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INDUCED SEISMICITY IN THE SE GEYSERS FIELD, CALIFORNIA, USA

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ABSTRACT

The expansion of geothermal development into the SE part of The Geysers field has been accompanied by the introduction of induced seismicity. Over 1000 microearthquake events are now recorded annually. One major cause appears to be injection, which results in the reservoir rock being rapidly cooled. A recent doubling in injection has increased by about 50% the number of M∗2.4 events being recorded, with no increase observed in M]2.5 events.

1. INTRODUCTION

The first power plant at The Geysers, PG&E Unit 1 (12 MW), began operating in 1960 near The Geysers Resort in what is now the NW part of The Geysers Field. During the 1960s and 1970s development was gradually expanded into the central part of the field. Seismic monitoring of The Geysers area began soon after the start of development. Lange and Westphal (1969) and Hamilton and Muffler (1972) indicated that the seismic events being recorded were shallow, less than 5km deep, almost exclusively microseismic (less than magnitude M=3.0) in nature, and strikingly localized to within only that part of the geothermal reservoir area then commercially developed. An initially observed rate of four events per day had increased to 25 to 30 per day by 1976 (Majer and McEvilly, 1979) as development was expanded.

In 1979 the USGS installed a permanent seismic array to continuously monitor The Geysers. Fig.1 shows the events of M]0.9 during 1979. Not one event occurred in the SE Geysers area in the year prior to the start of power generation.

2. DEVELOPMENT HISTORY OF THE SE GEYSERS

In 1974 the geothermal mineral rights owned by the U.S. federal government first became available for lease, thereby fully opening the SE Geysers area to exploration and development. The well drilling that quickly followed proved that the steam reservoir extended into this area. The first power plant began operating in 1980, followed with five additional plants by 1986, bringing the total generation capacity to 714 MW.

The history of the steam production and water injection related to the development of the SE Geysers generation capacity is illustrated by Fig.2. The level of steam production was incrementally increased as additional generation capacity became available. Production peaked at 101 billion pounds (4.6×10^7 metric tons) in 1987, one year after the final increment of generation capacity became operational. During the next two years steam production decreased 10% per year, despite the drilling of additional makeup wells. That decline rate was reduced to 5% per year from 1989 to 1996 by better resource management, with there being no production decline over the next two years.

The injection history seen in Fig.2 shows a similar trend. Until 1992 the only water generally available for injection was the condensate collected at the power plant cooling towers, so the injection volume was basically dependent on the amount of steam produced. Evaporative losses meant that only about 28% of the mass produced could be returned to the reservoir by injecting condensate. More recently, other sources of water have been created to maintain injection at a near constant level, up to the dramatic increase that took place in 1998.

In late 1997 the water injection and steam production history of this area was significantly changed by the startup of the SE Geysers Effluent Pipeline Project (SEGEP). As a result, injection was more than doubled in 1998, and steam production is no longer declining. Local reservoir pressures have increased with added injection-derived steam, allowing production to be increased from portions of the area.

3. INTRODUCTION OF INDUCED SEISMICITY

As shown in Fig.3, during the 1980-82 period immediately following startup of Unit #13, seismic activity was introduced with 80 microearthquake (MEQ) events of M]0.9, plus one event of M=3.1. These events were almost entirely in the northwestern part of the SE Geysers area, at that time the only part with continuous production and injection. As additional plants came on line and the production and injection area was expanded, the seismicity clearly increased over an enlarging area. During 1986-88 when steam production was greatest there were 293 events of M]0.9, with no event greater than M=2.8. During 1989-91 when steam production was most rapidly declining there were 557 events of M]0.9, including four events of M=3.0 to M=3.4, demonstrating that the yearly seismicity rate was neither proportional to the amount of steam produced, nor to the amount of injection taking place.

