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The impact of injection on seismicity at The Geysers, California Geothermal Field

Ernest L. Majer*, John E. Peterson

Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

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Abstract

Water injection into geothermal systems has often become a required strategy to extend and sustain production of geothermal resources. To reduce a trend of declining pressures and increasing non-condensable gas concentrations in steam produced from The Geysers, operators have been injecting steam condensate, local rain and stream waters, and most recently treated wastewater piped to the field from neighboring communities. If geothermal energy is to provide a significant increase in energy in the United States (the US Department of Energy goal is 40,000 MW by 2040), injection must play a larger role in the overall strategy, i.e., enhanced geothermal systems (EGS). Presented in this paper are the results of monitoring microseismicity during an increase in injection at The Geysers field in California using data from a high-density digital microearthquake array. Although seismicity has increased due to increased injection, it has been found to be somewhat predictable, thus implying that intelligent injection control may be able to control large increases in seismicity.
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Keywords: Seismic monitoring; Induced seismicity; Geothermal; Enhanced geothermal systems

1. Background

Water injection into geothermal systems has become a nearly universal and often required strategy for extended and sustained production of geothermal resources. To reduce a trend of declining pressures and increasing non-condensable gas concentrations in steam produced from The Geysers, operators have been injecting steam condensate, local rain and stream waters, and most recently treated wastewater piped to the field from neighboring communities. Monitoring of microearthquakes (MEQs) related to production and injection has been conducted since the mid 1970s. MEQ monitoring has been applied as a general indicator of fluid paths and general response to injection at The Geysers for over 20 years [1–14]. A dramatic increase in planned injection rates and spatial extent of injection due to the recent completion of a wastewater pipeline (from Santa Rosa, California) has raised concerns regarding the societal and economic impact of injection related seismicity. Two obvious questions to be asked is will the rate and size of the MEQ events place an upper bound on injection at The Geysers, or vice versa, and will there be larger and larger events as injection increases? Although the Santa Rosa injection has only been going on for a few years the operators are evaluating a 50 percent increase over the initial injection (41 million liters/day). Without this injected water the thermal capacity of The Geysers will be underutilized and The Geysers will not be able to provide as much energy as possible. Vapor-dominated geothermal reservoirs such as The Geysers by their very nature are water-short systems. If The Geysers was produced without simultaneously injecting water, reservoir pressures and flow rates from production wells would decline fairly rapidly, and would reach uneconomically small levels, while enormous heat reserves would still remain in the reservoir rocks. Furthermore, the Northwest Geysers, which contains a significant portion of the recoverable geothermal energy, is currently underutilized due to high concentrations of non-condensable gas and

*Corresponding author. Tel.: +1 510 486 6709; fax: +1 510 486 5686.
E-mail address: elmajer@lbl.gov (E.L. Majer).

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corrosive HCl. Mitigation of these deleterious components through water injection would significantly increase The Geysers resource. Therefore, the key to sustaining and enhancing energy recovery from The Geysers is water injection.

Water injection is not totally beneficial. Injected water may migrate along major fractures and quickly reach production wells, which may degrade production by lowering fluid enthalpy and temperature. Hopefully, injected water will be completely vaporized by contact with hot rocks before it reaches production wells, supplying additional steam, and increasing reservoir pressures and production well flow rates with minimal or even positive operational and minimal hazard impact. However, injection can also improve the quality of produced steam from a chemical viewpoint, by reducing concentrations of non-condensable gases such as CO_2 and corrosive gases such as HCl.

It is also not new knowledge that seismicity at The Geysers is linked to injection and production. Several studies have demonstrated that MEQs at The Geysers geothermal area are associated with both water injection and steam extraction [2,10,12,15–19]. These studies include correlation of spatial and temporal MEQ distributions with injection/production data. In a recent paper [19] the authors make a comprehensive correlation study based on induced seismicity and operational data from 1976 to 1998. They found three types of induced seismicity at high significance: (a) shallow, production-induced seismicity that has a long time lag on the order of 1 year, (b) deep, injection-induced seismicity with short time lag of less than 2 months, and (c) deep, production-induced, seismicity with short time lag of less than 2 months that appears to diminish in the late 1980s. For each of these three types of induced seismicity they also proposed failure mechanisms based on analytical modeling and reasoning.

For shallow induced MEQs, [19] the authors found that MEQ distribution closely matches mapped low pressures in the reservoir and the areas of maximum volume strain inferred from surface deformation data, suggesting that these events are caused by poroelastic stressing. The observations are consistent with a contracting reservoir, which as it shrinks, induces stresses and strains in the surrounding crust. Shear stresses on faults outside the reservoir can increase, causing subsidence. However, these results [19] suggest that shallow earthquakes are production induced, and are in contrast with results of [20]. Studying one specific case in detail, they found that shallow MEQs are well correlated to injection, rather than production, and with a relatively short time lag of about 1 week. For shallow MEQs there might be a long-term effect caused by the overall steam-production and local short-term responses related to injections. In addition, [21] hypothesized that there is a back front of seismicity produced that will cause extended periods of seismicity after injection has ceased. This was found during hydraulic fracturing cases not located at The Geysers.

For deep induced MEQs occurring after the 1980s, there seems to be a consensus that these are correlated to local injection rates with some time lag [12,15–18,22]. For example, [12] showed that plumes of MEQs are clustered around many injection wells, and the seismic activity around each injection well correlates with its injection rate. Also, it has been hypothesized that injection-induced MEQs are probably caused by thermo-elastic perturbation due to cold-water injection into a hot reservoir [19]. When cool water flows into hot rock fractures, the fracture faces contract by cooling, loosening the frictional forces across the fractures and thereby allowing stress release by seismic slip. Although [19] studied other mechanisms (e.g. loss of effective stress due to hydraulic pressure in the fracture), they concluded that it is the temperature contrast between the injected water and the hotter rock fracture surfaces that is probably the dominant mechanism driving The Geysers injection-induced seismicity. Finally, some have attributed deep production-induced seismicity to thermoelastic stressing caused by evaporative cooling [19]. They concluded that an evaporative-thermoelastic model could explain why deep production correlated seismicity declined in the mid 1980s as the reservoir dried out and evaporative cooling diminished.

It has also been found that where clusters extend some distance from the injectors, the production wells tend to show "heavy" isotopic signature of flashed injectate [12]. They therefore hypothesized that MEQs are induced where injected water is present as liquid. It was suggested that the MEQs occurring in this liquid zone might be a result of the effects of hydraulic head and/or cooling due to the injected water [12]. Recently, this hypothesis was used to explain the vertical pattern of induced seismicity in the Northern Geyser reservoir [18]. Historic Geysers earthquakes and injection data show that an area of approximately 8 km^2 underlain by a cluster of MEQs in the depth range of 3–5 km below sea level. The cluster lies far below the normal 240 °C isothermal reservoir and is in the underlying high temperature zone (HTZ), where temperature gradients can exceed 100 °C/km. Above this cluster there is a gap, 0.5–1 km thick, where few MEQs occur. Above the gap is a more typical pattern of The Geysers seismicity, including plumes of MEQs associated with injection wells. This was then used in a conceptual model to show that this pattern could be governed by the temperature contrast between injected water and the rock, and would imply that significant volumes of injected water have descended into the HTZ reaching a depth as great as 5 km below sea level [18]. Furthermore, monthly injection and seismic data from 1983 to 2002 was studied and was found that the deep injection induced seismicity was lagging behind by 3 months suggesting that it would take about 3 months for the injected water to descend to depths of 3–5 km.

