Deployment to Investigate Long Period Earthquakes and Remotely Triggered Earthquakes at The Geysers Geothermal Reservoir

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Abstract. The Geysers in Northern California is one of the most seismically active geothermal sites in the world, having at least one hundred earthquakes of magnitude greater than 1.4 per day [Ross et al., 1999]. Previous studies conducted suggests that there has been remote triggering within The Geysers, with at least 11 examples noted so far [Stark and Davis, 1996; Gomberg and Davis, 1996; Prejean et al., 2004]. Remote triggering is when regional events (> 100km distance) trigger a swarm of seismicity. There is some evidence that remote triggering is more common at geothermal sites, such as The Geysers. This year marks the first time that broadband seismometers were utilized in The Geysers. The four Guralp 6-TD broadband seismometers deployed in The Geysers are able to measure both the seismic waves of regional events and local earthquakes at the same time. The installation of the broadband seismometers can assist in the study of the relationship between regional events and its resulting seismic triggering. The goal of this project is to set up an Antelope database for the data collected and see if there is clear evidence of remote triggering. As well, geothermal areas like The Geysers often have long-period seismicity and we will investigate to see if this is evident in The Geysers reservoir.

Setting – The Geysers

The Geysers in Northern California, located just north of the San Francisco Bay area is one of the largest geothermal fields in California, with an area of about 75 km^2. This geothermal reservoir is situated in the southernmost part of Northern California's Coast Ranges with an average depth of 1 km below sea level [Mossop and Segall, 1997]. The Geysers geothermal field is surrounded and dotted by mountains, geothermal wells (Fig 1), by the Clear Lake volcanic field, and by active faults, such as the Healdsburg-Rogers Creek Fault (Fig. 2a.) [Stark and Davis, 1996]. The Geysers contains granitic batholiths and also highly fractured Franciscan greywacke [Stark and Davis, 1996; Mossop and Segall, 1997], which is composed of quartz and feldspar, making up ninety percent of the rocks in the Coast Ranges.

The Geysers and Clear Lake are believed to have been formed about 1.2 Ma [Dalrymple et al., 1999]. According to Dalrymple (1999), these two areas are formed when the Pacific and North American plates interacted, displacing the subduction of the Juan de Fuca plate. Also, the rise of the asthenospheric mantle along the subducted and abandoned oceanic lithosphere thrust beneath North America [Dalrymple et al., 1999], formed a lithosphere gap, resulting in decompressional melting creating The Geysers. The distribution of The Geysers is believed to be strongly influenced by deformation, including local subsidence and the pull-apart basin created by the right-lateral Mecuryville and Collayomi faults (Fig. 2b.) [Dalrymple et al., 1999; Mossop and Segall et al., 1997].

According to Dalrymple (1999), The Geysers used to be a high-temperature, hot-water system with surface temperature exceeding 300ºC, but quickly cooled to less than 260ºC about .26 Ma. Today, the Geysers are vapor-dominated with a near-constant temperature of 240ºC at the surface [Schmitt et al., 2003]. The transition from the original state of a high-temperature system to a low-temperature, vapor dominated system remains unclear. Previous tests conducted imply that the change in environment of the hydrothermal system emerged from quick cooling, quick fluid venting", and the following sealing of the vents [Dalrymple et al., 1999; Allis and Shook, 1999]. The geothermal source of The Geysers today is believed to be from either, a single convecting magma chamber, 20 km wide, with a depth of 7km, or a composite Quaternary plutonic body with a diameter and depth of 4km and 3km, respectively [Dalrymple et al., 1999].

In the past century, the vapors in The Geysers have produced vast amounts of geothermal energy from dry steam emissions from its wells. In the 1980's The Geysers was able to support a capacity of 2000 megawatts [Stark and Davis et al. 1996], which is equivalent to 10.7 million barrels of oil according to the National Renewable Energy Laboratory. However, since that time, energy production decreased with a rate of 5% per year, beginning 1989, but is believed to have stopped after "injection-derived steam" was added in 1998 [Smith et al., 2000].