This phenomenon of expanding seismicity with increased development originally observed elsewhere in The Geysers has led seismologists (Everhart-Phillips and Oppenheimer, 1984; Oppenheimer, 1986; Preiss *et al*., 1996) to conclude there is a direct relationship between production and seismicity. But Stark (1990) and others have demonstrated there are spatial and temporal correlations between injection and MEQ seismicity at The Geysers, which become diminished at increasing magnitudes (Barker *et al*., 1995). A seismological study of the Larderello-Travale steam field in Italy by Batini *et al*., (1985) had previously reached the same conclusions, that injection induces MEQ activity, and that those MEQ events have a magnitude ceiling of about M=2.0.

Fig.4 plots the USGS record of seismicity in the SE Geysers area for the 21 years of 1979-1999, shown relative to the production and injection. Despite the changing production and injection trends, a relatively steady increase in the number of M]1.2 events is being observed, reaching 290 events in 1998.

4. RECENT SEISMICITY OBSERVED BY THE USGS

Fig.5 shows that the annual number of events of M]2.1 and M]2.3 continues to increase. However, the number of M]2.5 events has recently leveled from 1997 through 1999. The maximum magnitude event recorded each year still continues to generally increase, recently topping at M=3.8 in 1999.

In September 1997 the 29-mile long SE Geysers Effluent Pipeline (SEGEP) began to deliver additional water to assist in recharging the reservoir and to therefore produce more injection-derived steam. The pipeline is capable of delivering up to 9.5 million gallons (36,000 metric tons) of water per day. As shown in Fig.4, the amount of injection in the SE Geysers area was more than doubled in 1998 and 1999.

The locations of the events recorded by the USGS in the 12 months following the first full use of the pipeline in November 1997 are shown in Fig.6 (map) and Fig.7 (cross section). Clusters of events are seen near several of the active injection wells, which are identified on the cross section.

The USGS database documents many of the important characteristics of the seismicity at The Geysers, and it is universally accessible at http://quake.geo.berkeley.edu on the Internet. However, station spacing limits the effective recording threshold to about M=1.2, as events of lesser magnitude are not fully recorded. Consequently, additional seismic arrays have been operated to improve the recovery of the lower magnitude MEQ events that are important to reach a fuller understanding of the induced seismicity.

5. USE OF DETAILED SEISMIC ARRAYS

In 1985 Unocal began monitoring portions of The Geysers field with a detailed 16 station array of analog seismometers (Stark, 1990). In 1989 that array was expanded by an additional 5 stations to included all of the SE Geysers area as part of a cooperative program to jointly monitor and assess the effects of injection within an area of depleted steam resources. Because of the initial success (Enedy *et al*., 1991) and later expansion (Goyal and Box, 1992; Beall, 1993) of that injection program, the Unocal array has remained and has continuously recorded the detailed seismicity of the SE Geysers area over the past 10 years. The database of over 10,000 events has a magnitude threshold of M_u=0.6. The Unocal array magnitudes (M_u) are slightly different and are systematically about 0.3 to 0.5 less than the comparable USGS standard magnitudes.

More recently the Lawrence Berkeley National Laboratory installed a detailed network of 13 digital seismometers at the SE Geysers in 1993. Sponsored by the U.S. Department of Energy, that array was operated intermittently to early 1999, and has been used to advance research on the source mechanisms of the local events, etc. (Kirkpatrick *et al*., 1996).

The number of events per magnitude as observed by the USGS and by the Unocal array during a two-year period are plotted in Fig.8, with the Unocal magnitudes increased by 0.4 to better equate to the USGS scale. Both arrays similarly record all the events of M]1.5, but the Unocal array is also capable of recording all the events down to M=1.0.

The frequency of events of M]1.5 follows the worldwide "normal" trend, as the number of events increases about tenfold for each full unit decrease in magnitude (Lee and Stewart, 1981). The number of events of M∗1.5 observed by the Unocal array are shown to have occurred far more frequently than typically observed. Instead of about 200 events of M=1.0, based on a projection of the normal trend, there were more than 1000 during this period. This array becomes increasingly incapable of detecting events of magnitudes progressively less than M=1.0, and the recorded event totals decrease to zero by M=0.6. The maximum magnitude event observed from within the SE Geysers during this two-year period was M=3.2.