The above studies have made progress in showing a general correlation of liquid injection and steam production with various types of induced MEQs at The Geysers. Furthermore, several plausible hypotheses have been proposed to explain the mechanisms producing those MEQs. The Geysers region is subject to active tectonic forces associated with the strike-slip relative motion between the North American and Pacific plates [11,18]. Many naturally occurring fractures may be stressed to near the failure point, so a small perturbation in the stress field could lead to failure. However, it is not at all certain that most MEQs at The Geysers are produced by shear slip along pre-existing fractures [17,23]. Others [24] conducted highly accurate moment tensor analysis for thirty recorded earthquakes in the area and showed that most of the earthquakes have a non-shear component in their focal mechanisms. They suggested that the sources might be explained by combinations of tensile cracks and shear movements accompanied by fluid flow. Cracks open in the presence of high-temperature and pressure fluids, rapid flow in the new void, possibly accompanied by water flashing to steam. In general, rapid cooling along a fracture is capable of creating thermally induced fractures (TIFs) in the rock matrix adjacent to the fracture [25]. In any case, it is likely that thermo-elastic responses, induced by rapid cooling, play a major role in inducing MEQs at The Geysers.

Lacking, prior to the work described here, was a detailed field-wide MEQ response to a large influx of water, such as the Santa Rosa Injection Project. New technology in MEQ acquisition and analysis (wide band width, multi-component), while used in parts of The Geysers for short periods of time, was not in place prior to this project. This data can potentially provide an improved understanding of the basic mechanisms for the cause of the induced seismicity and the potential for injected water to efficiently mitigate high concentrations of non-condensable gases and corrosive HCl. Although the routine MEQ data were being collected and analyzed, new methods of MEQ analysis have been developed in the last several years which could be applied to further improve our understanding of such attributes as location, magnitude, and source mechanisms, which in turn will allow an overall understanding of energy release in The Geysers and its relation to production and injection activities.

The most established use of earthquake data at The Geysers, the tracking of strain release and presumably injection flow paths, could be greatly enhanced if the many theories describing how earthquakes and injectate are related were better constrained by observation. This requires an improved understanding of the "triggering" mechanisms of both the injection and the production related induced seismicity and of any source mechanism peculiarities that naturally occurring earthquakes may have in geothermal regions. The locations of the earthquakes have also been used to characterize patterns of permeability in reservoirs. However, this is a very complex issue since in different circumstances earthquakes can be more closely associated with either relatively low or relatively high permeability. Because characterizing permeability of geothermal reservoirs is of great importance in targeting wells and predicting overall reservoir performance, reducing the uncertainty in such earthquake interpretations would have great value.

A recent success [26,27] has been reported in using MEQs as illumination sources to image physical properties within The Geysers reservoir area. For instance, "tomographic" imaging of seismic wave velocity can be periodically repeated to map temporal changes in water saturation. A decline in water saturation is often accompanied by a decline in production pressure and an increase in non-condensable gas concentrations. Therefore, the existing earthquake array was designed to also provide the needed data to address such issues.

Finally, although seismicity is currently being used as a reservoir management tool, it is also becoming a negative issue with some of the more populated communities nearby Geothermal Fields. Events with magnitude 2 and above have raised concern to the residents near certain fields for not only their individual, but cumulative effect. In addition, some fear that as injection and production increases, the events will not only increase in numbers but increase in magnitude. In particular, the general public's perception is that this induced seismicity may cause damage to structures on the surface, similar to that caused by "natural" earthquakes. The communities affected are concerned and would like to see efforts on how and why they occur and whether one can devise any procedures to reduce them. In addition, the operators also want to know how the seismicity is linked to reservoir performance and what can be learned from the seismicity.

It must be kept in mind that there are many different mechanisms that have been proposed for inducing earthquakes. Induced seismicity has not only been noted in geothermal reservoirs but in reservoir impoundment (water behind dams), waste injections, and oil and gas operations. Another type of induced seismicity is that associated with hydrofracturing. In this paper, however, we are only dealing with seismicity in naturally fractured systems although in such areas as Soultz in France, seismicity associated with hydrofracturing has become an issue.

2. Regional seismicity

If one examines the subsurface in enough detail one can find fractures, joints, and/or faults almost anywhere in the world. A fault is not defined in terms of size, (definition of a fault is a displacement across a fracture or fracture zone), however, most mapped faults range in size from very small (few meters) to very large (hundreds of kilometers long). The size of an earthquake (or how much energy is released) depends upon how much slip occurs on the fault, how much stress there is on the fault before slipping, how fast it fails, and over how large an area it occurs. In most regions where there are economic geothermal resources, such as in the western United States, there is usually tectonic activity. For example, Fig. 1 is a map of northern California and part of Nevada showing the location of earthquakes from

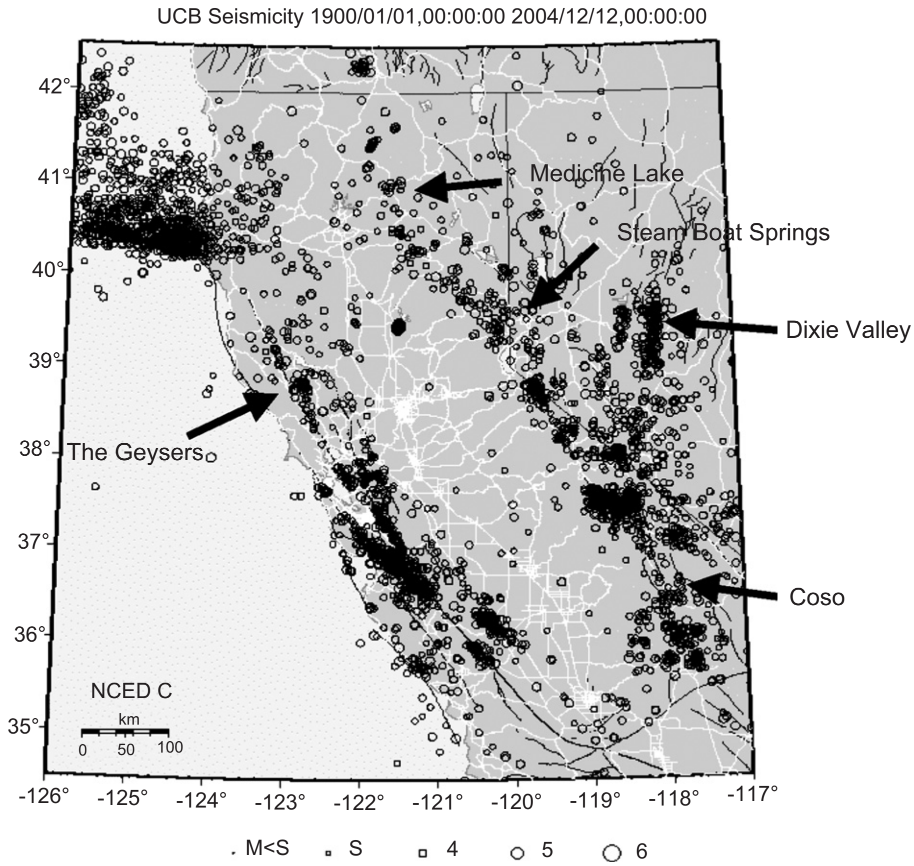

Fig. 1. Seismicity from 1900 to 2005 (from magnitude 3.0 to 5.0) relative to some of the Western US Geothermal Fields (from UCB Seismographic Station).