Motivation

Regional Triggering

The Geysers geothermal field in Northern California is known for generating remotely triggered micro earthquakes. Although 40-50 regular events per day occurs at the Geysers, ranging from M~0.2 to M~2.5 [Gomberg and Davis, 1996; Stark and Davis, 1996], the interest is on the series of remotely triggered micro earthquakes that occur with the Geysers. Some scientists believe that these series of micro earthquakes are triggered by regional events occurring within hundreds of kilometers to thousands of kilometers from the site. Other seismicity within The Geysers are of interest as well, such as the induced and/or triggered earthquakes caused by increased development of power generation [Stark and Davis, 1996], which includes steam withdrawal and water injection [Smith et al., 1996; Ross et al., 1999].

Previous observations have been performed at the Geysers showing the relationship between the micro earthquakes triggered by regional events. These remotely triggered earthquakes are known to begin minutes after the passing of seismic waves [Stark and Davis, 1996]. Evidence for these remotely triggered events in The Geysers was recorded beginning with the 1988 M_w 7.6 Gulf of Alaska earthquake with a swarm of 20 events (Table 1). Evidence were also recorded after the 1989 M_w 7.1 Loma Prieta earthquake, 1991 M_w 6.9 and 7.2 Gorda Plate earthquakes, and the 1992 M_w 7.0 Petrolia earthquake, with a swarm of 33 events, 23 events, and 30 events, respectively

[Stark and Davis, 1996]. However, great interest in remotely triggered seismicity did not occur until after the 1992 M_w 7.3 Landers earthquake. Landers is believed to have had a widespread effect on the seismicity across Western United States at distances up to 1,250 kilometers [Hill et al., 1993]. This event increased seismicity near active geothermal and volcanic systems, including Long Valley Caldera, the Cascades, Yellowstone, Cedar City Utah, Western Nevada, and the Geysers [Hill et al., 1993]. Compared to the other events that triggered heightened seismicity at The Geysers, Landers had the most, with a swarm of 48-58 events in a five hour period [Stark and Davis, 1993]. However, most recently, the 2002 M_w 7.9 Denali Fault earthquake had a greater effect at The Geysers, triggering a swarm of 64 events in an hour period [Prejean et al., 2004].

Other studies conducted at the Geysers indicate that development of power generation increased induced seismicity within the Geysers. According to Smith et al. (2000), before the development of geothermal power in the 1970's, there were only about 4 events with magnitudes less than 3 in the Geysers per day, but increased in to 25-30 per day with the years following. Also, they observed that previous areas that did not show increased seismicity in the Geysers, increased in activity, when geothermal power increased. The United States Geological Survey (USGS) observed that when a fluid injection pipeline was constructed in 1997 to deliver needed water in recharging the reservoir, remotely triggered earthquakes within the Geysers increased [Smith et al., 2000]. According to Ross et al. (1999), the fluid injection into The Geysers induced around 140 micro earthquakes per month with magnitude greater than 1.2. This indicates a major increase in seismicity within The Geysers compared to a few decades ago (Fig. 3).

The studies that have been previously done concerning remotely triggered events within the Geysers, is important in recognizing the connection between the triggering waves from regional events and the locally induced earthquakes. The induced seismicity caused by increased steam production within this geothermal field can hopefully assist in the detection of remotely triggered events. Although numerous studies have been performed concerning remotely induce earthquakes within the Geysers, further study is needed to increase understanding of this phenomenon. To accurately examine the relationship between the triggering waves and the local earthquakes it causes, a broadband seismometer is needed in the Geysers. The previous studies that have been conducted only dealt with data from seismometers from the late 1980's and early 1990's. This year, four Guralp 6-TD Broadband Seismometers have been installed within the Geysers, which have not been previously deployed in the Geysers. These instruments will examine the long-period waves that results in micro earthquakes within this region. According to Prejean and Brodsky (2003), the dense local short-period network of seismometers installed at Long Valley Caldera, just east of The Geysers, can show lack of seismicity right after regional events. This allows the comparison of data collected from the previously installed local short-period networks with the data collected from the newly installed broadband seismometers, which are able to detect other seismicity that the other network cannot, showing if there is evidence of triggering in Long Valley [Prejean and Brodsky, 2003]. This study is what we hope to accomplish at the Geysers with the installation of broadband seismometers. The study resulting from data collected with these instruments will further the understanding of long-range triggering of earthquakes, not only in Geysers, but other poorly documented global geological sites believed to have remote triggering, including Greece and Taiwan [Stark and Davis, 1996; Beresnev and Wen, 1995].

