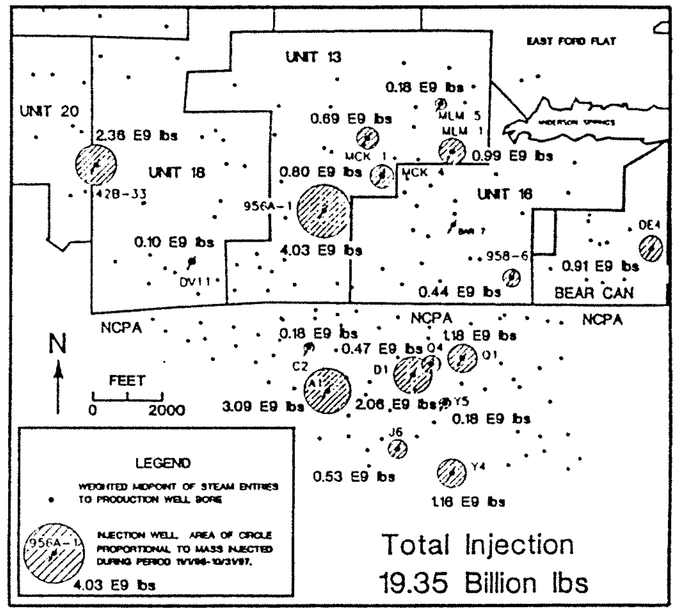

Figure 1. Map illlustrating the mass of water injected into each injection well in the Southeast Geysers during the period 11/1/96-10/31/97

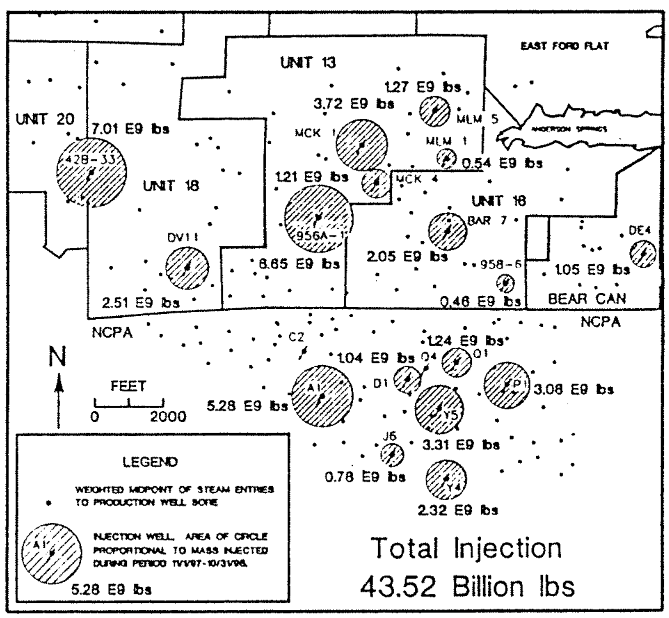

Figure 2. Map illlustrating the mass of water injected into each injection well in the Southeast Geysers during the period 11/1/97-10/31/98.

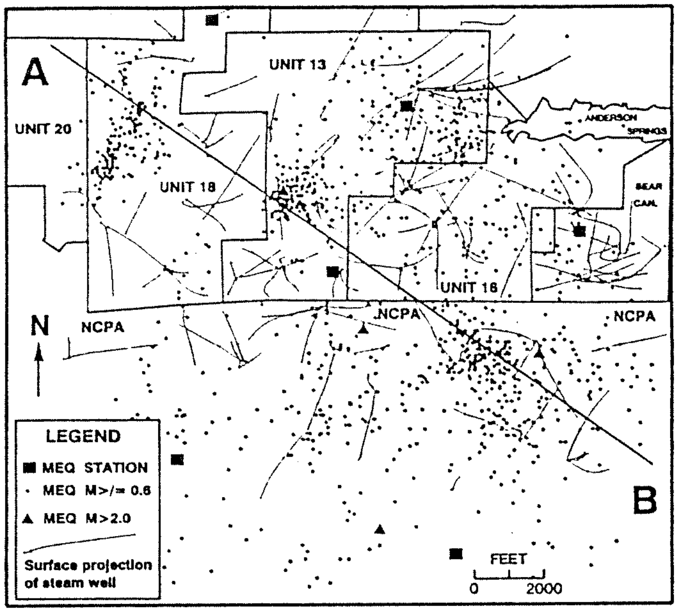

Figure 3. MEQ's (M>/=0.6) in the Southeast Geyser: seismic monitoring area during the period 11/1/96-10/31/97. Triangles represent MEQ's with M>2.0.