1900 to the present with magnitudes from 3.0 to 5.0. Also shown are some of the geothermal areas. It is not surprising that if the stresses are manipulated through injection and withdrawal of fluid that seismicity may change in these tectonic areas. Large or damaging earthquakes tend to occur on developed or active fault systems. In other words, large earthquakes rarely occur where there is not a fault large or long enough to release enough energy. It is difficult to create a large new fault because there is usually a pre-existing fault that will slip first, rather than a new fault being created.

A critical question that needs to be addressed is how injection will affect the seismicity, what does it imply for injection strategy, and how will it impact the local community as well as field operations. The Geysers is a prime candidate for enhanced geothermal systems (EGS) due to the very high heat content (especially the northwest Geysers) and a general lack of fluid. Injection is one of the few economic means to mine this heat (versus subsurface installed heat exchangers for example). The northwest Geysers has had production in the past, but over the last several years has been shut down and is now the target of increased production due to future injection. We view The Geysers in general as a laboratory for induced earthquakes due to its broad range of seismicity (from less than zero to above magnitude 4, as well as for the large number of events, from 2000 to 3000 locatable events per month). In addition, the northwest area is a unique opportunity to obtain the data before a large injection and increased production begins.

3. Objective of microearthquke monitoring work

There are two prime objectives of this work: (1) to understand the impact of EGS operations on induced seismicity and its environmental impact on the surrounding community. (2) To use microearthquake monitoring to intelligently manage the effects of fluid injections and stimulations to aid in the optimization of EGS.

These two objectives are related but separate. In the first objective we are trying to understand at what level the seismicity becomes a hazard to the community (and possibly the geothermal operations) and how can one possibly mitigate the hazard without severely reducing the output of the field. In the second objective we are trying to understand the relation between the reservoir properties (physical and chemical) and the link to seismicity and what the seismicity is telling us about those properties in order to optimize and manage the reservoir. Both objectives must be met to meet overall EGS objectives.

4. Data collection and processing

The purpose of this effort was to design and install a seismic monitoring system covering all The Geysers and its immediate surroundings with spatial resolution and detection threshold comparable or superior to the current array being maintained by the operators of the field (Calpine Corporation). That array is an analog system with voltage-controlled oscillators (VCO) and discriminators using mainly single vertical component sensors. A second array of stations covering The Geysers is the network of stations operated by the United States Geological Survey (USGS), again mainly vertical component with a bandwidth of less than 50 Hz. The system put in place that collected the current subject data was installed in two phases. The first phase installed twenty-three state-of-the-art, three-component short period seismometer sites continuously digitally (24 bit) telemetered at 500 samples per second (sps) for each of three channels to a central acquisition PC which would automatically trigger on events, pick arrivals, locate events and estimate origin time and magnitude. This first phase covered the existing production from the main Geysers Geothermal Field in order to monitor the effects of the Santa Rosa injection. The first phase of the array was completed and became operational in October 2003. The second phase of the array installed five more stations to cover a new injection area in the northwest section of The Geysers, i.e., the "Aidlin" area. The Aidlin area is in a more remote area, somewhat separated from the "main" field with a reservoir volume high in non-condensible gases yet high in temperature. The Aidlin stations were added in June 2004. Fig. 2 shows the location of the new stations and the Calpine stations relative to The Geysers central area and the existing USGS array. Also shown in Fig. 2 are the locations of several strong motion stations installed by Calpine near the bordering communities. The final entire array is shown in Fig. 3. Fig. 4 shows the difference in event detection between the USGS array and the LBNL array. The threshold of USGS locations is approximately magnitude 1.2 while the threshold of location for the

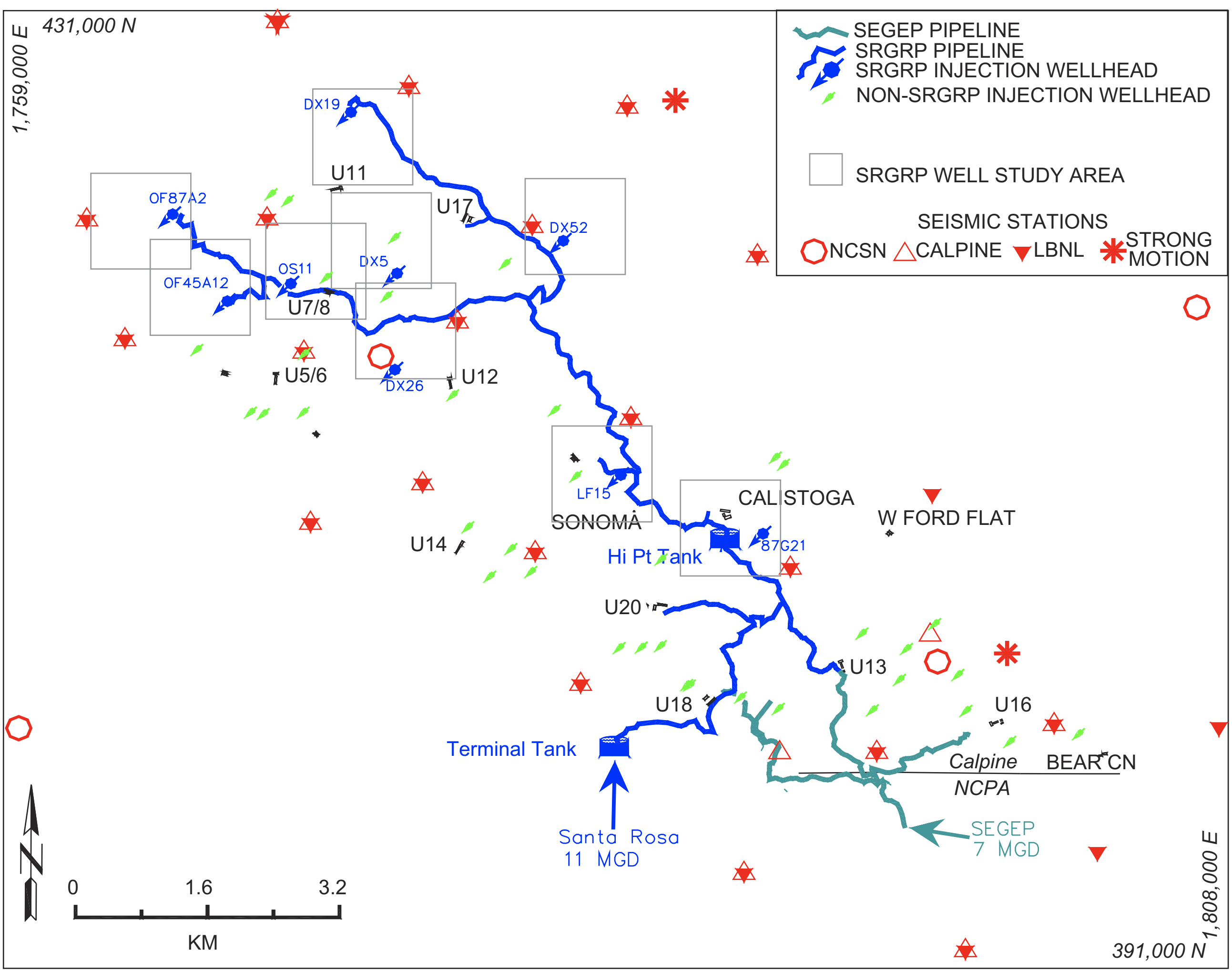

Fig. 2. Location of USGS (NCSN) stations, current Calpine array (pen triangles), and the first phase of the new stations (solid inverted triangles). Also shown are the locations of the pipelines used for the water from Santa Rosa. And the pipeline installed prior to this study in 1997 to inject water into the southeast Geysers (SEGP) at a rate of 26 million liters/day (7 million gallons/day, from [18]).