Long Period Earthquakes

Another important aspect that must be studied for further understanding of the triggered seismicity phenomena is evidence of long-period earthquakes at the Geysers. Many geothermal areas are known to have long-period events, which are caused by fluid movement within the geothermal field. These long-period events are believed to be an indication of fluctuating gas pressure within volcanic and/or geothermal systems and resemble small tectonic earthquakes [Chouet et al., 1996]. According to Fujita and Ida (2003), long period events indicate moving volcanic fluid, including magma, water layers, and even sill. This long period seismicity are also seen as a mechanism for a degassing process of a particular volcanic or geothermal area, but does not necessarily indicate volcanic eruption [Pitt and Hill, 1994]. For instance, geothermal fields like, Ngawha in New Zealand and Tongonan in the Philippines [Robinson et al., 1981; Scott et al., 2004], are located within or near active faults and are considered to be non-volcanic.

One of the goals of this project is to investigate continuous data from the deployed broadband seismometers in The Geysers, to determine if these long-period earthquakes are present in this geothermal field. The significance of studying long period waves within this geothermal site is to see if these have any significant effect in triggering of earthquakes in The Geysers. As well, the study will help with the understanding of the previously modeled source of geothermal energy at The Geysers. Studying the long-period events in The Geysers will surely expand our knowledge that we already have of these events by studying a place that has not previously been studied with broadband seismometers.

Antelope Database

In order to study remotely triggered seismicity within The Geysers, we need to organize the data collected from four broadband seismometers into an organized Antelope database. Antelope was developed to support seismic oriented processing and archiving. It creates organized data tables, allowing easy access, documentation, and manipulation of the collected data. The data tables created hold information, such as location, origin, time, waveforms, and magnitudes of earthquakes (Figure 4).

Here we will provide a general outline of how we've created our Antelope database for The Geysers:

1.) Gather sac files and make sure their header values includes required info, including, lat., long., elev., chan. orientation, and sta. name.

2.) Convert sac files from little endian format to big endian format.
3.) Set-up schema by writing a descriptor file, specifying the schema as rt1.0.
4.) Build waveform database using command, **sac2db**.
5.) Verify database using, **dbverify**, which trouble-shoots errors.
6.) To run database, use command, dbe, accesses data tables.
7.) Use **dbbuild** to build new data tables about the broadband seismometer.
8.) Run **dbdetect**, creates detection table, which contains the detection of earthquakes.
9.) Run **dbtrigger**. Dbtrigger will locate seismic events using the detection table created by dbdetect.
10.) Run **ttgrid**, which creates a program for computing a travel time grid file.
11.) Run **dbgrassoc** to associate. Takes the input file from dbtrigger that specifies a candidate list for event association.
12.) Run **dbml** to compute Richter magnitude for origin table in the database.
13.) Now you can locate earthquakes in your database using **dbloc2** (Figure 5).

Preliminary Results/Conclusions

-From the four Guralp-6TD broadband seismometers, around 138 earthquakes per month occurred at The Geysers (magnitude >1.6).

-Figure 6, shows the location of these earthquakes within The Geysers.

-We have not found any evidence of remote triggering at The Geysers as of now. No major earthquake has occurred since the four Guralp 6-TD broadband seismometers were installed on February 2004.

-Previous studies at The Geysers has shown evidence of remote triggering, we hope to do the same.

-If a major regional event occurs.

-We hope to compare the Antelope database that has been created to the continuous data collection from the broadband seismometer to see if there is an increase from the normal seismicity at The Geysers.