The monthly event totals observed by each array are compared in Fig.9 to the history of production and injection over a recent 55 month-long period. The large springtime reductions of steam production are the intentional result to limit power generation when inexpensive hydroelectric power is in surplus. The monthly injection totals have equally large variations, from summer minimums to maximums during the winter rainy season. The monthly changes in seismicity rates, as observed by both of these arrays, clearly appear to be more closely correlated with the changes in injection rates, rather than with steam production rates. The detailed array's more numerous results at lower magnitudes can be seen to better demonstrate this relationship.

6. CHANGE IN MEQ ACTIVITY ON SEGEP STARTUP

As shown in Fig.10, from November 1997 through October 1998, compared to the previous 12-month period, injection in the SE Geysers was increased from 18.44 billion lbs/yr. (8.4 $x10^6$ metric tons/A) to 42.47 billion lbs/yr. (19.3$x10^6$ MT/A) by the startup of SEGEP, as described by Beall *et al*., 1999.

The total seismicity recorded by the Unocal array during those same two 12-month periods is displayed in Figs.11 and 12 (from Beall *et al*., 1999). The number of events of M_u= 0.6 and greater increased by 52% from 1055 to 1599. During both time periods the MEQ clusters are particularly distinct around those injection wells located in the NW quadrant on this area. As seen near well DV-11, the large increase in injection was simultaneously accompanied by increased seismicity. The Fig.12 cross sections indicate that the MEQs occurred primarily within the depth interval of reservoir development. As seen also in Fig.7, in some cases they also extend to depths considerably below the injection wells, and this is most evident beneath the wells with the largest injection volumes (e.g. BEF42B-33).

7. CHARACTERIZING THE RECENT SEISMICITY

The "normal" trend line illustrated in Fig.8 represents the real tectonic events, caused by a lateral and/or vertical shear motion parallel to the fracture planes. These events have had a maximum USGS reported magnitude of 3.8 in the SE Geysers area, and of 4.3 elsewhere within The Geysers. The unusual abundance of events of magnitudes M<1.5 that were recorded by the Unocal array and plotted in Fig.8 may indicate that a second population of events also occurs that decreases in numbers more rapidly than normal toward increasing magnitudes. This second population can be visualized as those events that represent the area above the trend line in Fig.8, or about 90% of the events of M=0.5 to M=1.5 that occurred during this two-year period.

The MEQ events appear in the cross sections to follow the distribution of the water, even vertically beneath those injection wells where the water probably penetrates deepest before it boils to convert to steam. Consequently, these injection-related events probably result from the reservoir rock being cooled. The mechanism may in part be contraction-induced fracturing, or a form of spalling, with a component of movement being perpendicular to the fracture plane. The source mechanism study by Kirkpatrick *et al*., 1996 concluded that most of the MEQs studied from the SE Geysers area do have a small but significant component of volumetric strain.

8. SUMMARY AND CONCLUSIONS

The recent doubling of injection in the SE Geysers field has resulted in a 50% increase in low-level M∗2.4 MEQ activity, with no increase in M]2.5 activity. This pattern of increased seismicity, but at only lower magnitudes, is seen not only in proprietary data obtained with a detailed seismic array, as reported by Beall *et al*., 1999, but also in the public-domain data obtained and reported by the USGS.

9. ACKNOWLEDGEMENTS

We wish to express our appreciation to our respective employers for permission to publish these results.

REFERENCES

Barker, B.J., Koenig, B.A., and Stark, M.A. (1995). Water injection management for resource maximization; observations from 25 years at The Geysers, California. *Transactions*, World Geothermal Congress, Florence, Italy.

Batini, F., Console, R., and Luongo, G. (1985). Seismological Study of Larderello-Travale Geothermal Area. *Geothermics*, Vol.14, pp255-272.

