Lawrence Berkeley National Laboratory

Integrated High Resolution Microearthquake Analysis and Monitoring for Optimizing Steam Production at The Geysers Geothermal Field, California

Authors

Majer, Ernest
Peterson, John
Stark, Mitch
et al.

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"Integrated High Resolution Microearthquake Analysis and Monitoring for Optimizing Steam Production at The Geysers Geothermal Field, California"

FINAL REPORT

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DISCLAIMER

EXECUTIVE SUMMARY

A state- of- the- art 23 station, digital, high frequency, multi-component, microearthquake monitoring array has been installed at The Geysers geothermal field in Northern California. One of the primary drivers was to monitor the increased injection from Santa Rosa wastewater pipeline. The purpose of the array is to provide to the scientific community, as well as the public, detailed location and waveform data on the seismicity of this field in close to a real time fashion. This will provide the scientific community the ability to perform a more detailed analysis of the microearthquakes and to examine the source mechanisms. It is anticipated that this will lead to a better understanding of the cause of the seismicity and in turn not only allow the operators to optimize electricity production, but help design mitigation of any potential unwanted seismicity. This could be accomplished in several ways, different rate of injection, different volumes of injection, or varying the injection with the production in the area. The array currently locates 8 to 10 times the number of events that the United States Geological Survey (USGS) array locates in The Geysers field area and approximately the same number that the Calpine array locates. The Lawrence Berkeley National laboratory (LBNL) array, however, has a higher bandwidth (100 hertz versus 30 hertz) than the current Calpine array and also has all three-component sensors versus partial three component sensors for the Calpine array Public access is provided through the Northern California Earthquake Data Center (NCEDC) operated by the USGS and The Berkeley Seismographic Station. The LBNL array was installed as a permanent deployment with hardened sites and solar panel power. As the array operates over the next few years it is planned that the current Calpine array will be phased out such that the LBNL array will serve both the industry, scientific and public needs. Future activities at the Geysers over the next several years will include a Department of Energy (DOE) Geothermal Program funded activity to operate the current LBNL array as well as expand the array to the Northwest Geysers (Aidlin) as the injection program also expands to the Northwest. To date there are no conclusive scientific results on the overall effect of the increased water injections from the Santa Rosa pipeline. The injections were delayed for well over a year from the assumed schedule of this project (original planned start of injections was fall of 2002, actual start was December of 2003). Effects of the injections are being seen, however, in the form of increased seismicity around the injection wells. This has often been observed at The Geysers due to injections. A magnitude 4.4 earthquake was observed in the northern part of the field in February of 2003, as were several magnitude 3's. Whether they were "triggered" by the injections or if the total energy release will increase over time is still not known, but as more data are gathered and the total response of The Geysers field is examined it will become possible to address these questions.

ABSTRACT

In December of 2003 a large amount of water from the Santa Rosa wastewater project began being pumped to The Geysers for injection. Millions of dollars are being spent on this injection project in the anticipation that the additional fluid will not only extend the life of The Geysers but also greatly increase the net amount of energy extracted. Optimal use of the injected water, however, will require that the water be injected at the right place, in the right amount and at the proper rate. It has been shown that Microearthquake (MEQ) generation is a direct indicator of the effect of fluid injection at The Geysers Majer and McEvilly 1979; Eberhart-Phillips and Oppenheimer 1984; Enedy et al. 1992; Stark 1992; Kirkpatrick et al. 1999; Smith et al. 2000). It is one of the few, if not only methods,

practical to monitor the volumetric effect of water injection at The Geysers. At the beginning of this project there was not a detailed MEQ response, Geysers-wide, to a large influx of water such as will be the case from the Santa Rosa injection project. New technology in MEQ acquisition and analysis, while used in parts of The Geysers for short periods of time had not been applied reservoir-wide to obtain an integrated analysis of the reservoir. Also needed was a detailed correlation with the production and injection data on a site wide basis. Last but not least, needed was an assurance to the community that the induced seismicity is documented and understood such that if necessary, mitigation actions can be undertaken in a timely manner. This project was necessary not only for optimizing the heat recovery from the resource, but for assuring the community that there is no hazard associated with the increased injection activities. Therefore, the primary purpose of this project was to develop and apply high-resolution micro earthquake methodology for the entire Geysers geothermal field such that at the end of this project a monitoring and process definition methodology will be available to:

a. Optimize the economic development of The Geysers (as well as other areas) by providing improved information on fluid flow and reservoir dynamics,

b. Aid in the mitigation of environmental impacts of increased fluid injection by improving the understanding between fluid injection and seismicity.

c. Provide a cost-effective blueprint such that the technology can be applied on a routine basis in the future.

INTRODUCTION

Background and Past Work

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 related to production and injection has been conducted since the mid 1970's. MEQ has been applied as a general indicator of fluid paths and general response to injection at The Geysers for over 20 years (Majer, 1978, Majer and McEvilly 1979, Marks et al., 1978; Ludwin and Bufe, 1980; Peppin and Bufe, 1980; Bufe et al., 1981; Allis, 1982; Denlinger and Bufe, 1982; Ludwin et al., 1982; Eberhart-Phillips and Oppenheimer, 1984; Oppenheimer, 1986; Stark, 1992, Stark and Majer, 1989, Beall et al., 1999, Smith et al., 2000). A dramatic increase in planned injection rates and spatial extent of injection due to the recent completion of the Santa Rosa wastewater pipeline has raised concerns regarding the societal and economic impact of injection related seismicity. It is possible that the rate of MEQ events may place an upper bound on injection at The Geysers. Already the operators are evaluating a 50 percent increase over the initial Santa Rosa injection. Without this injected water the thermal capacity of The Geysers will be underutilized and The Geysers will not be able to provide California with as much low cost electricity as possible. Vapor-dominated geothermal reservoirs such as The Geysers by their very nature are water-short systems. If The Geysers were 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 corrosive HCl. Mitigation of these deleterious components through water injection would significantly increase The Geysers resource. The key to sustaining and enhancing energy recovery from The Geysers is water injection.

Water injection is not automatically beneficial. Injected water may migrate along major fractures and quickly reach production wells, which may degrade production by lowering fluid enthalpy and temperature. At its best, 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 societal impact. Injection can also improve the quality of produced fluid from a chemical viewpoint, by reducing concentrations of non-condensable gases such as CO_2 and corrosive gases such as HCl.

Several studies have demonstrated that MEQs at The Geysers geothermal area are associated with both water injection and steam extraction (Majer and McEvilly 1979; Eberhart-Phillips and Oppenheimer 1984; Enedy et al. 1992; Stark 1992; Kirkpatrick et al. 1999; Smith et al. 2000; Stark 2003; Mossop and Segall 2004). These studies include correlation of spatial and temporal MEQ distributions with injection/production data. In a recent paper, Mossop and Segall (2004) 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: i) Shallow, production-induced seismicity that has a long time lag on the order of 1 year; ii) deep, injection-induced seismicity with short time lag, < 2 months; iii) deep, production-induced, seismicity with short time lag, < 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, Mossop and Segall (2004) 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, Mossop and Segall's (2004) suggestion that shallow earthquakes are production-induced is in contrast with results of Rutledge et al. (2002). 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, Parotidis et al (2004) 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 (Stark 1992; Enedy et al. 1992;Romero et al. 1995, Kirkpatrick et al. 1999; Smith et al. 2000; Stark 2003). For example, Stark (1992) showed that plumes of MEQs are clustered around many injection wells, and the seismic activity around each injection well correlates with its injection rate. Mossop and Segall (2004) hypothesized that injection-induced MEQs are probably caused by thermo-elastic perturbation due to cold-water injection into a hot reservoir. 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 Mossop and Segall (2004) 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 Geysers injection-induced seismicity. Finally, Mossop and Segall (2004) attributed deep production-induced seismicity to thermo-elastic stressing caused by evaporative cooling. 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.

Stark (1992) found that where clusters extend some distance from the injectors, the production wells tend to show "heavy" isotopic signature of flashed injectate. Stark (1992) therefore hypothesized that MEQs are induced where injected water is present as liquid. He 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. Recently, Stark (2003) used this hypothesis to explain the vertical pattern of induced seismicity in the Northern Geyser reservoir. Historic Geysers earthquakes and injection data shows an area of approximately 8 km^2 underlain by a cluster of MEQs in the depth range of 3 to 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 per km. Above this cluster there is a gap, 0.5 to 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. Stark (2003) used 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. Furthermore, Stark (2003) studied monthly injection and seismic data from 1983 to 2002 and 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 to 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 (Stark, 2003, Oppenheimer 1986). 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 (Julian et al. 1993; Kirkpatrick et al. 1999; Ross et al 1999). Ross et al. (1999) 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 sources may 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 (Perkins and Gonzalez, 1985). 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 this project, 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. These 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 are 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, 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 (Julian et al., 1996, Foulger et al, 1997) has been reported in using microearthquakes 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.

Project Objectives

The overall goals of this GRDA project were to:

1. Provide scientific data supporting public awareness and acceptance of seismic issues related to increasing or sustaining geothermal resources in California using wastewater injection.

2. Provide a routine approach and methodology for continued monitoring at The Geysers.

3. Develop and apply microearthquake analysis methods that allow the operators of The Geysers (or other) geothermal fields to improve the understanding between seismicity and injection such that electrical generation can be optimized.

Technical Objectives

1. Establish and maintain a 23 station, three-component, digital (minimum 16 bit) telemetered array, which can detect and locate below magnitude1.0 events (target is 0.5) in the production area at The Geysers. The data would be obtained in real time and processed for location (in space and time), size, and source characteristics.

2. Establish a comprehensive data base of all waveforms recorded by the array

3. On a subset of the data, establish the relation between injection parameters and seismic attributes through correlation with available production, reservoir, and injection data.

4. Provide a database to the general community of seismicity in real time for all events above magnitude 2.0

Report Organization

This report is organized into three main sections, the background, rationale, and objectives of the work, the approach we took in meeting the objectives of the projects, and the results of the work. As will be seen a major effort of the project was putting in place a capability that could be used by the scientific community to study seismicity associated with fluid injection in geothermal reservoirs. Examples are given on the use of the data; however, it was impractical to include the thousands of events and the data. In the conclusion section references are made to websites which one can access the data and get the locations, magnitudes of the events and waveforms.

PROJECT APPROACH

The overall strategy was to upgrade and expand the previous LBNL array, which operated in the southeast section of The Geysers prior to this project, in order to cover the entire Geysers production region. Shown in Figure 1 is the current USGS array of instruments that is used for locating earthquakes in Northern California. While useful for general seismicity patterns it cannot, nor was intended to provide, the detailed information needed for the goals of this project. Figure 1 also shows the upgraded array, a combination of existing stations now operated by Calpine, LBNL stations, and new stations as part of this project. The new array is operated from a public access point of view, providing near-real-time information on event hypocenters and magnitudes independent of industry control, (yet maintained in the future by the industry) as well as state-of-the-art data needed to support both research on subsurface fluid flow issues of interest to the geothermal energy producers and fundamental research on earthquake mechanisms.

Independent research organizations experienced in this technology like LBNL and the USGS will more easily promote the public confidence that would make the enhancement of geothermal electrical generation through wastewater injection feasible.

The overall technical goals of this work were to:

1. Provide scientific data supporting public awareness and acceptance of seismic issues related to increasing or sustaining geothermal resources in California using wastewater injection.

2. Provide a routine approach and methodology for continued monitoring at The Geysers.

3. Develop and apply microearthquake analysis methods that allow the operators of The Geysers (or other) geothermal fields to improve the understanding between seismicity and injection such that electrical generation can be optimized.