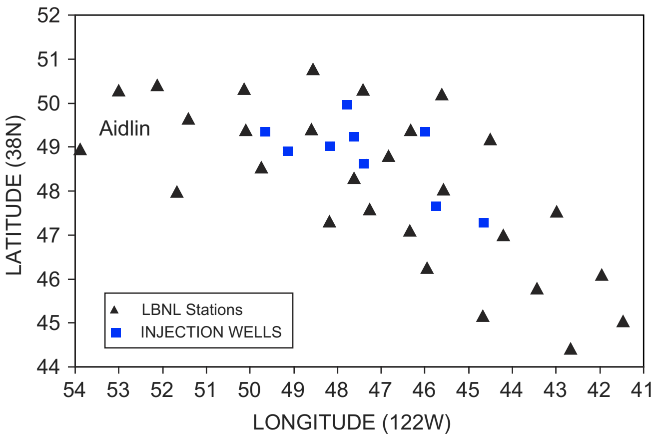

Fig. 3. The entire current array including the Aidlin stations, the squares are the injection wells for the Santa Rosa water.

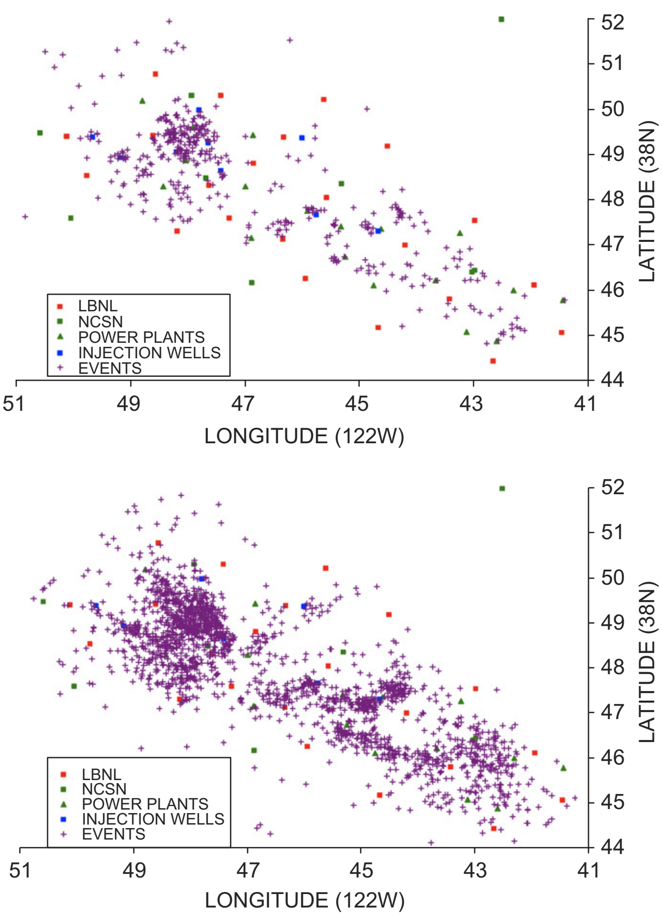

Fig. 4. One month (April 2004) of data from the USGS array (top) and the LBNL array (bottom figure).

LBNL array is about magnitude zero. In September 2004, a large fire swept through the southeast Geysers and destroyed several stations. A reconfiguration in 2005 left the five Aidlin stations and 18 stations covering the reset of The Geysers for a total of 23 stations. This did not affect the threshold of location however.

To achieve the processing goals we needed to locate the earthquakes as well as possible, in both time and space, yet do so with a large numbers of events. We have demonstrated in past work at The Geysers that we can locate events to within 50 m of precision and 100 m of accuracy in The SE Geysers by using the technology used in this project [17]. We also needed to detect and locate events down to very small events, possibly down to magnitude zero, or lower. We felt that this level of precision and accuracy was necessary Geysers wide to have the quality and volume of data to meet our objectives. The analysis and processing carried out consisted of "routine locations", magnitude determination and correlation with the injection parameters to establish relations between seismicity and reservoir performance. The general operation of the data flow is as follows: an event is defined as valid if six or more stations detect a trigger (a trigger is present if the short term average of a 16-point rectified average of the data exceeds the long term average (4096 points) in a 0.5 s time window). This procedure follows the processing stream developed by [28]. The P-arrival times are then gathered (with criteria set out by [2]) and are used to locate the event with a 1-D model. In addition to the 1-D model, a three-dimensional inversion using cubic splines was also used to invert for a velocity model and locations. Fig. 5 shows the difference in locations when one uses two different starting models for a three dimensional inversion. For 1000 events the residual difference of locations is mostly less than 100 m (length of each line), with no particular preference in direction (circle in Fig. 5). There are lines longer than 100 m but those events are mostly for events on the edge of the array. It seems that due to the large number of events are masking the heterogeneity, thus making it difficult to tell the significant difference in small changes in the velocity model. Therefore, for the routine locations we decided to use a 1-d velocity model (model 1).

The magnitudes are determined with an average coda length of all the triggered stations. A duration magnitude was determined for the events by fitting the log duration from the LBNL events to the USGS magnitude for the same events. The magnitude is estimated for each event by

$$\text{Magnitude} = 0.37 \log 10(\text{duration(s)}) - 1.39. \tag{1}$$

The duration is defined as the time at which the short-term average drops below 1.25 for more than 0.25 s, i.e., following [2].

The location, P-times, magnitude and waveforms are then sent to the USGS via internet and placed on their internet site. In addition, all events located are then sent to the larger database at the University of California/USGS Northern California Data Center (NCDC).

On average over 3000 events are detected and located per month down to a magnitude of zero in real time. Due to the large volume of data it would be prohibitively expensive to provide "hand" processed results in real time. However, it is critical for public and scientific reasons that this never-before-obtained resolution, three component,