-No information on the evidence of long-period earthquakes at The Geysers has been found, further research time needed.

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(a)
(b)

Figure 1. (a) Steam emission from a well in The Geysers. (b) another geothermal well venting off steam.

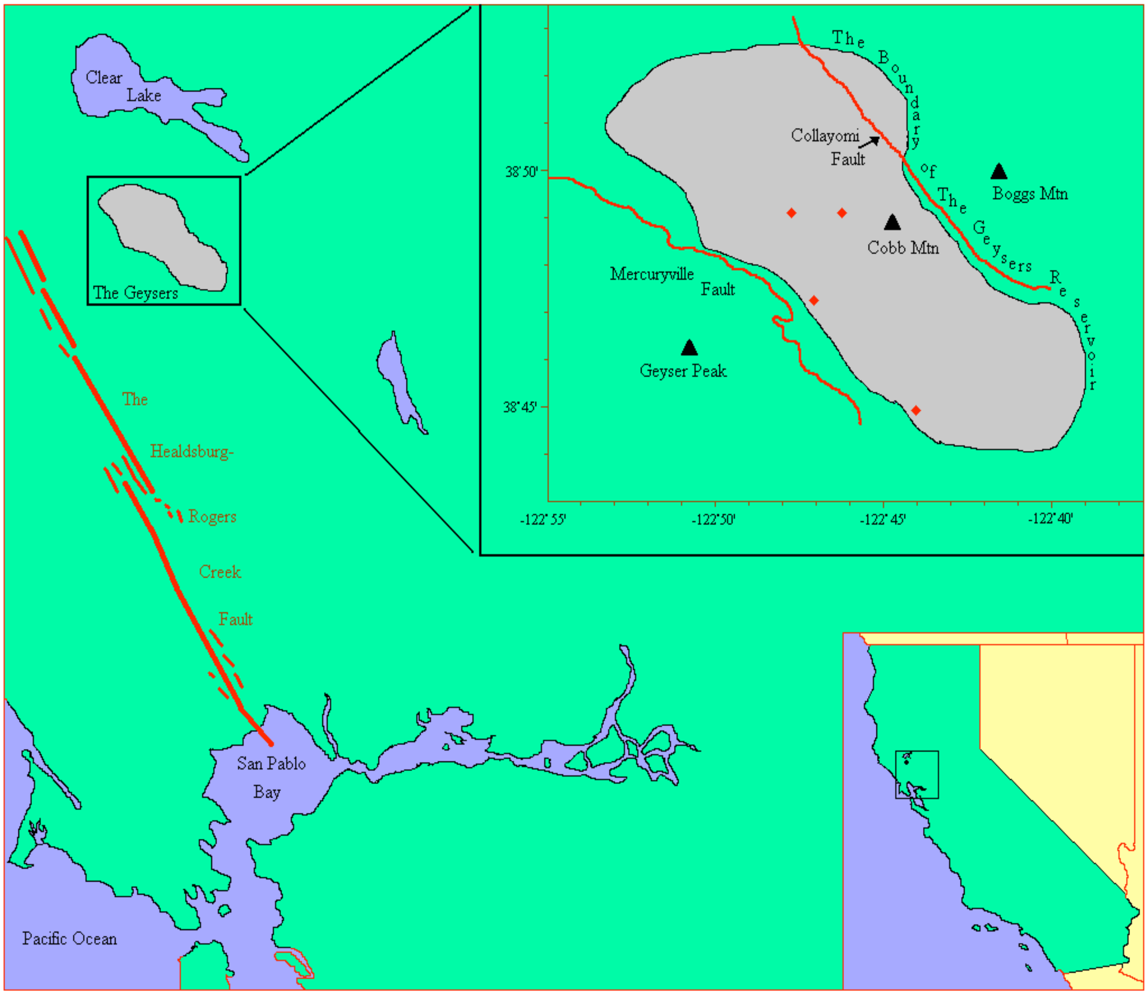


Figure 2. (a) Map showing the location of The Geysers in California and its relative distance from the Healdsburg-Rogers Creek Fault. (b) Shows the relative size of The Geysers geothermal reservoir. Red diamonds show location of 4 broad- band seismometers; the Mercuryville and Collayomi Faults; grey area is the steam production zone; and shows location of mountains.