In order to meet the stated goals the work was divided into three main tasks: 1. High resolution, wide-band data acquisition and coverage, 2. Processing, analysis, and integration of the data with reservoir data, and 3. Data transfer and availability. As stated above, our general approach was to test and demonstrate state-of-the art seismic monitoring and analysis. The goal is to provide a readily available, continuous high-resolution wideband data set that can be used to investigate the relationship between fluid injection/withdrawal and seismicity and provide a publicly accessible data set for both independent research and public scrutiny.

Task 1 Data Collection

The purpose of this effort was to design and install a seismic monitoring system covering all of The Geysers and its immediate surroundings with spatial resolution and detection threshold comparable or superior to the temporary 1997 LBNL SE Geysers array. The system now includes 23 state-of-the-art short period seismometer sites continuously digitally 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. (See Figure 1 for locations of the stations relative to The Geysers and the existing USGS array). Remote GPS timing and three component sensors are providing the desired capability with 23 stations of coverage over the area. Full array downtime should be less than 1% of each year and degraded sensitivity due to system failures less than 5% each year. There will be an overlap of the existing array in order to assure repeatability and a comparison of the new array versus the old array data.

To achieve our processing goals we must be able to locate the earthquakes as well as possible, in both time and space. We have demonstrated in past work at The Geysers that we can locate events to within 50 meters of precision and 100 meters of accuracy in The SE Geysers by using the technology used in this project, (Kirkpatrick, et al, 1999). We must also be able to detect and locate event down to very small events, possibly down to magnitude 0.5, or lower. We feel that this level of precision and accuracy is necessary Geysers-wide to have the quality and volume of data to meet our objectives. The analysis and processing being carried out consists of high precision locations; source mechanism studies, and last but most importantly, correlation with the injection parameters to establish between seismicity and reservoir performance. Although all of the data is being recorded, this project does not require detailed processing of all of the events. A subset was selected in the main injection area and compared to areas outside of the injection in order to determine an optimal yet cost effective long term processing strategy which could be employed after this project is completed.

Task 2 Availability of MEQ data

The prime objective of this project is to make a high-resolution comprehensive dataset available to the public and research community. The scope and budget of this project does not allow for complete analysis of every event recorded. However, the complete waveform data will be there for future and additional analysis by the operators or other who wish to use it. To satisfy the public need we felt that it was necessary to implement near-real-time public availability of the MEQ's via the Internet. This would include an event list for The Geysers short period array: origin time, magnitude, location (in Lat-Lon or, by choosing an option on the host page, in CA State Plane Lambert Coordinates), and subsea depth (km or CA State Plane ft) at a magnitude level of 2.0 and above. These data will be sent to the USGS and provided on their Internet site. In addition all events located would also be in the larger database at the UC Berkeley/USGS Northern California Data Center (NCDC)

In addition to the seismicity above magnitude 2.0, there is the seismicity below 2.0 down to the detection threshold of the array (assumed to be near magnitude 0.5). These data are of tremendous research value in developing an understanding of the dynamic nature of the relationship between seismicity and fluid flow in the subsurface. Upwards of 2000 events were recorded per month down to a magnitude of 0.5. Due to the large volume of data it would be prohibitively expensive to provide processed results in real time. Nor was it anticipated that this project will totally process every event recorded, only a subset is needed for the research objectives. However, it is critical this never-before-obtained resolution and bandwidth in a seismically active area as this be made available in a timely fashion to the research community and other interested people. Therefore, a complete list of all events recorded will also be available such that the general public can request all time series and station data in a standard format. Complete time series for a recent subset of events will be publicly available at no cost by FTP file transfer. For large requests requiring media transfers, any charge for such a service should directly reflect standard LBNL charges for similar services provided.

Task 3: Data Processing, Analysis and Integration

One goal of studying the earthquake locations and source characteristics is to determine the physical mechanisms at work, which generate the seismicity. A subset of events in the injection area was selected for detailed analysis. All events above the detection threshold were recorded and autopicked and located for the entire array. On the subset of detailed events in the injection area the data were examined for the temporal and spatial variation of the size (magnitudes, moment), and energy release. These attributes were then correlated with available reservoir characteristics. Constraints on inducing mechanisms will be provided both by the location of seismicity in relation to known reservoir parameters and conditions, as well as by results from analysis methods that attempt to model displacements or forces at the source directly from characteristics of the waveform from a particular event. For example, a comparison of LBNL's SE Geysers MEQ hypocentral locations with spatial variations in reservoir pressure in the Calpine area revealed that MEQs were not present in the areas of highest pressure, even though these were areas of active production and/or injection (Joe Beall, pers. comm., Kirkpatrick et al, 1997.

The nature of displacements at the actual event hypocenter was studied by considering the radiation pattern generated by various source models and their orientations. Early studies of source mechanisms utilized the polarity of P-wave arrivals to determine "fault plane solutions" for Geysers earthquakes

(Hamilton and Muffler, 1972; Denlinger and Bufe, 1982; Oppenheimer, 1986), assuming that the source is simple sliding along a planar surface (double couple). These early studies generally found that the types of failure were mostly strike-slip and normal faulting, similar to regional events; orientations of fault planes were also similar to that observed for regional events. An important result indicating that the regional tectonic stress is acting in the Geysers MEQ generating process. The inducing mechanism must be a "trigger" which causes reduction of the local stresses opposing the tectonic forces, or, alternatively, locally increases strength so that an aseismic, creep-type response to the regional stress, is converted to a stick-slip type of response, as suggested by Allis (1982). The three-component, high resolution, broad band data from the proposed array allows moment tensor evaluations to be performed, a similar but more sophisticated analysis which utilizes both polarity and amplitude of both P and S-wave arrivals. For example, Ross et al (1997) used the PASSCAL data collected by the USGS in 1991 to determine well-constrained moment tensors for 24 events at The Geysers. Most events could be modeled by a double couple, but 25 percent of the events strongly departed from double couple and had significant positive volumetric components. Ross et al (1997) suggested that combined shear and tensile failure, or fluid flow-accompanying failure could account for the observations, and that the injection of water is likely to be the cause of the volume increase. Steam extraction might be expected to cause events with negative volumetric components, but such events were not observed. Geodetic measurements have documented that horizontal and vertical contraction of the reservoir has occurred; if no events with negative volumetric components can be found, then a question to address is, is such strain occurring by non-seismic processes. Other models have been advanced to explain this, but are yet to be verified. A key goal of in this project was to collect the necessary data to sort out the different mechanisms associated with the seismicity in order to have a better understanding of the overall reservoir behavior as a function of time.

PROJECT OUTCOME AND RESULTS

Array Installation

As stated above the plan was to cover The Geysers area with a modern digital, high dynamic range, wide band array using 3-component geophones. Part of the cost sharing was to augment the 13-station system which was already owned by LBNL with 10 more multi-component digital stations. The existing equipment was a Nanometrics 16 bit, multi-channel, 480 samples/second system (RD3) which was telemetered to a central site with wide band with (50,000 hertz) Ultra High Frequency radios (436-440) Mhz band). Purchased through this project was an upgraded Nanometrics 24 bit multi-channel 500-samples/second system (Trident). In addition to the digitizer in the new system there also resides at each site a communications controller (Janus-IP) which is aligned to universal time with a Global Positioning System receiver. This new system then sends data to a central site via spread spectrum radios (900Mhz.). Although the two systems were from the same manufacturer there was considerable effort involved in mating them together. During the first seven months of the data recording (April 2003 through September 2003) the two systems (RD3 and Trident) each ran independently (essentially two different arrays) each with similar triggering thresholds (6 stations must receive a trigger within a specified time window) and archiving the data at the central site. The data were then sent to LBNL and combined for processing. Data were transferred between the two data hubs via an internet connection provided by Calpine. At first the network connections could not handle the data rates so LBNL had to purchase data repeaters so that the data rates over the long transmission distances could be maintained at an acceptable rate. Figure 2 shows all of the stations in the LBNL array. This figure also shows the points where the new electronics are installed (Trident system) and the points where the old electronics (RD3) are located. As can be seen the new electronics are installed in mainly the Southeast Geysers and the older electronics are installed over the rest of the field, there is some overlap, however. Although this was not an optimal configuration for the array it did provide six months of consistent background data prior to the Santa Rosa injection which started in early December of 2003.

In October of 2003 Nanometrics finally provided the software to combine the data such that all of the stations could be treated as one array. At this point in time the array was operating as designed. Then in November of 2003 lightning struck (which is very unusual for this area) at the northern hub, taking out all of the stations telemetered to this site, essentially the old electronics. We had installed lightning arrestors on all the electronics, which protected the computers, but almost all of the front-end electronics in the radio receivers (eight) were blown out. Due to the type of radios and age of the radios, they had to be sent to the original manufacturer (Monitron in Tulsa Oklahoma). Unfortunately, the repair was not finished until late February of 2004. Data were still being recorded with the new electronics but the array was again not operating at full strength. In early March of 2004 the array was again up to full strength and has continued that way to date of this report.

Shown in Figure 3 is an example of two different sizes of events (small event magnitude 0.7, and a larger event magnitude 2.12) recorded on the LBNL system and the Calpine system. One of the main reasons for installing the LBNL array was to increase the dynamic range of the data. The importance of doing so is illustrated in the top four panels of Figure 3. As can be seen the small event is recorded on both systems without clipping, but on the larger event the data are clipped, thus preventing accurate waveform analysis. Also of note on these waveforms is the accuracy of the automatic picks and the "hand" picks. The Calpine data are digitized at 100 samples/second, thus only allowing on an auto picker 10 millisecond accuracy on an auto pick, where as the LBNL are digitized at 500 samples/second allowing 2 millisecond accuracy on automatic picks. In addition the LBNL autopicker even beats the hand picks on the large events by a small amount and the by a much larger amount on the small events. We have come to the conclusion that for almost all events (95%) the auto picks beat the hand picks on the LBNL system, and is much more consistent than hand picks which are subject to human variations, especially if different people are doing the picking.

Data Analysis

The goal was to develop a data analysis procedure that permits real-time automation of all the processing steps, from the retrieval of the events as they come in to the system to the forwarding of waveforms, picks, and locations to a website. The process is initiated by event file transmittal from the acquisition computer, located at The Geysers, to the processing computer located at LBNL. The events are sent every hour via FTP in zipped format. As the events arrive, they are unzipped and converted from the Nanometrics format to the more standard SEG-Y format. The SEG-Y event files are then processed.

Event processing entails the picking of P-wave arrivals for all stations, quality determination of these picks, location of the event, and magnitude determination of the event. In the following discussion, several constants are used for averaging, comparison with the ratio of Short Term Averaging (STA) to Long Term Averaging (LTA), and determining other parameters. These constants were all determined empirically through many trials using several different values. The pick program is based on the

Automatic Seismic Processor (ASP) programs for the automatic detection and analysis of microearthquakes (McEvilly and Majer, 1982). The event time series $X(t_i)$ for the vertical component of each station is manipulated to prepare for the automatic picking routine. Initially, the mean is removed form the time series, and a new time series, $X^{'}(t_i)$ is formed by:

$$X^{'}(t_i) = \frac{\sum_{j=i-n}^{i} |X(t_i)|}{n}.$$

Where n is taken to 16 is this case based several trials.