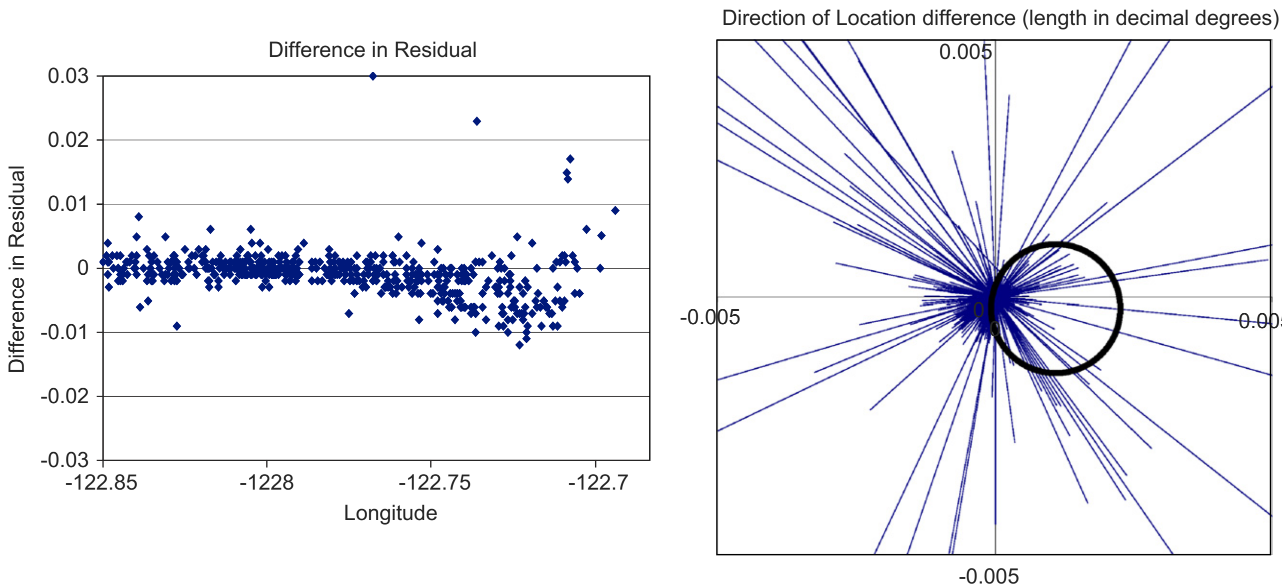

Fig. 5. Change in residual and location found by using different velocity models. The average difference in location is 100 m (radius of circle) with no preferential direction.

and bandwidth data set from The Geysers be made available in a timely fashion to the research community and other interested people. Therefore, a complete list of all events recorded is available at the NCDC such that the general public can request all time series and station data in a standard format.

5. Results

Our working hypothesis for the increased MEQ activity at The Geysers is that the seismicity is due to a diverse set of mechanisms. That is, there is not one universal "triggering" mechanism (other than stress) but a variety of mechanisms in operation that may work independently, together, or superimpose to enhance or possibly reduce seismicity. For example, as one injects water into the reservoir there is obviously cooling, a change in pore pressure (at least locally around the well) and possibly wider ranging stress effects. There has also been a debate in the literature about the relation between the location of the MEQs and the location of the fluids. If the events are due to thermal contraction from cooling the rock matrix one would assume that would take a very long time, i.e., the thermal front travels orders of magnitude slower than the fluid front. As it is, the fluid front does not travel in one continuous manner but it fingers it way through the fractures in a lace-like manner. Unlike the rock matrix, fracture surfaces can cool very quickly as they are contacted by the fluid front. By examining the spatial and temporal rate of change in seismicity one may be able rule out or confirm certain mechanisms. Also, as the injections proceed effects may be felt on a field wide basis. As the local stresses change around each injection well they may superimpose upon the existing regional stresses or link up to form a larger local effect that in turn may affect a wider region within the field. Fig. 6 shows the rate of seismicity from 1965 to the present (early 2006) at The Geysers as derived from the USGS database. The data are for magnitudes above 1.2 as determined from the USGS data set at the Northern California Earthquake Data Center. As can be seen, as the injection increases the seismicity increases, but not at all levels. If one only looks at the larger seismicity, it has stayed fairly constant since 1985 (magnitude 3 events). There is also no clear relation

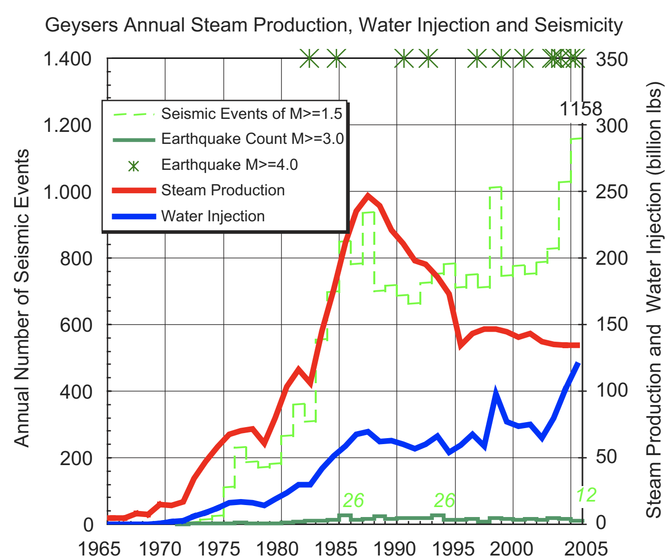

Fig. 6. Historical seismicity at The Geysers from 1965 through October 2005 using all events above magnitude 1.2 from the USGS array (from M. Stark, Calpine Inc. and B. Smith, NCPA). The largest event recorded was a magnitude 4.6 in 1982. The injection and production is an average per year in billion gallons.

between total injection and seismicity, except if one looks at all events above 1.2. Magnitude 4 events, however, have been increasing. As can be seen there are peaks in seismicity in 1986 and again in 1998, and more recently due to the latest injections. It is also important to point out that as steam production has decreased since 1986 the overall rate of seismicity has remained fairly constant. Recent data does show that there has been an increase in seismicity due to the recent injection in 1997 and 2003. It should be noted that for 2005 the seismicity has already reached above past years levels. Fig. 7 shows the trend in seismicity as recorded by the LBNL array between October 2003 and September 2006. The two "gaps" in seismicity are due to array problems (from wild fires etc.). Also shown is the approximate start time of the Santa Rosa wastewater injection (up to 11 millions gallons per day). The injection did not start exactly on any one date but was brought on line over several months between October and December of 2003. As can be seen, there is a definite increase in seismicity in 2004 continuing to the present. Fig. 7 shows that initially the seismicity sharply increased, but has not been increasing as much as injection continues.

Fig. 8 shows the injection history for the entire Geysers field from 2000 to mid 2006. The oscillations are due to injecting more water in the winter when it rains and there is also less evaporation from the cooling towers, thus there is more water available to be reinjected, compared to the summer when it almost never rains. Therefore, there is much more injection in the winter months than in the summer months. This figure also shows the general upward trend in total injection. Fig. 7, shows that at least in the number of events (versus total energy release) that there is not a strong correlation between the oscillation in the injection the oscillation in the seismicity. Fig. 9 shows 1 month of data before the Santa Rosa injection (October 2003) and a typical 1-month of data after the full injection start (April 2004). As can be seen, there has been a definite increase in seismicity in the area of the injection wells. There is a definite clustering of events around the injection wells, but there is also seismicity in other areas. As stated before this is typical of seismicity at The Geysers, and some or all of the increase may just be normal seasonal variation as the non-Santa Rosa water injection ramps up. Low-magnitude seismicity increased in the SE Geysers when supplemental injection began there [14,15,17] and it is not

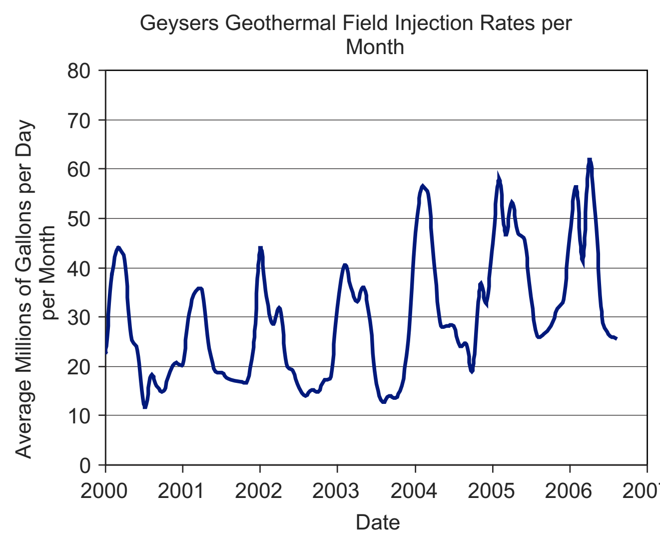

Fig. 8. Total injections per day, averaged per month from 2000 through mid 2006 in millions of gallons for the entire Geysers field.