Table 1. Earthquakes that Triggered Micro Earthquakes at The Geysers, California

Event	Date	Mw	Distance from the Geysers (km)	Number of Events
Gulf of Alaska	03/06/88	7.6	2500	20
Loma Prieta	10/18/89	7.1	210	33
Gorda Plate	7/13/91	6.9	445	
	8/17/91	7.2	400	23
Petrolia	04/25/92	7	220	30
Landers	06/28/92	7.4	763	48-58
Denali Fault	11/03/02	7.9	3250	64

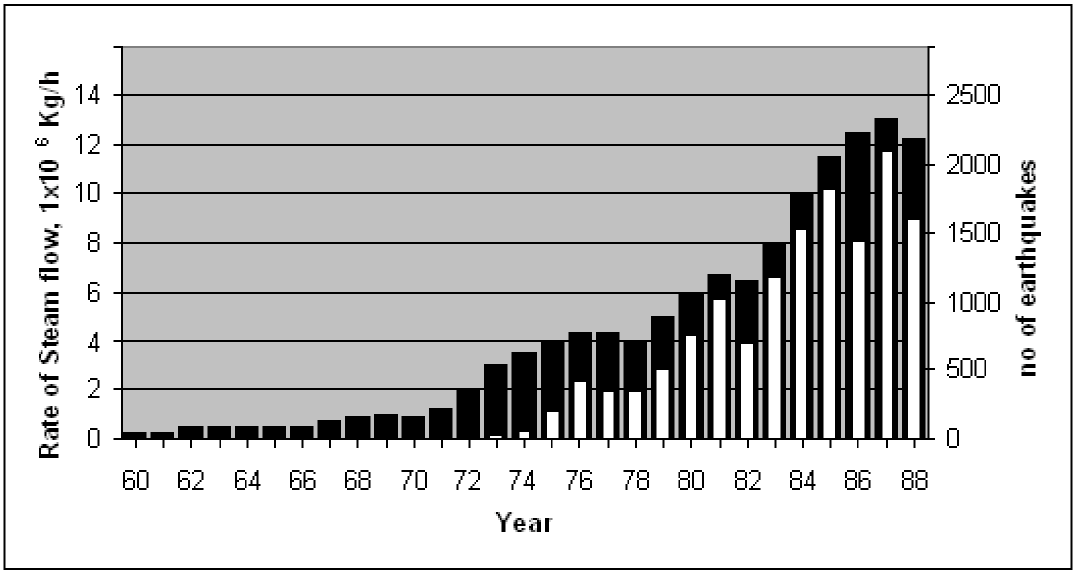


Fig.3. Black columns represent avg. steam flow per hour (1960-1988). White Columns indicate the no. of earthquakes with magnitudes >1.2 recorded in The Geysers (1973-1988) (modified from Ross et al., 1999).