A long-term average (LTA) of $X'(t_i)$ is calculated to estimate the background noise for the particular component and event. Based on many trials using several different averages, the LTA is calculated as the average of the first 2048 non-zero values of. Zero values are ignored because they are most likely due to radio dropouts and should not be calculated with the LTA. A short-term average (STA) is determined at each point in $X'(t_i)$ to be the average of the following 16 values, again determined by several trials to perform best. Beginning at the first value of $X'(t_i)$, the STA/LTA ratio is evaluated at each point and when this value reaches 6.0, a “trigger” point is defined. If this never occurs, the station is discarded, and the time series from the next station is evaluated. This trigger point occurs after the actual first arrival time. After a trigger point is defined for a station, the STA/LTA ratio is again evaluated from the beginning of X’(t_i) and a preliminary P-wave pick is defined when the ratio reaches 4.0. The STA/LTA evaluation process then reverses itself from this point, and the P-wave arrival is determined to be the point where the STA/LTA ratio drops below 1.2. After comparing many of these picks to where the actual P-wave arrival would be picked by a human, it was observed that the picks were often very early for high amplitude stations. Therefore an algorithm was added to improve these picks by finding the first significant change in the first derivative of the summed traced, $X'(t_i)$ after a pick was determined using the previous method.

After the P-wave arrival is determined, the duration is calculated by finding the length of time in $X'(t_i)$ after the arrival time that it takes the STA/LTA ratio to drop below 4.0. If this does not occur (due to the limited length of the time series that is stored), the duration was estimated by adding a value of 80 x LTA/STA to the total time. A duration magnitude relation was empirically determined using durations and the corresponding USGS magnitudes for several hundred events:

$$M = 2.94 \times \log_{10}(\text{duration}) - 0.57.$$

The polarity of the arrival is determined by taking the sign of the average of four samples after the pick and four samples before the pick. A pick quality (PQ) is defined as the ratio of the sum of the 64 values after the pick over the 64 values before the pick. The quality of the P-wave arrival picks is checked using several methods:

1. If the duration is less than 0.20 seconds the pick is removed;

2. If several samples before the arrival have the same value, it is assumed that there is a radio drop-out and the pick is removed;

3. Using a weighting scheme:

a) If PQ ≤ 2.5 the pick is removed

b) If 2.5 < PQ ≤ 4.5 the weight is 4

c) If 4.5 < PQ ≤ 5.5 the weight is 3

d) If 5.5 < PQ ≤ 7.5 the weight is 2

e) If 7.5 < PQ ≤ 10.5 the weight is 1

f) If 10.5 < PQ the weight is 0

The location program will not use a pick with a weight of 4, but the picked is saved for other possible uses.

After the time series for each station is processed for a P-wave arrival, the event can be located. The event is located using a program developed by Michelini (1991) which can also be used to perform a simultaneous inversion for location and velocity model. At this point, the program is used only to determine the location of the event. The velocity model used is taken from that used by the Calpine array:

Table 1 Velocity model used by both Calpine and LBNL

Depth (km)	Velocity (km/s)
0	4.00
1	4.43
2	5.12
3	5.47
4	5.58
5	5.62
6	5.86

If a good location is found for the event, the location and travel time picks are re-formatted into the USGS hypocenter format and this is bundled together with the SEG-Y file in a tape-archive (tar) file for transmission to the UC Berkeley Seismographic Station.

Automated Processing

A Perl script was written to automate the processing steps. The program works on both UNIX and Windows systems with minor adjustments. Presently the events are automatically processed and sent to USGS using the following steps:

- Unzip the event directories
- Format the “Y” files into a single SEG-Y file
- Automatically pick the first arrivals using the method described above
- Perform bookkeeping of the data

- Locate the events
- Reformat the pick files and location files to standard USGS format
- Tar the files into a “send” directory
- The “tar” files are automatically sent to Berkeley, using send file, the second they are moved to the “send” directory
- Berkeley archives the results and sends them to USGS where they are integrated into the NCDC and archived

These steps take only a few seconds to perform once the event file is sent from The Geysers to the “processing directory” at LBNL. The USGS website where the locations can be found is

Results of Data Processing

One of the primary objectives of this work was to examine the seismicity and changes in seismicity due to a large influx of water from the Santa Rosa pipeline. The array was deployed over the entire Geysers field rather than just the planed injection region to examine the field -wide response to injection rather than just in the injection area. The hypothesis being that the increased microearthquake activity is due to a diverse set of mechanisms. That is, there is not one “triggering” mechanism 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 always been a debate about the relation between the location of the microearthquakes 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. Unfortunately, the injections were delayed for well over a year from the assumed schedule of this project (the original planned start of injections was fall of 2002, actual start was December of 2003). This allowed only a few months of monitoring after the injections started before the scheduled end of this project.

Figure 4 shows the rate of seismicity from 1965 to the present. The data are for magnitudes above 1.5 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 events (magnitude 3’s the seismicity has stayed fairly constant since 1985. There is also no clear relation between total injection and seismicity, except if one looks at all events above 1.5. As can be seen there are peaks in seismicity in 1986 and again in 1998, where there were peaks in injection. It is also important to point out that as steam production has decreased since 1986 the overall seismicity has remained fairly constant.

If one considers the energy release over time, rather than just a count of earthquakes, then one gets a different picture. We took the same information in Figure 4 from 1984 to the present and looked at the energy release over time by using an energy-magnitude relation Log 10 E = 11.4 + 1.5 M, (E = energy in ergs, M = magnitude of the event). Figure 5 shows the rate of seismicity (total events above M = 1.5) for The Geysers area since 1984. If one converts the magnitudes to energy one obtains the results in Figure 6. As can be seen the rate of energy release is actually decreasing as a function of time.

If one looks at the SE Geysers a slightly different picture emerges. The SE Geysers had an increase in injection in 1997 from the Lake County pipeline. Seismicity has been steadily increasing since the mid-1980's, as can be seen in Figure 7, as has the energy release (Figure 8). In recent years there has been a leveling-off of the energy release, and, to a lesser extent, the seismicity.

In terms of data from the new array no definite conclusions can be drawn yet due to the short time of monitoring of the effects of the Santa Rosa pipeline. Also, the LBNL array has had different times of monitoring with different modes of operation during the startup. A constant, however, which one can possibly normalize to, is the number of triggers on the new electronics, the 10 stations that have been operating almost continuously since early 2003. Figure 9 shows the number of triggers (6 stations had to detect and event in a one second window to be a trigger). Triggers are not as susceptible to number of stations as are locations, that is, many events that are triggered on are not located due to signal to noise ratio. As can be seen the number of triggers in 2003 are fairy constant. The large gap in October is when all stations were operating, so the data are not shown. Figure 10, however, shows the number of triggers when the October data are included. As can be seen the number of triggers increases slightly when 22 stations are operating, but by not a great amount, thus somewhat proving that triggers from the 10 stations is a good indicator of seismicity.

Shown in Figure 11 and 12 are the events located by the LBNL array for 10 days in March of 2004 and all of March 2004. Figure 13 are all of the events located by the LBNL array in October of 2003, i.e. one month prior to the start of injection. Also shown in these figures is the location of the magnitude 4.4 on February 18, 2004. The October and March time periods were chosen because the seismic array was fully operational during these times and the October period is before the injection and the March period is after the injection start up in December of 2003. These plots clearly show there is an increase in overall seismicity in the injection area. 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 (Kirkpatrick et al, 1999; Beall et al, 1999; Smith et al, 2000) and it is not surprising that is occurring now. If past experience is any indication the system will reach an equilibrium as time proceeds and seismicity will level off and possibly decrease. It has been our experience that the initial injections will perturb the system, cause an increase in seismicity, then level off and/or decrease. The time period will be a function of the size of the disturbance and the volume of the affected area. Rate 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. Also, as pointed out about the historical seismicity at The Geysers, the yearly energy release is actually decreasing. The recent injections may reverse this trend but it is to early in the monitoring process to determine. Last but not least, what will be the impact of the maximum event size? The maximum event at the Geysers was back in 1982 (4.6), but in the past year there have been 3 events of magnitude greater than 4.0 (see Figure 4). 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 has been no faults mapped in The Geysers which would generate a magnitude 5.0 or greater. This is not an absolute guarantee that one would not happen, but does lower the likelihood.

All of the above issues will be addressed over the next several years as the network continues to operate and the injections continue and possibly increase the then NW. The Aidlin project will be particularly important because the injections will start out small and increase over time. The new DOE project will address the basic issues and provide the data to more fully understand induced seismicity.

DISCUSSIONS

Benefits to California

Our project emphasizes the approach necessary to optimize the use of injected water at The Geysers California geothermal field. It also addresses important environmental issues that may control the rate of the injection. It does so by providing scientific data supporting public awareness and acceptance of seismic issues related to wastewater injection programs aimed at increasing California's electricity producing geothermal resources. This project is expected to build public confidence in the management of wastewater injection, reduce the costs associated with injection, and improve the overall electricity output of this environmentally friendly, renewable, electrical energy source.

Use of wastewater injection for support of electricity producing geothermal resources is important because it addresses environmental concerns ranging from air quality to water quality. For example, injection of 7.8 million gallons per day of a wastewater-Clear Lake water mix, piped from Lake County's Southeast Regional Wastewater Treatment Plant to The Geysers, California geothermal field, is increasing generation, and extending the useable life of the resource. It is estimated that these effects have resulted in up to 70 megawatts of generation, beyond what the field would have otherwise provided, that will continue to serve the electrical needs of approximately 90,000 residential customers over the 23 year operating life of the project. Thus wastewater injection effects enhance the availability and longevity of an inherently low pollution form of electrical generation. In addition, this injection of Lake County wastewater eliminates overflow of treated sewage into Clear Lake/Cache Creek, and lowers the already low carbon dioxide emissions of associated geothermal power plants by as much as 10%.

Seismicity associated with wastewater injection will become an increasingly important issue at The Geysers. The City of Santa Rosa is evaluating the possibility of expanding their disposal from the current 11 million gallons per day of water from their treatment plant to as much as double that volume. As with the Lake County project, Santa Rosa liquids will, over the 20-year life of the project, contribute to equivalent low air pollution generation increases of up to 85 megawatts, serving up to 115,000 residential customers. The City of Santa Rosa selected The Geysers option as the lowest cost beneficial use alternative, and to overcome the intense water quality-based opposition to increased wastewater disposal into the Russian River. Use of The Geysers will eliminate the need for disposal of the treated water in the Russian river. Thus, Geysers injection of treated Santa Rosa wastewater addresses environmental issues related to water quality, and reclaims the water for the beneficial use of California electricity ratepayers.

The potential economic impacts of seismicity-related public opposition to, or speculative regulation on, Geysers wastewater injection could be substantial. Tax and royalty revenues, as well as employment, could be impacted. Property tax and royalty revenues to county governments from wastewater related contributions to generation would amount to approximately $500,000 annually. Similar figures for total Geysers generation are approximately $3,000,000. In addition, the California State Lands Commission and the US Bureau of Land Management each receive over $4 million annually in Geysers royalties. Currently, approximately 475 individuals are employed in direct support of Geysers electrical output. Limited availability of, or elimination of, wastewater injection to boost and extend Geysers power output, would reduce both short-term and long-term power generation capacity. Initially, county revenue effects are larger than anticipated manpower reductions. Over a five to ten year period, loss of the extended commercial viability afforded by wastewater injection, would result in significantly accelerated: resource decline, power plant retirements, and lost jobs. Geysers power plant capacity lost to such accelerated retirement will have to be replaced with another, possibly less environmentally friendly, and more expensive, source of power.