Beall, J.J., (1993). The history of injection recovery in the Units 13 and 16 area of The Geysers steamfield. Geothermal Resources Council, *Transactions*, Vol.17, pp.211-214.

Beall, J.J., Stark, M.A., Smith, J.L.B., and Kirkpatrick, A. (1999). Microearthquakes in the SE Geysers before and after SEGEP injection. Geothermal Resources Council, *Transactions,* Vol.23, pp.253-257.

Eberhart-Phillips, D. and Oppenheimer, D.H., (1984). Induced seismicity in The Geysers geothermal area, California. *Journal of Geophysical Research*, Vol.89, pp.1191-1207.

Enedy, S., Enedy, K., and Manley, J. (1991). Reservoir response to injection in the Southeast Geysers. *Proceedings of the 16th Annual Workshop on Geothermal Reservoir Engineering*, Stanford University.

Goyal, K.P. and Box, W.T. Jr., (1992). Injection recovery based on production data in Unit 13 and 16 areas of The Geysers field. *Proceedings of the 17th Annual Workshop on Geothermal Reservoir Engineering*, Stanford University.

Hamilton, R.M. and Muffler, L.J.P. (1972). Microearthquakes at The Geysers geothermal area, California. *Journal of Geophysical Research*, Vol.77, pp.2081-2086.

Kirkpartick, A., Peterson, J.E. Jr, and Majer, E.L. (1996). Source mechanisms of microearthquakes at the Southeast Geysers geothermal field, California. *Proceedings of the 21th Annual Workshop on Geothermal Reservoir Engineering*, Stanford University.

Lange, A.L. and Westphal, W.H. (1969). Microearthquakes near The Geysers, Sonoma County, California. *Journal of Geophysical Research*, Vol.74, No. 19, pp.4377-4378.

Lee, W.H.K. and Stewart, S.W., (1981). Principles and Applications of Microearthquake Networks. In: *Advances in Geophysics, Supplement 2*. Academic Press, New York

Majer, E.L. and McEvilley, T.V. (1979). Seismological investigations at The Geysers geothermal field. *Geophysics*, Vol.44, pp.246-469.

Oppenheimer, D.H., (1986). Extensional tectonics at The Geysers geothermal area, California. *Journal of Geophysical Research,* Vol.91, pp.11,463-11,476.

Preiss, J.S., Walter, S.R., and Oppenheimer, D.H. (1996). Seismicity maps of the Santa Rosa 1° by 2° Quadrangle, California for the period 1969-1995. U.S. Geological Survey Miscellaneous Investigations Series.

Stark, M.A., (1990). Imaging injected water in The Geysers reservoir using microearthquake data. Geothermal Resources Council, *Transactions,* Vol.14, Part II. pp.1697-1704.

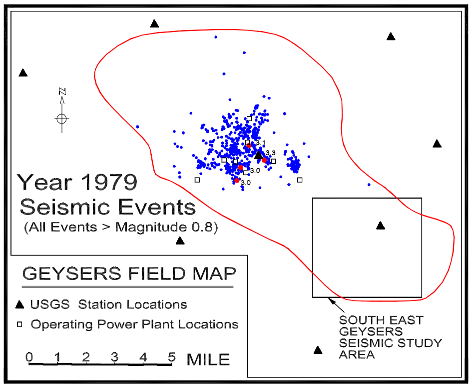

Fig.1 Location of USGS recorded seismic events, 1979.