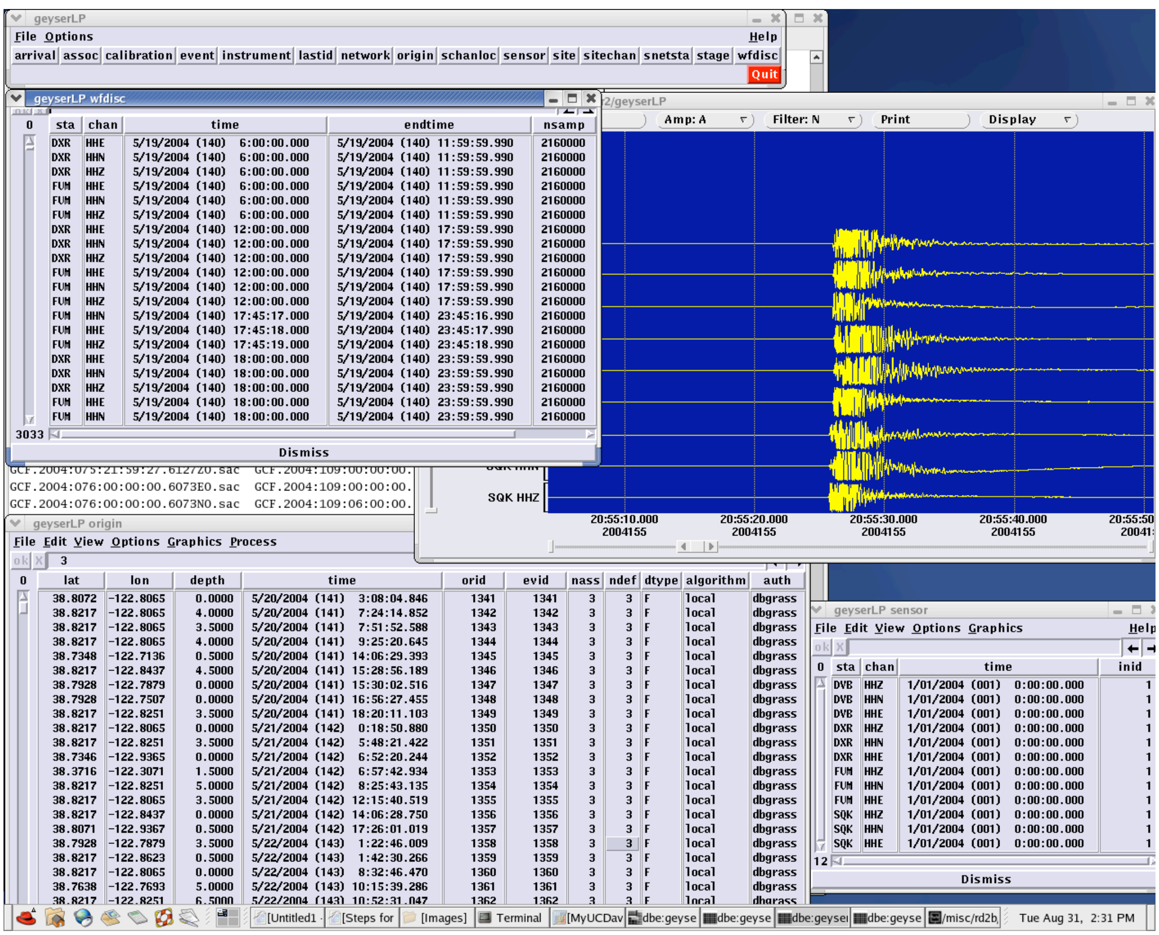


Fig. 4. Screenshot showing the Antelope database. Data tables shown: waveform, origin, and sensor.