Benefits of our work apply both to the public and private sectors. The project will open a new era of ready public access to high quality, state of the art, and seismic information, on a scale never previously available from The Geysers. The information will be provided in a standardized format with several levels of complexity in order to meet a range of needs from concerned citizens to seismologists. Basic scientific knowledge acquired from the work should be applicable to any environment associated with fluid injection or withdrawal in the Earth's crust. Geysers related geothermal industry benefits will include establishment of an non-industry monitoring and reporting system capable of providing the high quality, publicly credible, seismic data, 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 scientific and/or practical knowledge derived from this project is beginning to reach the appropriate end users. Raw and reduced data produced from the monitoring efforts is, by design, being rapidly and automatically processed by a data reduction system, and made available in near "real-time" mode via web pages on the Internet. This task is being handled by the University of California Seismological Station, which acts a clearinghouse for seismic data collected throughout the State of California and the U.S. Geological Survey Northern California Earthquake Center. Public and private researchers have complete access to available data. It is believed that ready availability of these data to a broad spectrum of researchers could result in an increased understanding of the fundamental processes involved in fluid movement in the Earth's crust. This information may find application in several disciplines including geothermal energy production, non-geothermal electrical energy production, petroleum recovery, and earthquake studies. Results are also being made available to public scrutiny through meetings of the Seismic Monitoring Advisory Committee, a Lake County body mandated by the EIR process associated with the Southeast Geysers Effluent Pipeline (Lake County wastewater) project. This information is also of keen interest to residents in the vicinity of The Geysers who experience felt earthquakes.

In a research projects such as this it is difficult to quantify the total economic impact. It is likely, however, that during the life of this project information will be gained which will be the prime motivator for operational decisions which will increase net production by at least several megawatts. Currently, there is a large untapped portion of The Geysers 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 the Northwest Geysers, where 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 life times and retrofitting of power plants to handle the high gas contents. Access to this large underutilized resource will significantly increase the energy capacity and output of The Geysers.

Integration with Production and Injection Activities

The array is currently operating as designed. Approximately 80 to 100 events are located each day with this array. The data are being archived at LBNL and the USGS. One can search the USGS database by time, area or both thus providing a means to correlate the MEQ data with different parts of the field. As demonstrated in the results of the data processing section there is a strong correlation with the injection activities and wells in the field. As noted many times there is also seismicity away from the injection wells which is not as “clustered” as the seismicity associated with the injection wells.

Effects of the injections are being seen in the form of increased seismicity around the injection wells. This has commonly been observed in The Geysers due to injections. A magnitude 4.4 was observed in the northern part of the field on February 18 of 2003, but a considerable distance away from any injection wells. Several magnitude 3’s have also been observed since the start up of the Santa Rosa injection. As more detailed data are gathered and the total response of The Geysers field is examined due to injection will we be able to study these larger events in the context of the overall seismicity.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The primary objectives of this project have been met:

1. Installing an upgraded array which can be used for many years into the future for monitoring the seismicity at The Geysers with increased bandwidth and dynamic range using multi-component sensors.
2. Integrating the data into the USGS database and providing real time access to the locations and magnitudes. All locations, magnitudes and waveforms will be available to the public and scientific community. Access can be gained by logging on to the website http://quake.geo.berkeley.edu.

3. An initial analysis of the effects of the Santa Rosa injection on the seismicity base at The Geysers. This initial analysis shows that the Santa Rosa injection has caused an increase in seismicity around the injection wells, not inconsistent with past experience.

Unfortunately this project ended with just a few months of data after the start of the Santa Rosa injections. Effects of the injections are being seen in the form of increased seismicity around the injection wells. This is a very common effect at The Geysers when injection starts. Since the start up of the Santa Rosa injection several magnitude 3s and one 4.4 has occurred. From past experience however, this is not unexpected, and similar rates of activity were observed prior to the Santa Rosa injection start-up from other injections. Whether they were "triggered" by the injections or if the total energy release will increase over time, level off or keep increasing as rate of injection increases is still a subject of debate, but as more detailed data are gathered and the total response of The Geysers field is examined will we be able to address these questions.

Commercialization Potential/Technology Transfer

Almost all components used in this work are from current commercial vendors. The innovative products would be in the processing and software developed for this project. The algorithms are available to the public which were published by McEvilly and Majer (1982). These algorithms were recoded by LBNL and could be licensed for commercial use. The main benefit will be to the geothermal community in general in using the future data from The Geysers array (see benefit to California section) to understand the effects of injection on induced seismicity.

Recommendations/Suggestions for Future Work

In January of 2004 the US Department of Energy funded an extension of this work to keep the array running and expand the array to coverage of the Aidlin area, a region northwest of the current main production area. This area is the target of an Enhanced Geothermal Systems project by DOE to maximize the steam out put. The current array installed by this project is state-of-the-art in every way: station electronics, digitization, GPS, radio link (spread spectrum) and central data processing. The LBNL array that existed prior to this project is also state of the art in every way except in the radio link. That array does not use spread spectrum radios but UHF (400 Mhz.) radio links. In 2001 that was adequate technology but as cell phone technology, wireless data transmission and other RF sources have increased at The Geysers, the interference has increased to an unacceptable level. (One can observe this by the great increase in the number of antennas on Cobb Mt). This interference causes dropouts in the data from the UHF stations, creating holes in the data stream. At a minimum one should replace 6 of the radio pairs with spread spectrum radios which are not susceptible to the interference. The second suggested upgrade would to redistribute the electronics of the existing array by placing 5 wide bandwidth stations (30 seconds to 100 hertz) throughout The Geysers. These 5 wide bandwidth stations would be interspersed with the existing stations to provide spatial coverage of The Geysers. The short period electronics from the 5 stations replaced by the broadband stations would be used for the Aidlin expansion. This would provide broadband coverage as well as high frequency coverage of the entire field. The advantage would be a more complete coverage of data for understanding source mechanisms. The reason that this is important is that one hypothesis of the induced seismicity is stress induced seismicity from long period data (distant large magnitude events). The long period data would provide information to address this hypothesis.

Another possible future activity would be to apply advanced analysis of the MEQ data. The original work with the Geysers data (Kirpatrick et al, 1999), and carried on to the subject work, was motivated primarily by the desire to have a processing capability that would allow the thousands of seismic events per month to be analyzed in real time and extract any general seismic parameters that could be associated with production and injection data. The primary emphasis was on seismic parameters such as event locations that could be associated with fluid migration and second-order moment tensors that could be associated with mode of failure in terms of opening, closing, or sliding of cracks. In order to meet the requirements for rapid automatic processing with the computers available at the time, it was necessary to make a number of simplifying assumptions in setting up the processing software, such as a simple velocity model, frequency-independent ray theory, and characterization of a seismic phase with the two parameters of arrival time and amplitude. By taking advantage of improvements in computer speed, developments in the theory of elastic wave propagation, and new ideas about seismic sources, it is now possible to make a number of significant improvements in the methods that were developed for processing the Geysers seismic data.

Given the number of stations now recoding high frequency digital seismic data, it is necessary to develop a more detailed velocity model for The Geysers field. This could be done in two parts, a one-dimensional model describing the average depth dependent material properties and three-dimensional model describing perturbations from this model. Developing the model in this manner has advantages in terms of the inversion methods used to estimate the model, such as the Born inversion methods as well as the methods used for forward wave propagation in source location and moment tensor estimation.

Currently we are using the first arrival amplitudes to compute moments of the events. Improvements in computer speed and new theoretical methods make it feasible to locate seismic events and estimate moment tensors by processing the complete waveforms recorded on seismograms. This avoids most of the sources of uncertainty associated with identifying phases, measuring arrival times, and estimating amplitudes that are contained in the current processing methods. This part of the research would be closely connected to the estimation of an improved velocity model that is described above, which means that there would be a continuous monitoring of any temporal change in the material properties of the reservoir.

Another improvement over the last two years is the interpretation of source data in terms of an asperity model for an earthquake. Recent analyses of small earthquakes along the San Andreas Fault have resulted in the development of an asperity model of an earthquake that provides an alternative to the conventional model that has dominated the interpretation of seismic data for the past forty years. Given the large number of small seismic events and the opportunity to estimate stress changes caused by the withdrawal and injection of fluids, the Geysers appears to be an ideal site for applying some of the techniques that were developed for the study of the small San Andreas events. Should the data indicate that the asperity model helps to explain the seismic events at the Geysers, our understanding of why these events are occurring could be significantly advanced.

Furthermore, with the density of stations and large number of events it will be possible to interpret velocity anomaly data in terms of fracture density. Composite medium theory is a useful method of explaining the material properties in complex near-surface sites where rocks of various types, voids, and fluids are all present. Efforts are now underway to extend this theory so that it more accurately incorporates the effects of fractures and any fluids that they may contain. An important property of this theory is that it produces frequency-dependent velocities, which means that some of the uniqueness problems that are encountered when interpreting seismic velocities in terms of material properties can be addressed, particularly with the high-frequency data that are recorded by the seismic arrays at the Geysers. A particularly attractive scenario that exists at The Geysers is the possibility of interpreting in a uniform manner any temporal changes in event location, moment tensor, and material properties in terms of fracture density, orientation, and fluid content.

It should be pointed out that while the enhanced analysis is being tested and developed all of the data will be processed with the current data flow. Also, all of the data will be archived in full waveform so that all of the data can be reprocessed with the new data flow if necessary.

Last but not least one should determine which new processing methodology could be integrated into the routine automated flow.

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FIGURES

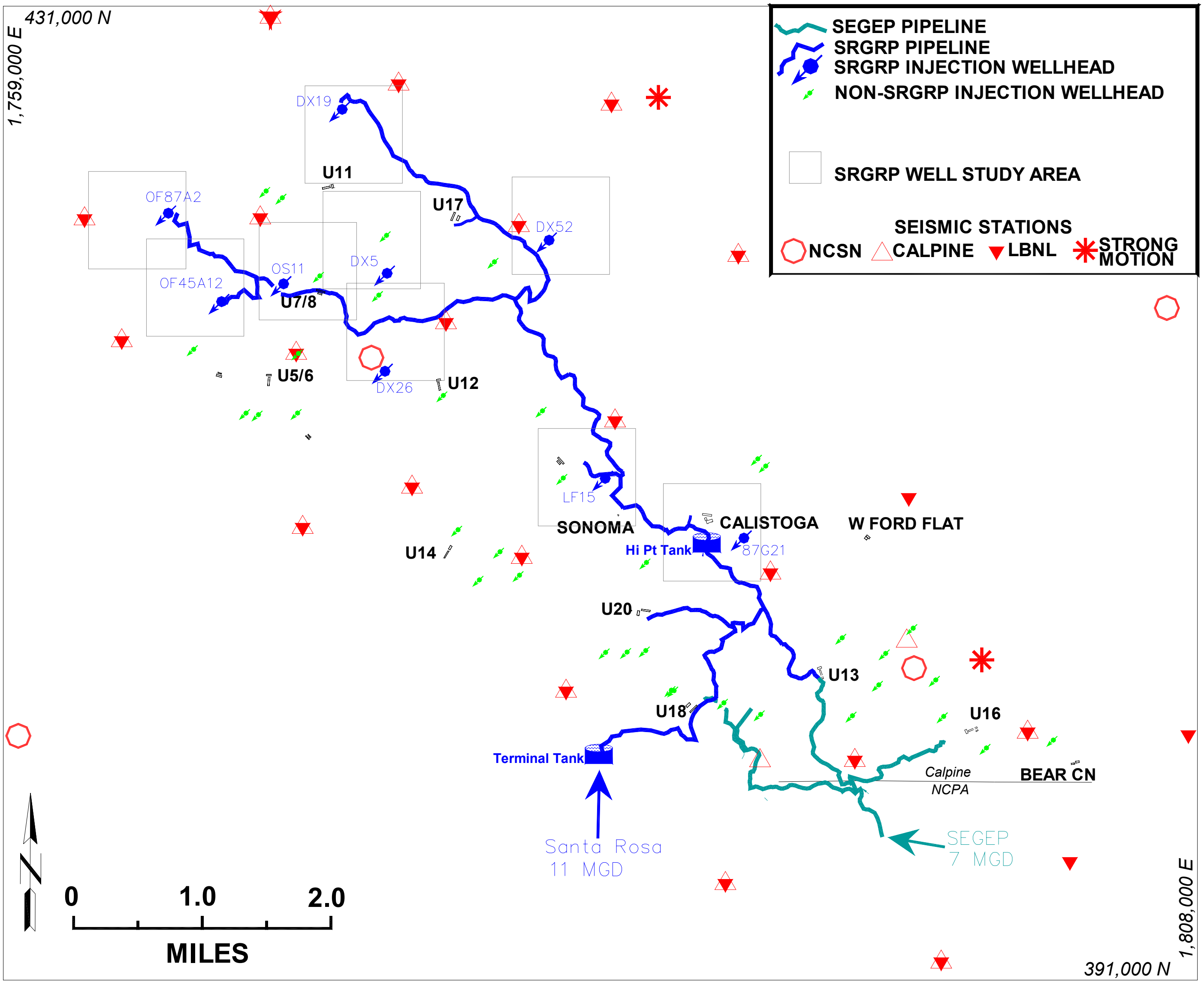

Figure 1. Location of USGS stations, Current Calpine array, and the new LBNL stations. Also shown are the locations of the pipelines used for the water from Santa Rosa.