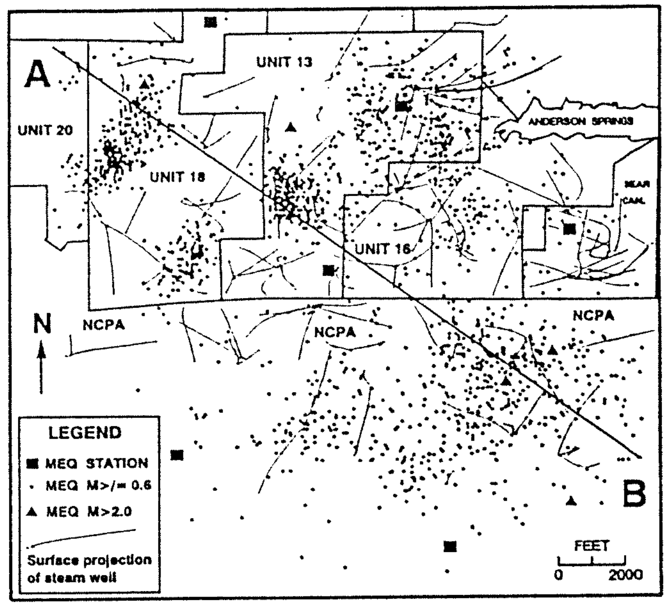

Figure 4. MEQ's (M>/=0.6) in the Southeast Geyser: seismic monitoring area during the period 11/1/97-10/31/98. Triangles represent MEQ's with M>2.0.

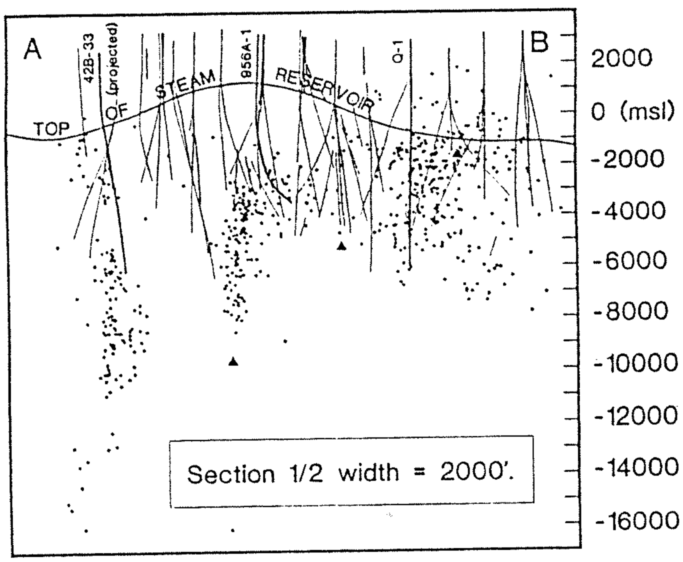

Figure 5. Cross section A-B of Figure 3 showing MEQ's during the period 11/1/96-10/31/97. Elevations are in feet (msl datum). Triangles indicate M>2.0.

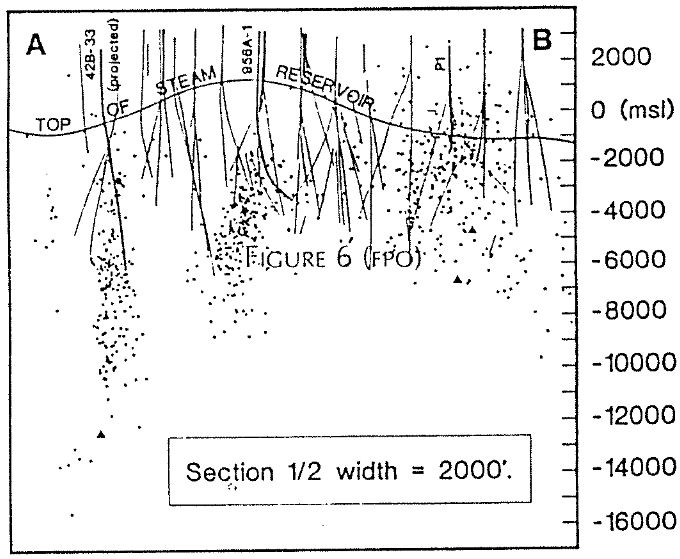

Figure 6. Cross section A-B of Figure 4 showing MEQ's during the period 11/1/97-10/31/98. Elevations are in feet (msl datum). Triangles indicate M>2.0.