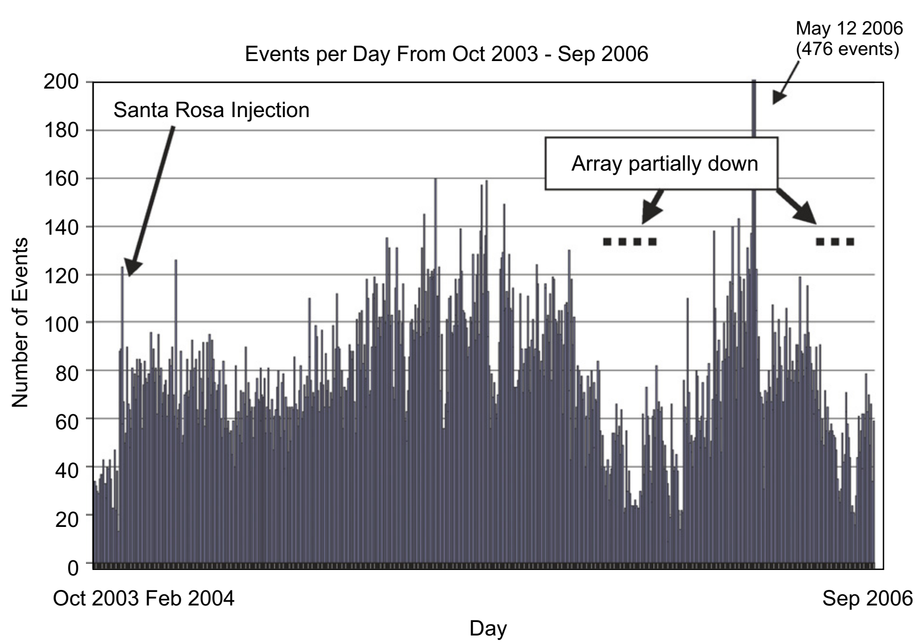

Fig. 7. The rate of seismicity before and after the Santa Rosa injection as recorded by the LBNL array, the start of injection was December of 2003. The times marked with the array partially down was due to fires destroying parts of the array.

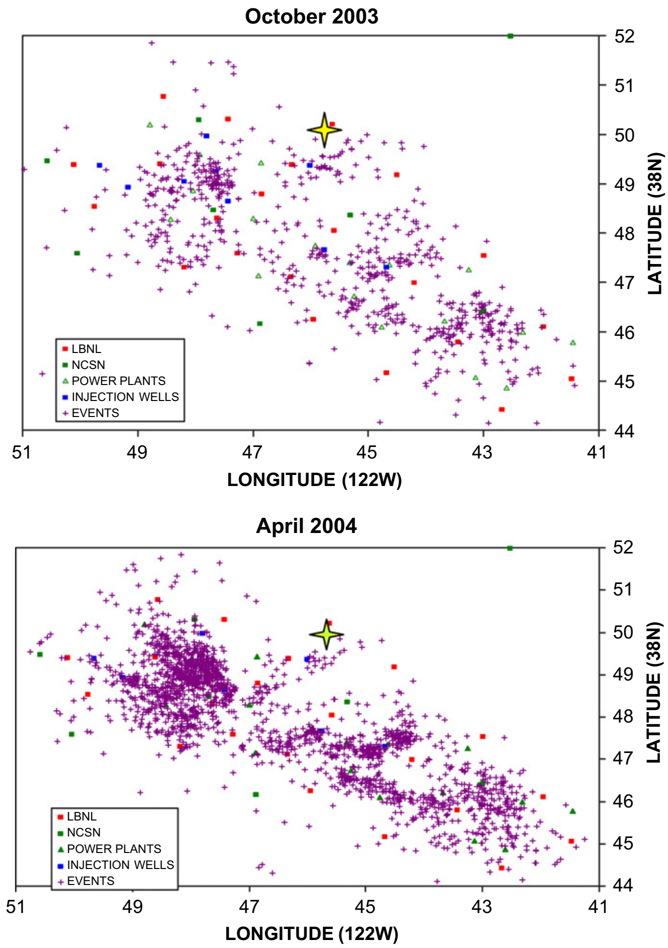

Fig. 9. Top figure is 1 month of data recorded on the LBNL array before the Santa Rosa injection (October 2003) The bottom figure is 1 month of data (April 2004) after the Santa Rosa injection started. The star is the location of a February 2005 magnitude 4 event.

surprising that is occurring now with the Santa Rosa injection. Looking at a longer period of time a similar pattern emerges. Figs. 10–13 show The Geysers field, the location of injection wells for the Santa Rosa injection (blue squares), the LBNL array at the time and all the located events in two different time periods, October 2003–September 2005 (2 years), and from October 2005 to September 2006 (1 year). It should be noted that injection and production is occurring field wide but there is a strong correlation to not only the Santa Rosa injection well but to other injection wells (see Fig. 3 for the location of other injection wells). Also shown in these figures are the locations of the magnitude 4 events (large stars in Figs. 10 and 12). It is interesting to note that there is only a loose correlation between the magnitude 4 events and the zones of injection. In fact it seems that the larger events occur on the edges of the seismicity or away from it. Fig. 11 shows the location of only the larger events (2, 3, and 4 s) for the first period and Fig. 13 shows the location of the larger events in the second time period. It is interesting to note the location of the 4's, and also a line of 3's in the southwest part of the field away from the main cluster of events.

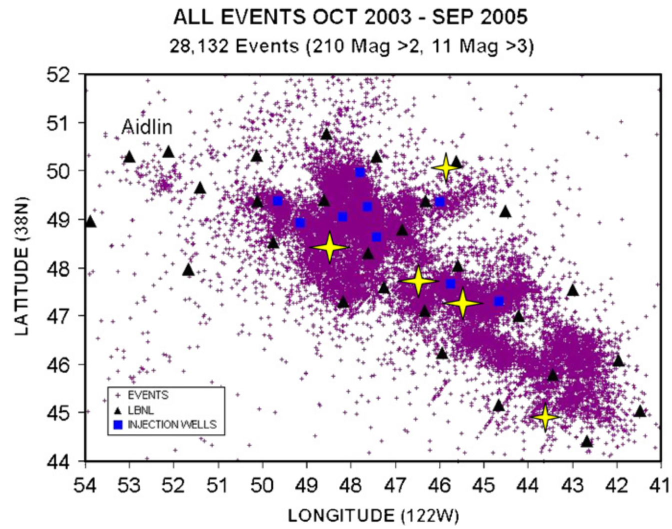

Fig. 10. Locations of all events from October 2003 to October 2005, Geysers wide, note the relatively lack of events in the Aidlin area, this is prior to a large increase in injection in the Aidlin area, injection started in late 2005. The blue boxes are the injection wells for the Santa Rosa water injection. The large stars are magnitude 4 plus events (February 2004, December 2004, May 2005, October 2005). The linear trends in the data are artifacts of the automatic location.