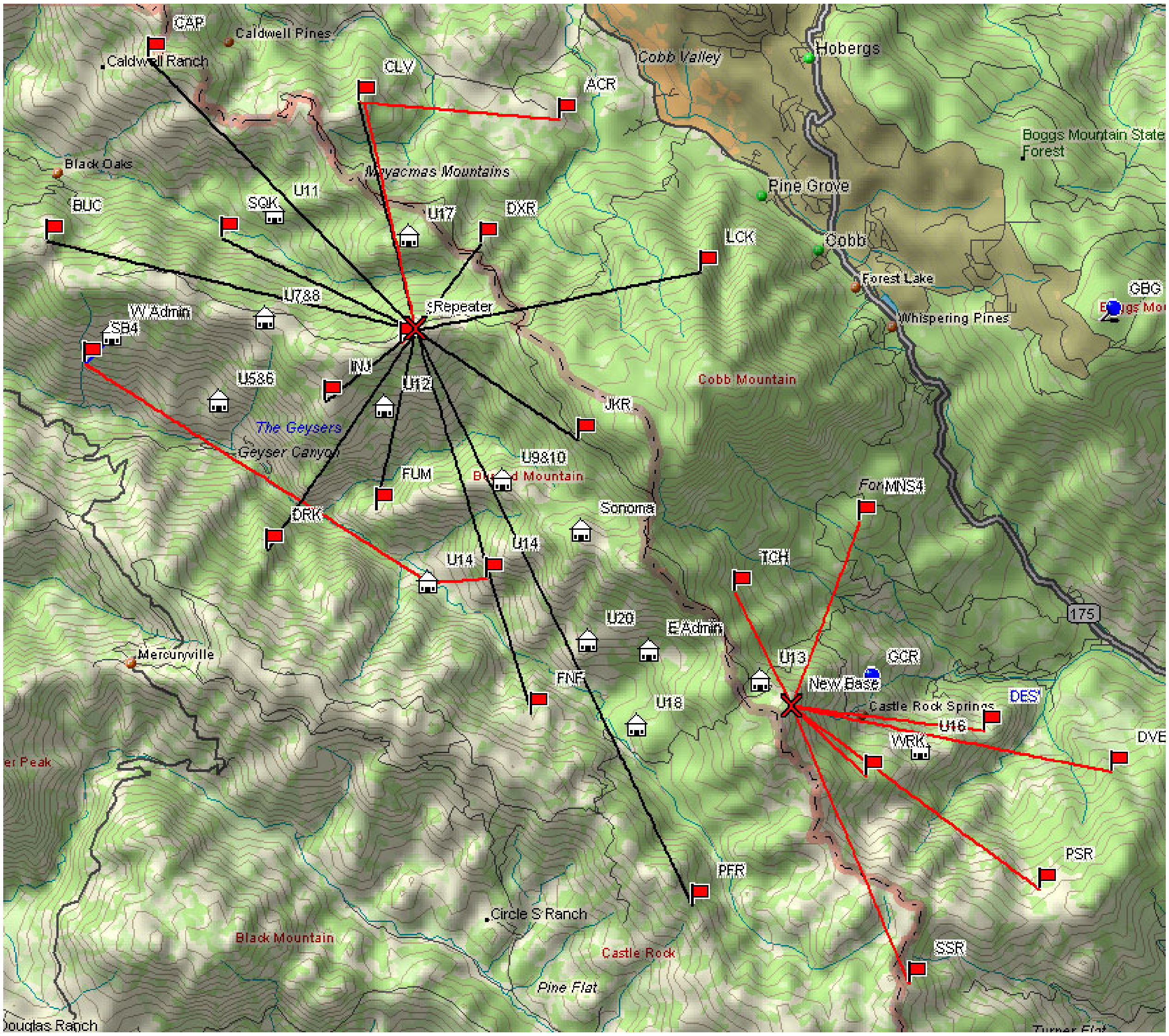

Figure 2. The locations of the different LBNL stations showing the new electronics (red lines) and the old electronics (black lines). Also shown are the locations of the power plants.

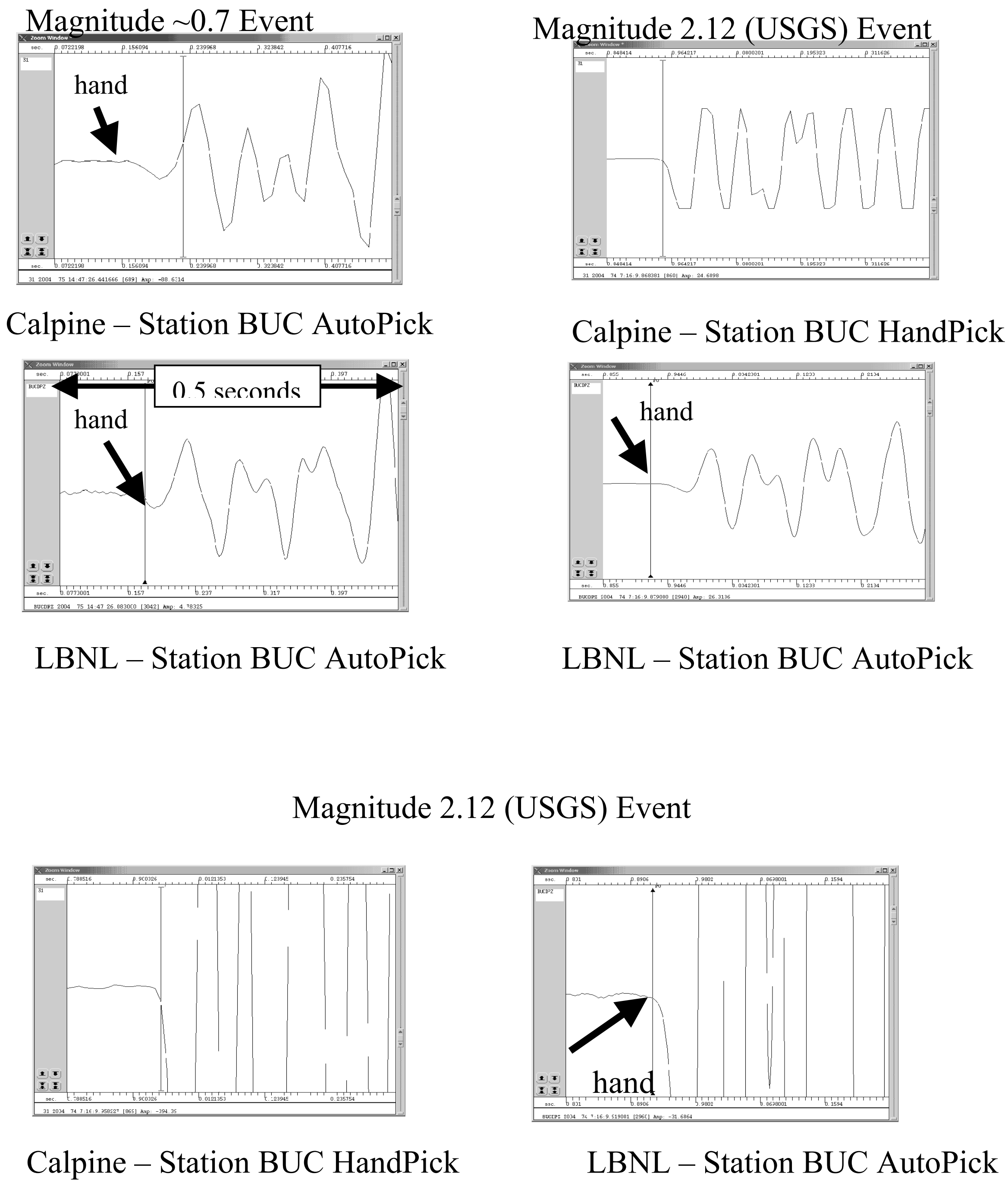

Figure 3. Top four plots compare the pick of the LBNL auto pick to the pick of the Calpine system. As can be seen the LBNL automatic picks are better than the Calpine automatic picks, especially on the small events and better than the Clapine hand picks, even on the large events (see bottom two plots, comparing the LBNL auto pick to the Calpine hand picks). The arrows are where one would pick the first arrival by hand on the auto picks . In all cases of the LBNL system the hand picks are where the auto picks are. The time scale in all figures is about 0.5 seconds in all plots.

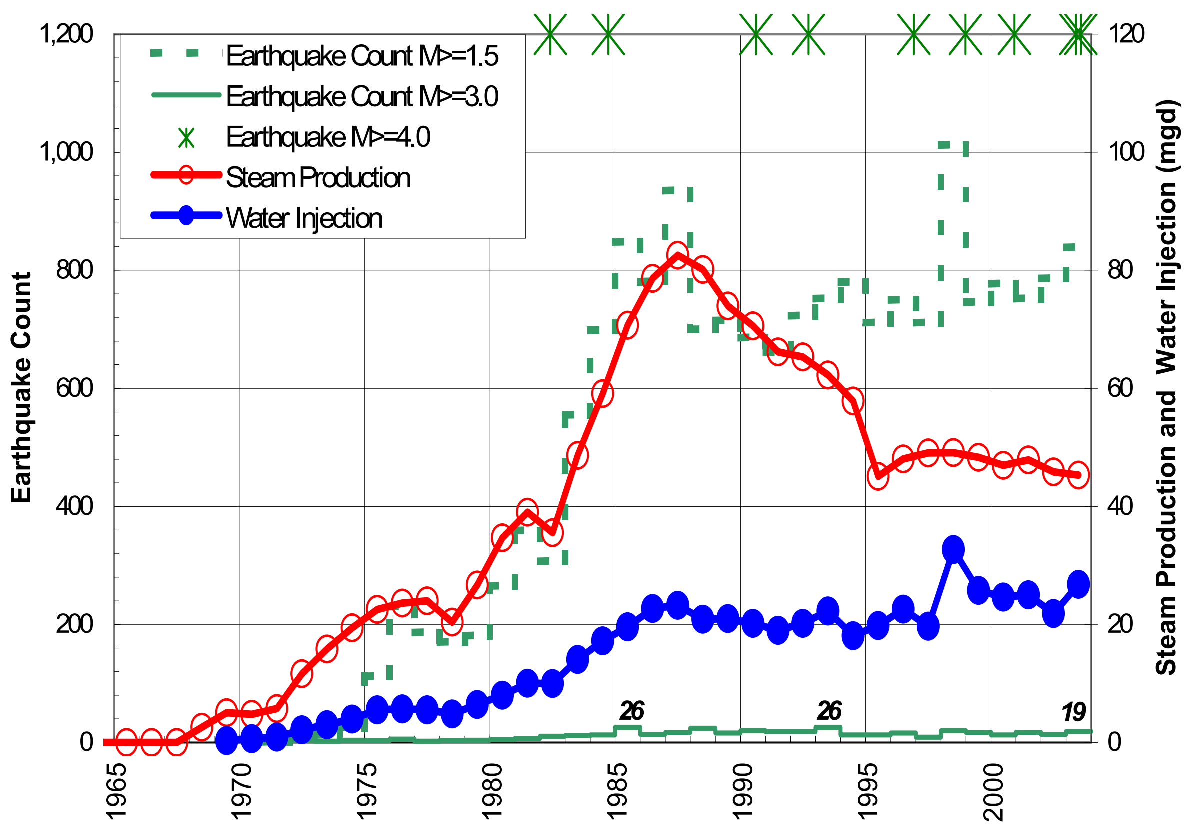

Figure 4. Historical seismicity from 1965 to the present at The Geysers. Data are from the NCEDC.