Relationship Between Injection, Production, and Seismicity

Figures 1 and 2 show the locations of Southeast Geysers injection and production wells and illustrate graphically the injection rates for the 12 months before and after SEGEP start-up. Figures 3 and 4 show the MEQ epicenters ($M \geq 0.6$) recorded during those equal duration time periods. Average injection rates in the SE Geysers before and after SEGEP start-up were 1.6 billion lbs per month and 3.6 billion lbs per month, respectively. From these maps it is clear that distinct clusters of MEQ's were associated with some, but not all, injection wells. In Figure 3 prominent MEQ clusters extend northeast from injector 42B-33 (the western-most injection well), and westward from injector 956A-1 (southern Unit 13 area). Other injection wells, such as A1 (NCPA area), are not clearly associated with a concentration of MEQ's. In Figure 4 similar clusters appear, along with a new cluster associated with DV11 (southern Unit 18 area). In the pre-SEGEP period there was little injection into DV11 and few MEQ's associated with it (Figure 3). In both

Figures 3 and 4, events of magnitude > 2.0 are shown as large triangles, which are far less numerous than lower magnitude events. Some of the M > 2.0 events were located in the injection-related clusters, but the spatial association with injectors is not as obvious as with the M ≤ 2.0 events.

Figures 5 and 6 are cross-sections along line A-B of Figures 3 and 4, respectively, showing wellcourses, MEQ's and the upper limit of the steam reservoir. In both sections the MEQ concentration associated with 42B-33 extends about 16,000 feet below sea level and defines a nearly vertical fault zone. Immediately to the southeast, a seismic "gap" exists (both sections). The MEQ cluster associated with injection well 956A-1 (southern Unit 13 area) also appears to define a vertical zone extending to greater depths than the wells. The southeast ends of the cross sections show more diffuse concentrations of MEQ's at generally shallower depths.

Figure 7 shows the monthly count of MEQ's of magnitude ≥ 0.6 recorded for the time period January 1995 through February 1999, compared against monthly Southeast Geysers injection and steam production totals. The plot clearly shows an increase in MEQ activity since the November 1997 SEGEP start-up.

Also apparent in Figure 7 are seasonal fluctuations of injection, production and seismicity. During wintertime more water is recovered for injection due to increased rainfall and increased retention of cooling tower condensate. Steam production fluctuations are generally governed by power market demand and plant overhaul schedules. The seasonal peaks in MEQ activity appear to be controlled by some combination of these production and injection cycles.