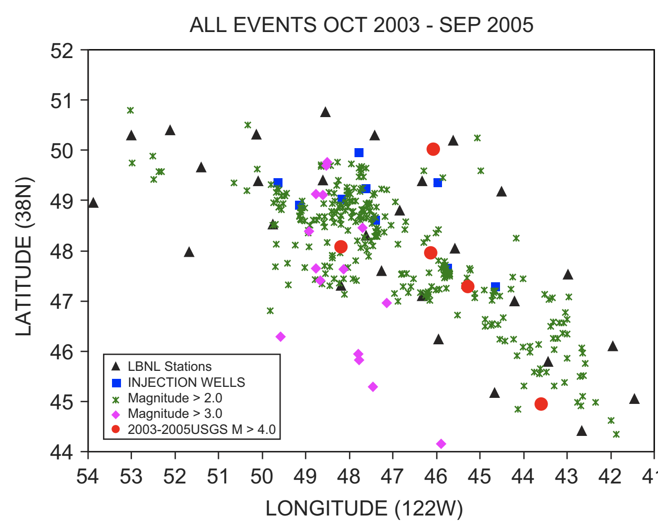

Fig. 11. Location of magnitude 2, 3 and 4's from October 2003 through October 2005. The injection wells are only for the Santa Rosa water.

Also as part of this study, as was mentioned before, we expanded the array in early 2004 to cover the northwest area of The Geysers field, the Aidlin area. This is an area where the subsurface temperatures are very hot (well over 250 °C) and there are large concentrations of non-condensable gases. In late 2004 injection began in this area (see Fig. 14) at relatively small volumes, it held relatively steady at this rate until September of 2005 when the injection sharply increased. As can be seen from Fig. 14 the seismicity generally tracked this injection. The three large increases in injection generally occurred after injection changes. In some cases there is a lag in seismicity. Fig. 15 shows the plan view and an east-west cross section through

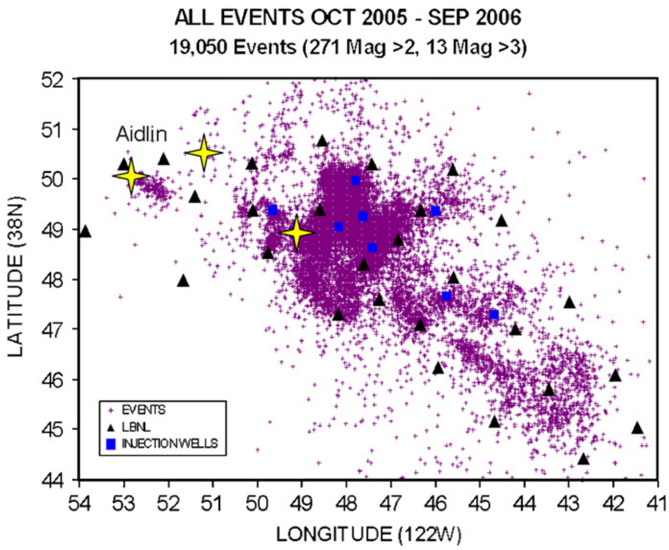

Fig. 12. Locations of all events from October 2005 through August 2006, Geysers wide, note the increased clustering of events in the Aidlin area after injection has occurred. The blue boxes are the injection wells for the Santa Rosa water injection. The stars are magnitude 4 plus events (May 2006).

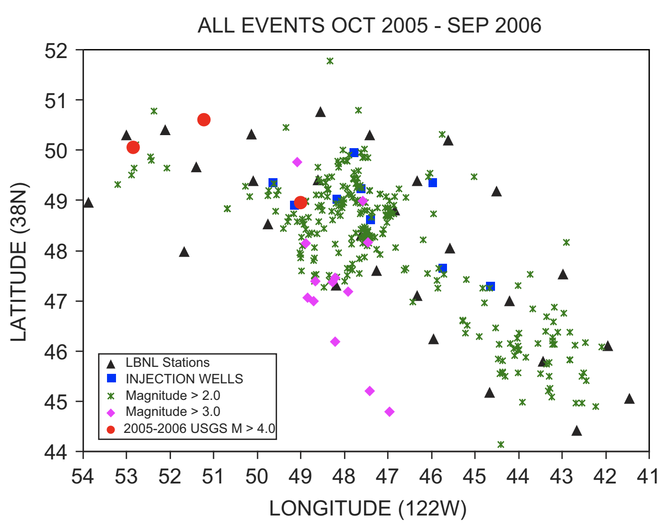

Fig. 13. Location of magnitude 2, 3 and 4's from October 2003 through October 2005. The injection wells are only for the Santa Rosa water.

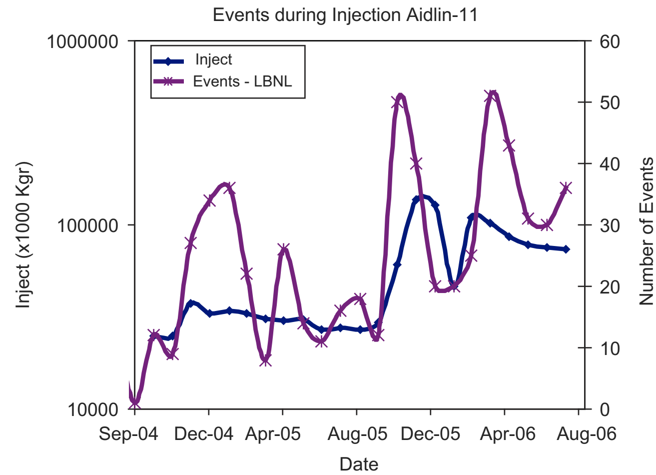

Fig. 14. Injection history (total injection for each month) and seismicity (number of events per month) in the Aidlin area. Note that the injection volume is plotted on a log scale.

the center of the cluster as well as the trace of the well. The seismicity is near the bottom and extending away from the well. Also shown is the location of a magnitude 4 event that occurred in October of 2005, near the edge of the cluster of seismicity at a depth of 2.5 km. Another magnitude event occurred in May 2006, in the northwest Geysers but well away from the Aidlin cluster of events (see Fig. 12).

6. Discussion and conclusions

If past experience is any indication, the system will reach equilibrium as time proceeds and the seismicity may level off and possibly decrease (see Fig. 6). It has been our experience that the initial injections will perturb the system, cause an increase in seismicity, then level off and/or decrease. This is again being noted in the Aidlin area. The time period will be a function of the size of the disturbance and the volume of the affected area. Rate of injection seems to be an important factor also. One hypothesis worth considering is that if the rate of increase injections is varied (give the system a chance to equilibrate) there may be less initial seismicity. The recent injections may reverse this trend but it is too early in the monitoring process to determine. Finally, what will be the impact of the maximum event size? The maximum event at The Geysers was in 1982 (4.6), but in the past year there have been 3 events of magnitude greater than 4.0 (see Fig. 12). The maximum event will depend upon the size of the fault available for slippage as well as the stress redistribution due to injection and production. To date there have not been any faults mapped in The Geysers which would generate a magnitude 5.0 event or greater. This is not an absolute guarantee that one would not happen, but does lower the likelihood.