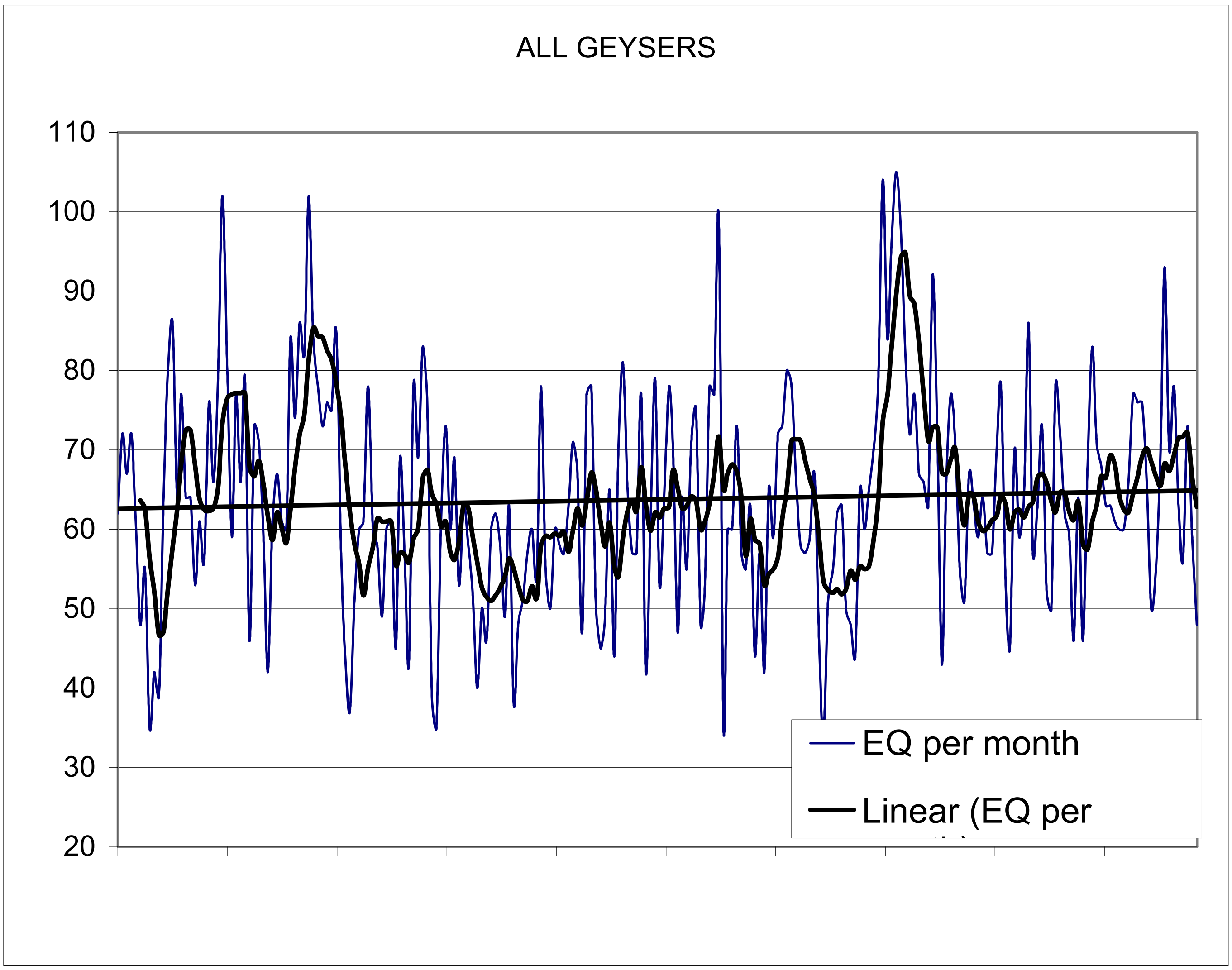

Figure 5. Rate of seismicity for the entire Geysers area since 1984. The line fitted to the data is a linear fit of a 12-month running average.

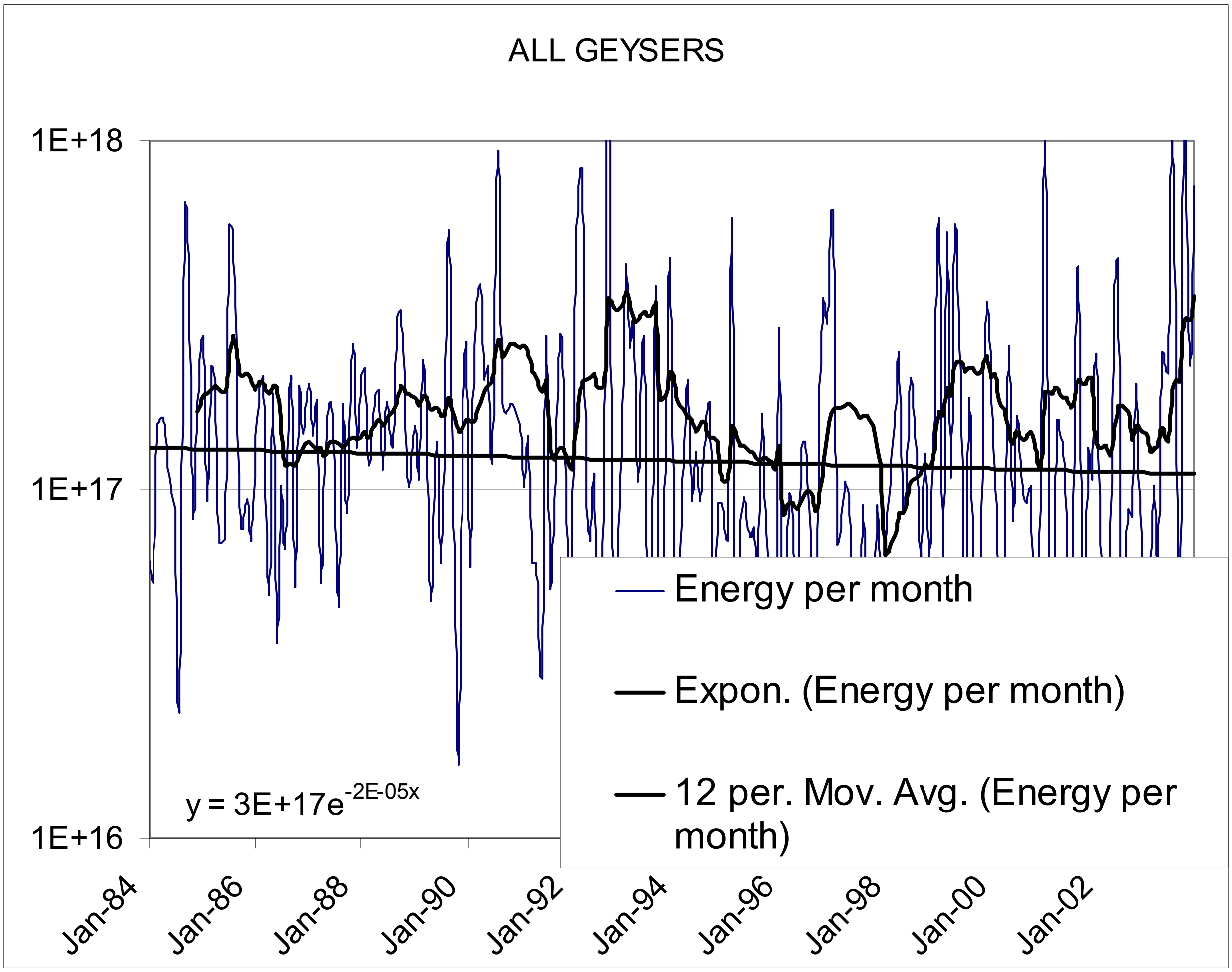

Figure 6. Energy release over time since 1984, the line is a linear fit to a 12-month moving average.

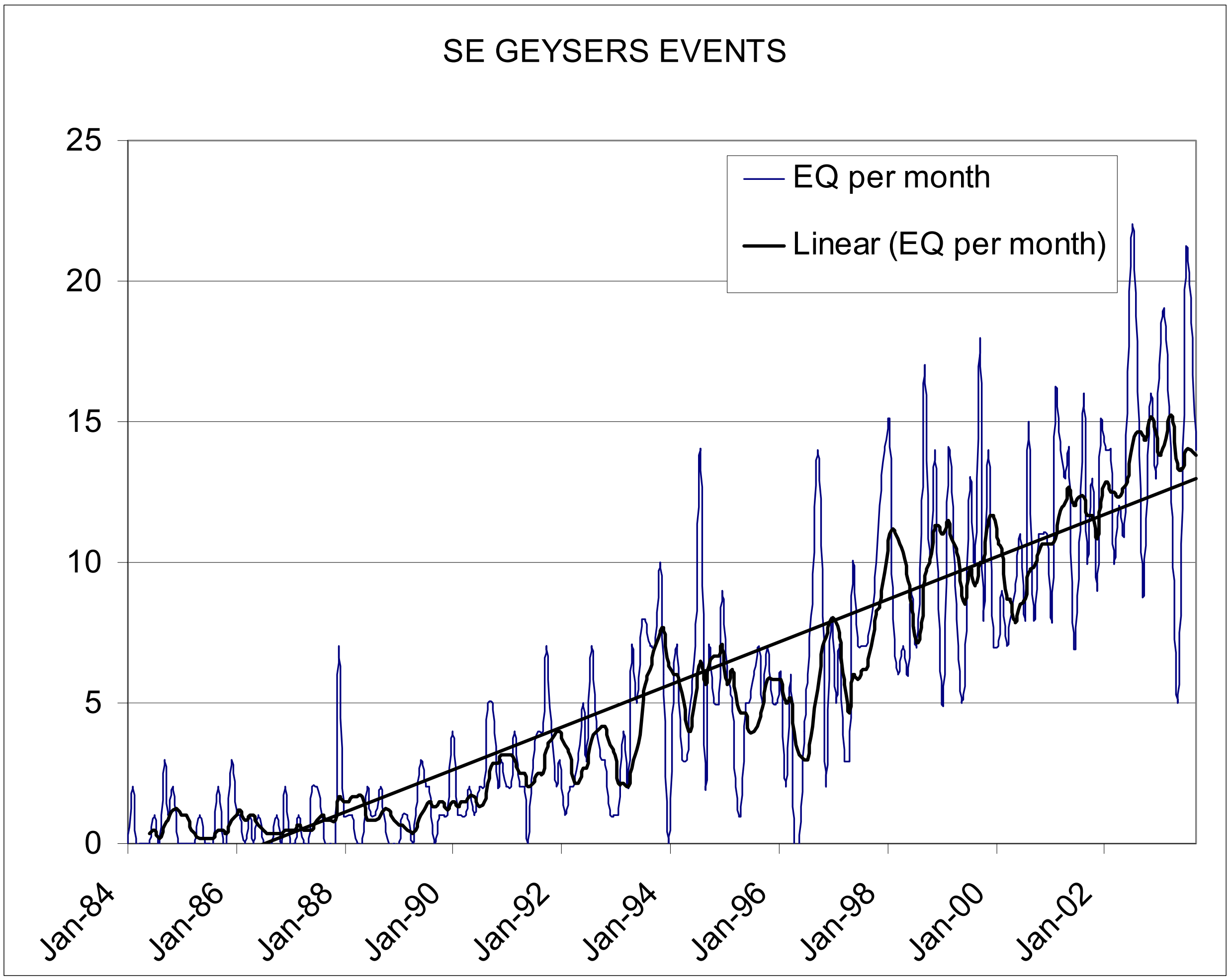

Figure 7. Rate of seismicity for the SE Geysers since 1984. Straight line is a liner fit to the 12 month moving average.