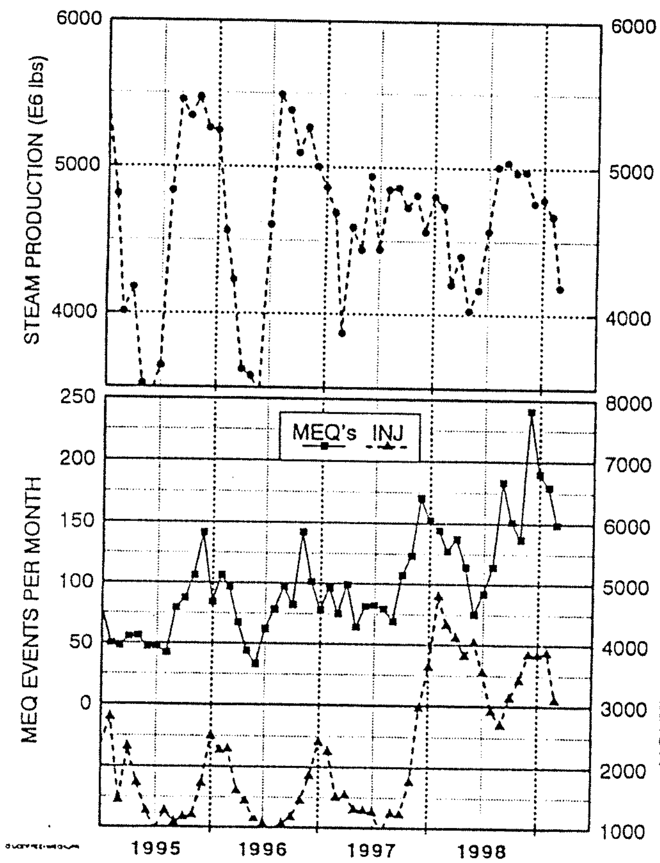

Figure 7. Monthly MEQ's (M>0.5), Steam Production and Injection

In summary, Southeast Geysers MEQ activity shows a temporal correlation with both injection and production, and a strong spatial correlation with injection, but only a diffuse spatial correlation with production. This is not surprising, because injection wells are much less numerous, while production wells are distributed throughout the steamfield. Moreover, injecting cold water under hydraulic head into a hot, underpressured reservoir can be expected to cause an immediate and local impact on formation stability, regardless of the specific MEQ triggering mechanism assumed. Steam production, on the other hand, causes a broad decline in reservoir pressure that is not strongly tied to the individual production wells, so the production-triggered MEQ's can be expected to occur in a more spatially diffuse pattern.

MEQ Magnitudes vs. Frequency

Empirical seismological observations worldwide have shown that, in general, the number of earthquakes per unit time increases approximately tenfold for each unit decrease in magnitude (Lee and Stewart, 1981). Consequently, the greater the array sensitivity to smaller events, the greater the number of seismic events which can be recorded in a given time period.

Figure 8 shows the magnitude versus frequency distribution in the Southeast Geysers for the pre- and post-SEGEP time intervals. Following seismological convention, magnitude values (x-axis) are plotted versus the log of the cumulative number events of that magnitude or greater (y-axis). The slope of the linear regression is known as the b-slope. The event counts are normalized to a per-year basis, to facilitate comparison between the rates of occurrence pre- and post-SEGEP.

At the smallest magnitudes, the flattening b-slope trends reflect the failure of the array to fully detect such small events, indicating a complete detection threshold of about M = 0.6. For the larger events of M > 2.0 the slope of the data points appears to steepen, but there are too few events in that range to resolve a b-slope regression. Between these extremes, roughly linear trends are observed. A b-slope of 1.0 is typical of worldwide seismic observations. The higher SE Geysers values of b ~ 1.6 (both pre- and post-SEGEP) suggest that this population of

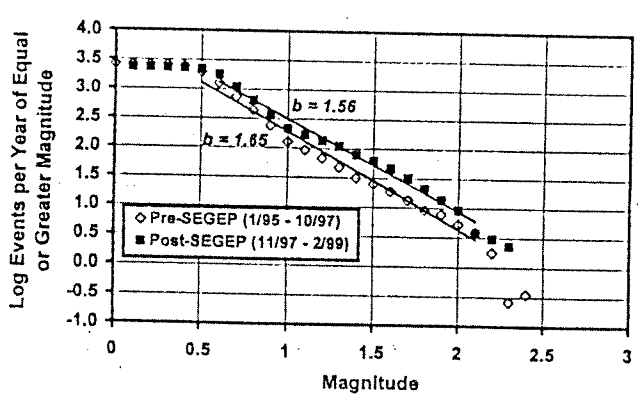

Figure 8. Southeast Geysers b Plot

events is relatively enriched in smaller MEQ's. However, the Unocal magnitude calculation is not calibrated to standard Richter magnitudes, so the b-slope may be biased by the particular magnitude calculation used. In any case, there is no evidence for a change in the b-slope since SEGEP start-up.

Overall MEQ activity above the $M \geq 0.6$ threshold increased by 40%, from 1268 events per year pre-SEGEP to 1776 events per year post-SEGEP. During the entire study period (January 1995 - February 1999) there were 16 SE Geysers events of $M > 2.0$. Eleven of those occurred in the 34-month pre-SEGEP period, for an average rate of 3.9 per year. Five events of $M>2.0$ occurred in the 16-month post-SEGEP period, for an average rate of 3.8 per year. Thus, there has been no increase in the frequency of these larger events. Moreover, the very largest events occurred in the pre-SEGEP period: M=2.6 in October 1996 and M=2.4 in February 1996.

Summary and Conclusions

When the SEGEP project was completed, injection rates into the Southeast Geysers more than doubled. The increased injection has been accompanied by an increase in MEQ activity, but this increase is restricted to events of $M \leq 2.0$. Spatially, for wells where injection was increased, the associated increased seismicity tended to occur in the same general volume. New MEQ clusters were observed where new injection occurred.

Acknowledgements

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