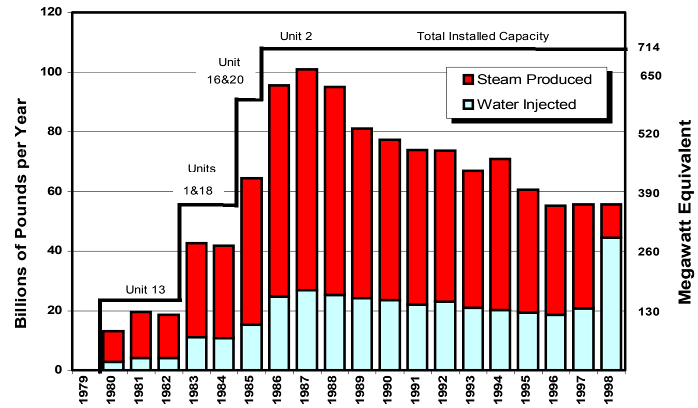

Fig.2 History of Production & Injection in SE Geysers area

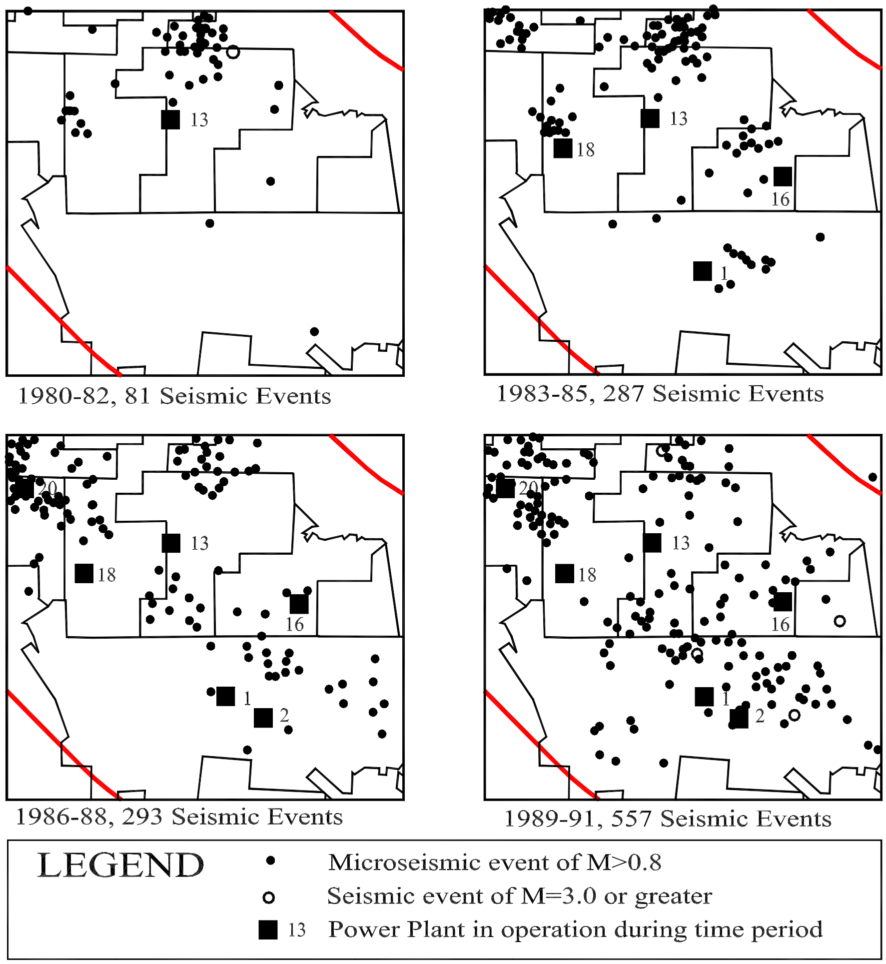

Fig.3 Location of M>0.8 seismic events recorded by the USGS, in four 3-yr periods from 1980-1991