To realistically examine the overall benefit of injection one must look at both the public and private sectors. Access to high quality, state-of-the-art seismic information will be important for both public acceptance and industry reservoir management. For example, at The Geysers, related geothermal industry benefits will include establishment of a non-industry monitoring and reporting system capable of providing the high quality, publicly credible, seismic data base needed to gain public acceptance of wastewater injection; and the basic scientific knowledge regarding the relations between seismicity and fluid movement in the crust.

The most established use of earthquake data in geothermal regions, the tracking of strain release and presumably injection flow paths, could be greatly enhanced if the many theories describing how earthquakes and injectate are related were better constrained by observation.

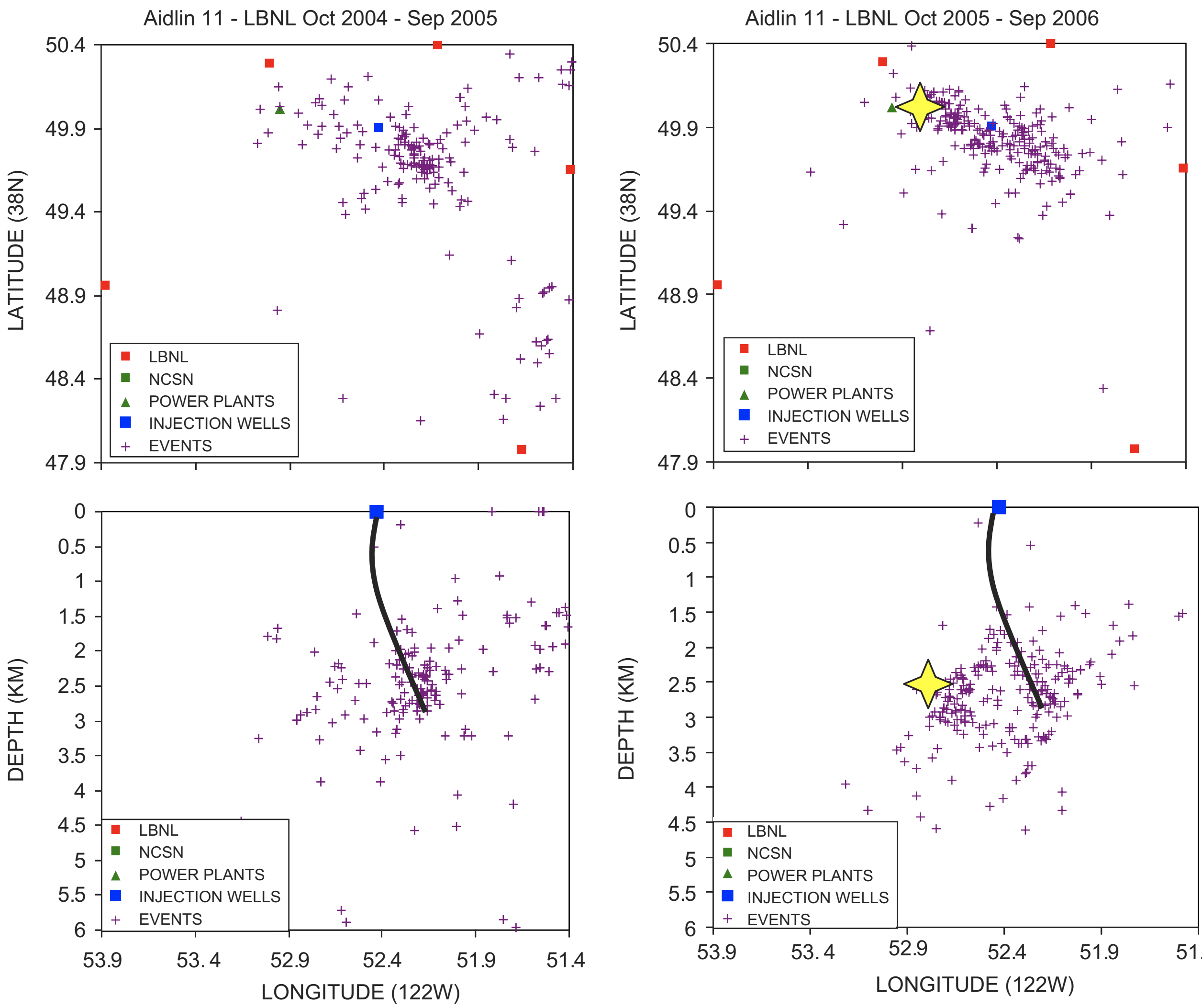

Fig. 15. Location and depth of events in the Aidlin area of The Geysers. Also shown is the location of a magnitude 4 event in the vicinity that occurred in October of 2005.

This requires an improved understanding of the ''triggering'' mechanisms of both the injection and the production related induced seismicity and of any source mechanism peculiarities that naturally occurring earthquakes may have in geothermal regions. The locations of the earthquakes have also been used to characterize patterns of permeability in reservoirs. However, this is a very complex issue since in different circumstances earthquakes can be more closely associated with either relatively low or relatively high permeability. Because characterizing permeability of geothermal reservoirs is of great importance in targeting wells and predicting overall reservoir performance, reducing the uncertainty in such earthquake interpretations would have great value.

Specific to The Geysers, it is also likely that, during the monitoring of the seismicity, information will be gained which will be the prime motivator for operational decisions, which will increase net production. For example, there is a large untapped portion, which could be exploited if proper injection and production strategies are designed. Due to concerns regarding MEQ generation one must also take into account the impact of injection on seismic as well as reservoir conditions. If injected under the right conditions and rates, wastewater may mitigate deleterious high non-condensable and corrosive gas concentrations in the reservoir. In situ mitigation will alleviate the economic and technological issues presently preventing exploitation of much of a high temperature reservoir characterized by high concentrations of CO_2, H_2S, and HCl in the vapor contaminates the production stream, requiring costly surface mitigation strategies, diminished well lifetimes and retrofitting of power plants to handle the high gas contents.

It has been demonstrated that the seismicity is largely a function of fluid injection, although there is not a strict one to one correlation in time and space. We view this as positive because it indicates that by balancing the injection and fluid withdrawal the seismicity can be controlled. The challenge is to optimize the production as well as control the larger events, which may have impact on the local community. In terms of the seismicity being a hazard to the community, the risk does not seem high. The region surrounding The Geysers is tectonically stressed, cut by numerous faults, and subject to a high level of earthquake activity. In The Geysers field, there are no mapped faults active in the last 10,000 years [11]. The Collayomi Fault, running approximately 1 mile NE of the field limit, is mapped as an inactive fault. The nearest active fault is the Mayacamas Fault, located 4 miles SW of the field limit. On the northeast side, the active Konocti Bay fault system is located approximately 8 miles north of the field limit. Therefore one must speculate if there even exists a fault large enough in the region to create a large event.

In conclusion, injection-induced seismicity is observed in the form of "clouds" of earthquakes extending primarily downward from injection wells. At such a well, the cloud generally appears shortly after injection begins, and earthquake activity within each cloud shows good temporal correlation with injection rates. It has been demonstrated that injection-induced seismicity is generally of low magnitudes ($\leqslant 3.0$). On a fieldwide basis, seismicity of magnitudes $\geqslant 1.5$ has generally followed injection trends, but this correlation has not been observed for earthquakes of magnitudes $\geqslant 3.0$.

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