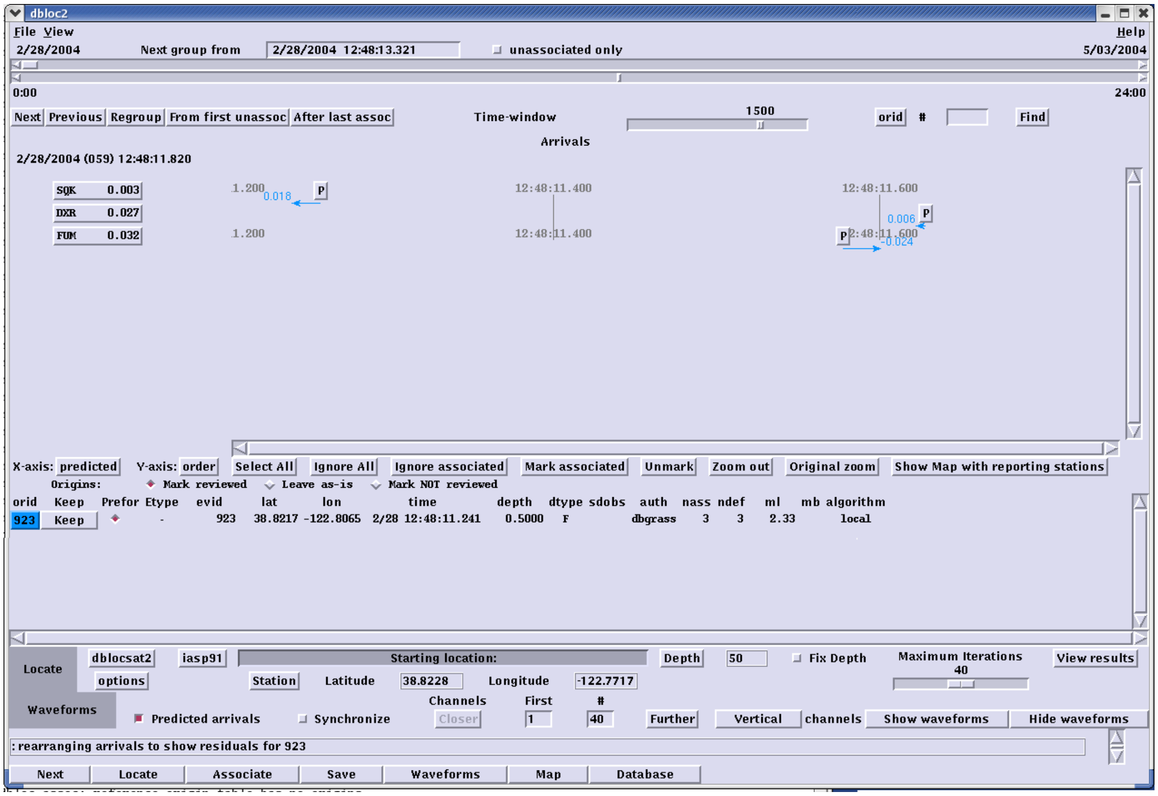
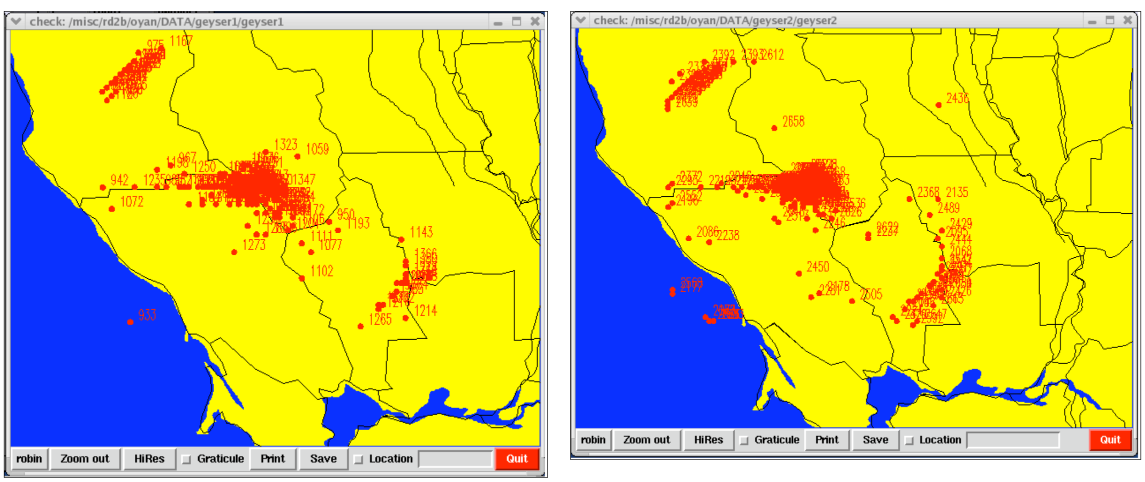


Fig. 5. Example of using dbloc2, shows the arrival time, location, and magnitude of an earthquake.



(a) (b)

Fig. 8. (a) Location of earthquakes at The Geysers from (2/25/04-5/19/04). (b) Location of earthquakes at The Geysers from (5/19/04-7/28/04). The large red cluster for both (a) and (b) indicate the location of The Geysers geothermal reservoir.