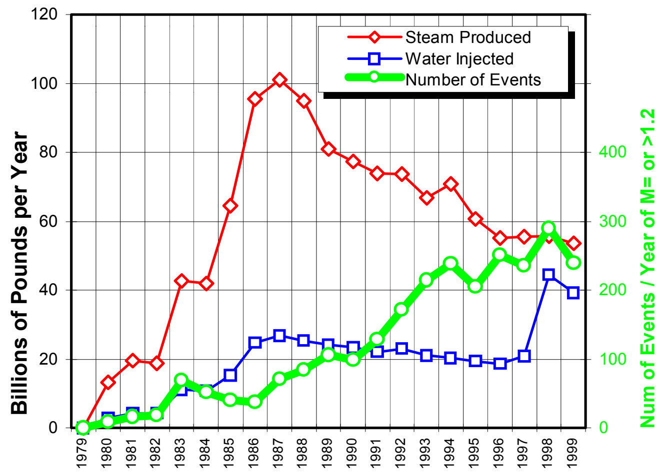

Fig.4 Annual Production, Injection & Seismicity, SE Geysers

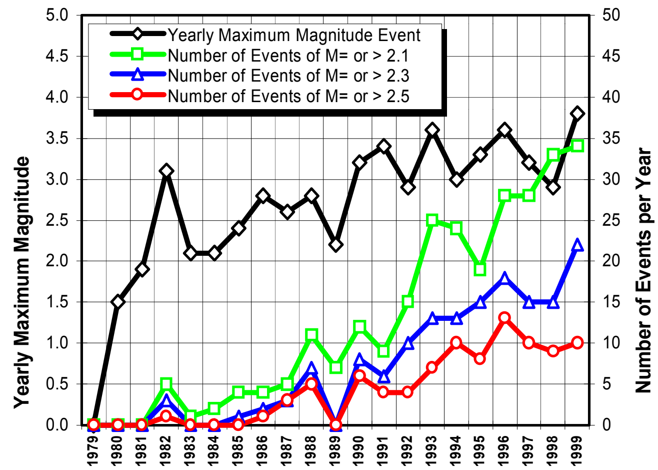

Fig.5 Number and Magnitude of USGS Events, SE Geysers

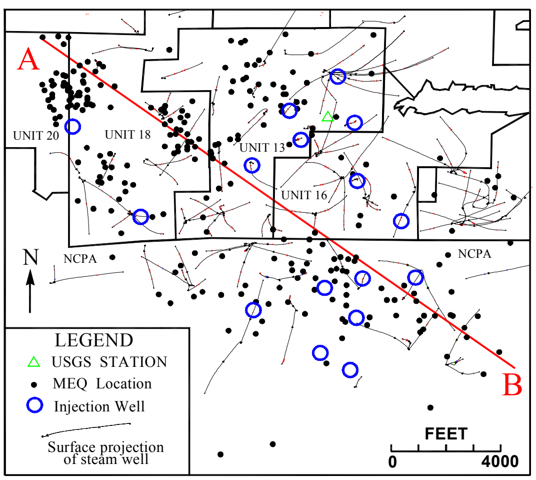

Fig.6 Map of USGS Events from 11/1/97 to 10/31/98

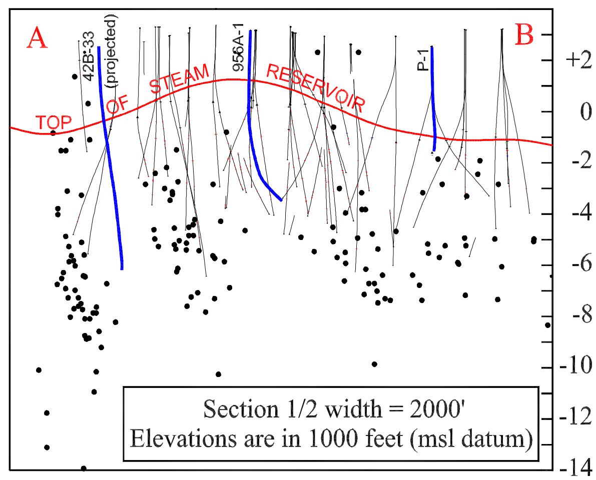

Fig.7 Cross section of USGS Events, 11/1/97 to 10/31/98