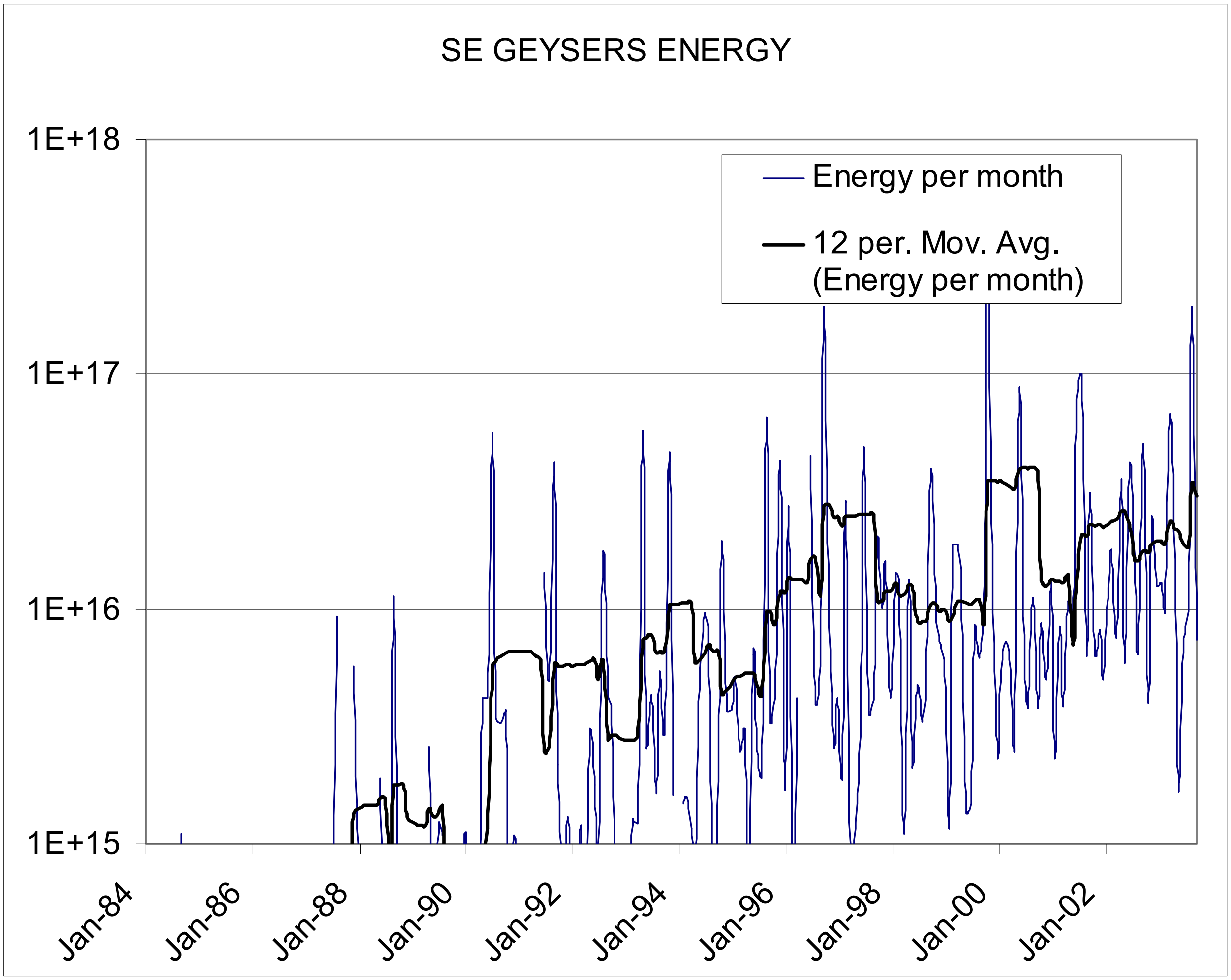

Figure 8. Rate of energy release for the SE Geysers, the black line is a 12-month moving average.

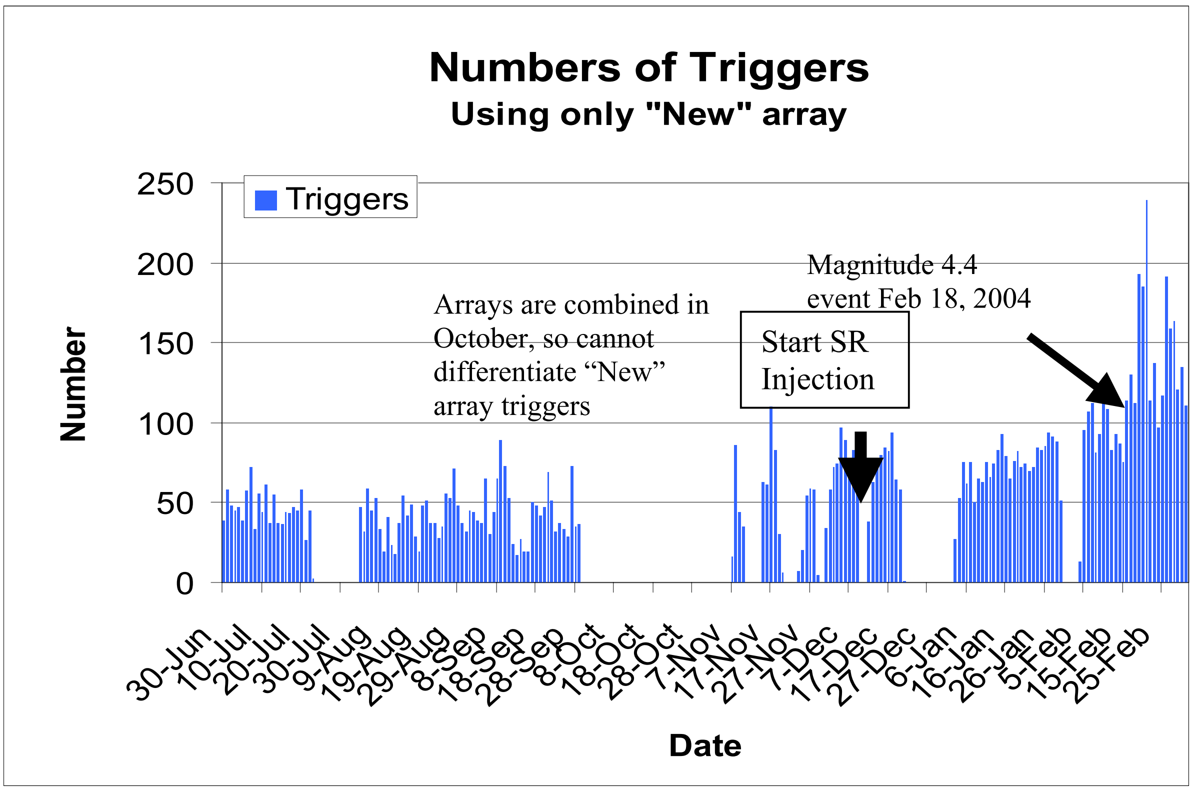

Figure 9. Rate of seismicity in The Geysers as measured by triggers on the LBNL “new” array from 6 months prior to the Santa Rosa injection start to April of 2004.

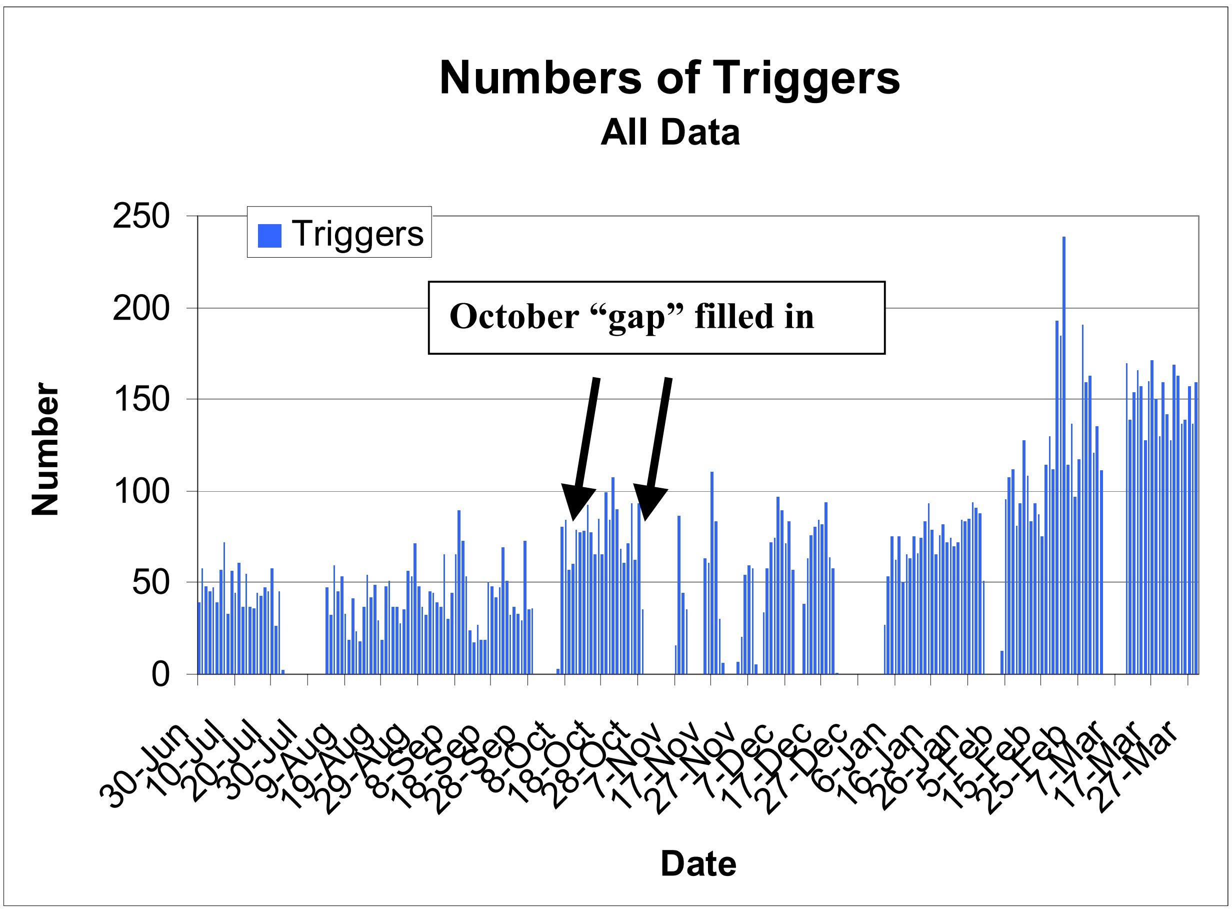

Figure 10. The number of triggers from the LBNL array as a function of time (2003 – 2004) illustrating that the array sensitivity to event detection is not greatly affected by a reduced number of stations. Also of note is the gradual rise in seismicity after the start of Santa Rosa injection in December of 2003.