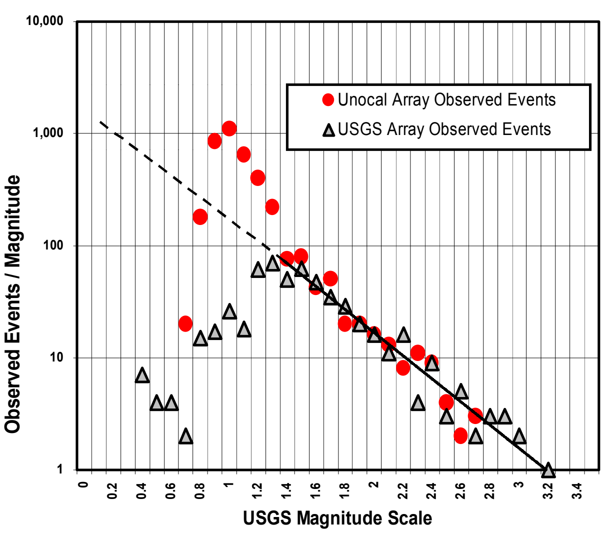

Fig.8 Number of MEQ events observed per 0.1 increment of Magnitude, 11/1/96 thru 10/31/98

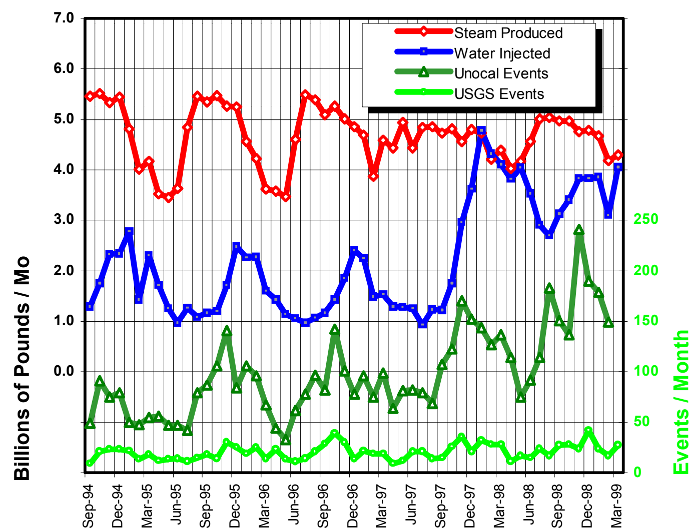

Fig.9 Monthly Production, Injection & Seismicity, SE Geysers

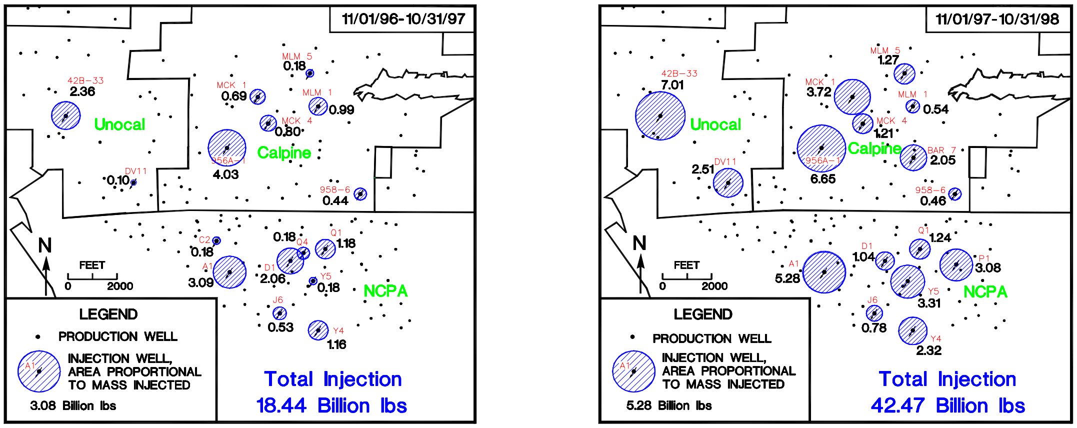

Fig.10 Maps illustrating the increase in annual injection in the year following startup of the SE Geysers Pipeline in Nov. 1997

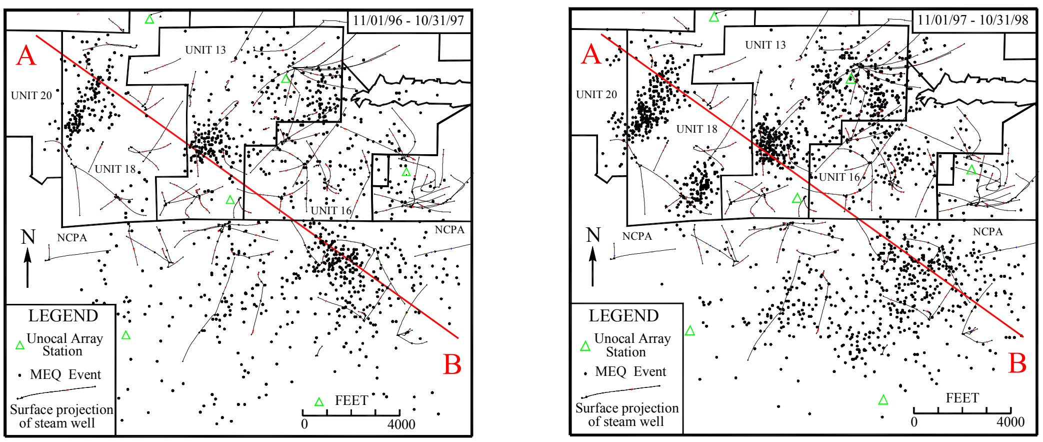

Fig.11 Maps illustrating the increase in MEQ activity in the year following startup of the SE Geysers Pipeline in Nov. 1997

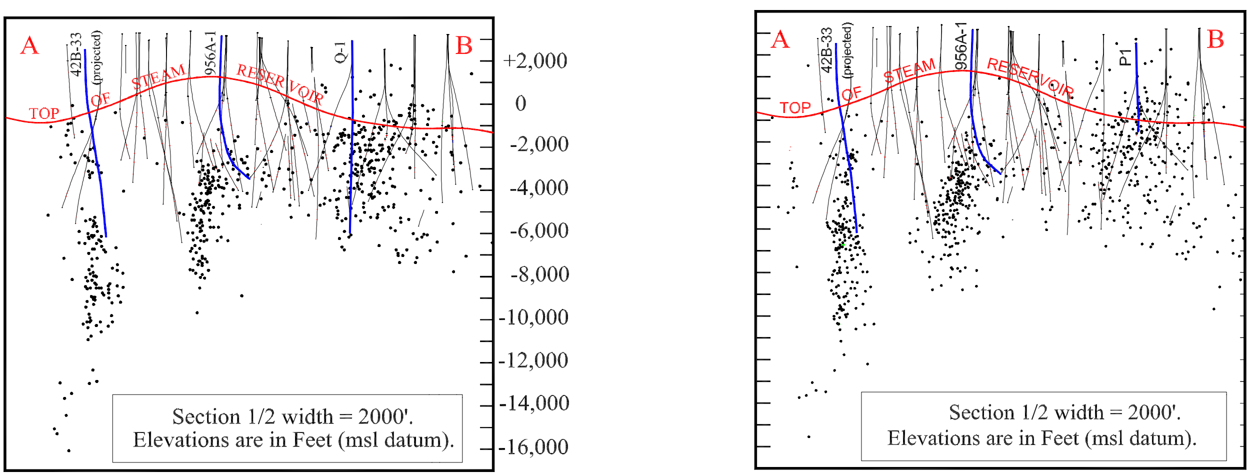

Fig.12 Cross sections A-B of Fig.11 showing MEQs observed from 11/01/96 to 10/31/97, and from 11/01/97 to 10/31/98