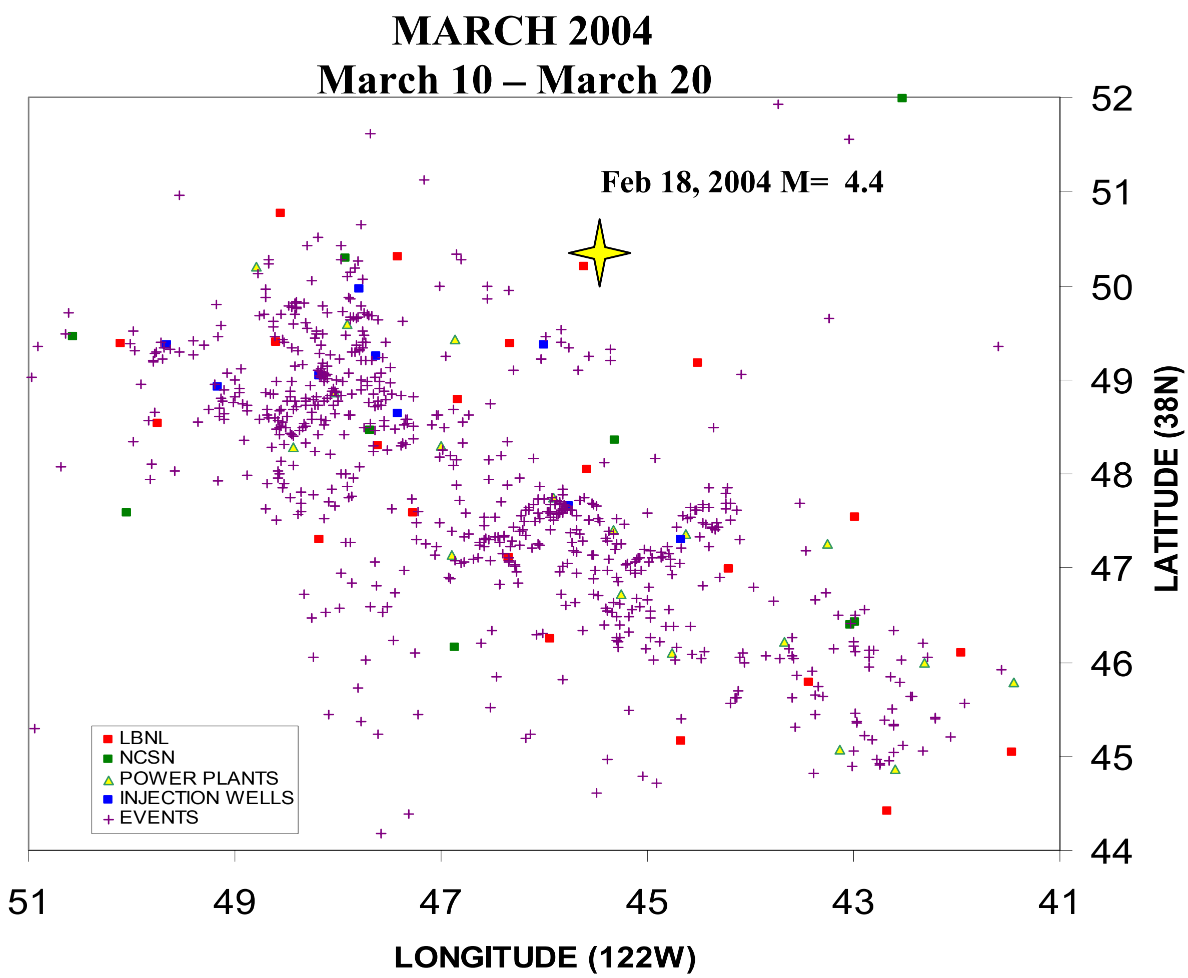

Figure 11. Event distribution for 10 days in March of 2004. The Injection wells are the blue squares.

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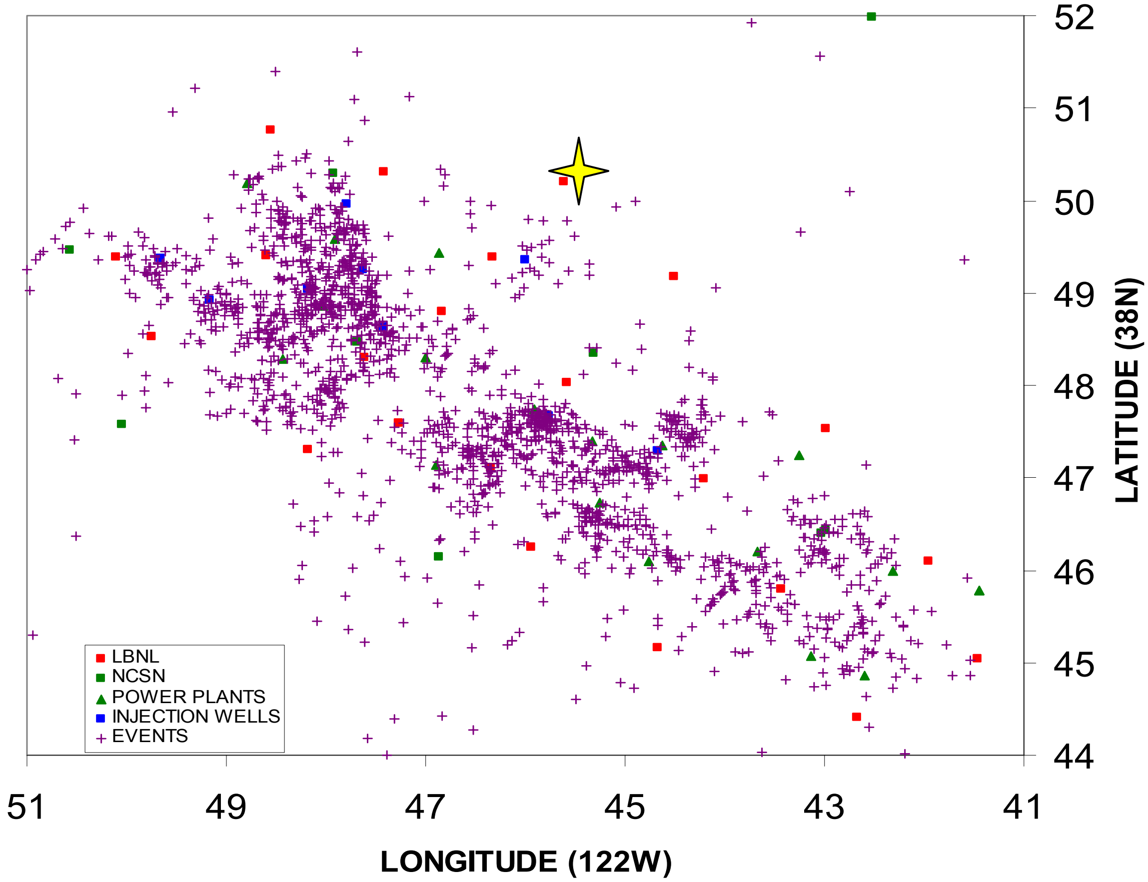

Figure 12. . The seismicity in all of March 2004. The blue squares are the injection wells; yellow star is the magnitude 4.4 that occurred on Feb 18, 2004.

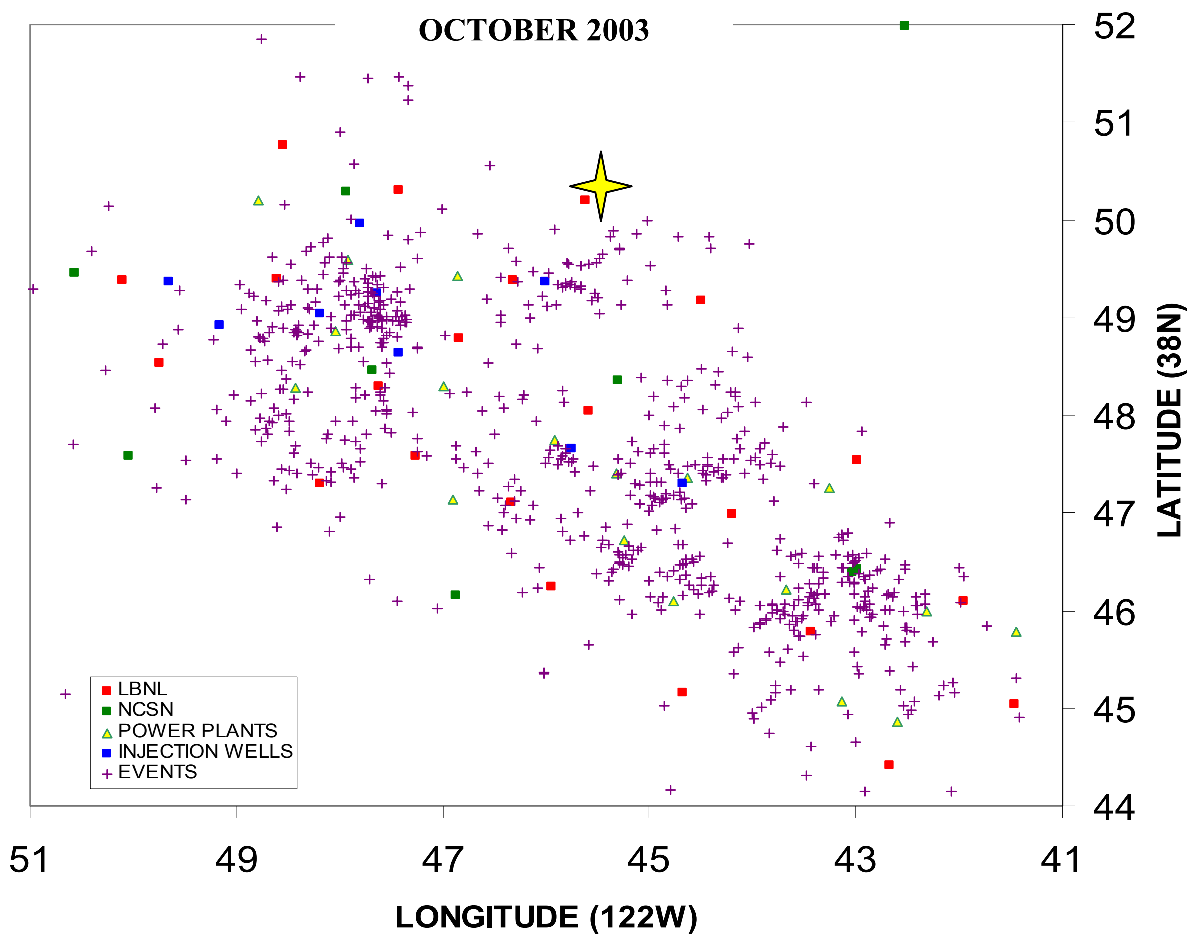

Figure 13. Location of all events in October of 2003, two months prior to Santa Rosa injection. Blue squares are the location of the injection wells. The yellow star is the approximate location of the magnitude 4.4 on February 18, 2004.