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DOE REAL-TIME SEISMIC MONITORING AT ENHANCED GEOTHERMAL SYSTEM SITES

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ABSTRACT

Lawrence Berkeley National Laboratory (LBNL) at the direction of the United States Department of Energy (DOE) Geothermal Technologies EGS Program is installing, operating, and/or interfacing seismic arrays at multiple Enhanced Geothermal Systems (EGS) sites. The overall goal is to gather high resolution seismicity data before, during and after stimulation activities at the EGS projects. This will include both surface and borehole deployments (as necessary in available boreholes) to provide high quality seismic data for improved processing and interpretation methodologies. This will allow the development and testing of seismic methods for understanding the performance of the EGS systems, as well as aid in developing induced seismicity mitigation techniques that can be used for a variety of EGS systems in the future. Current sites include Desert Peak and Brady's Hot Springs, Nevada, the NW Geysers project, as well as the entire Geysers area, Raft River, Idaho, Brady's Hot Springs, Nevada, New York Canyon, Nevada and Newberry Caldera in Oregon. Additional sites will be instrumented as DOE adds projects. Reported are the current status and results from the initial injections and how the public can access the data.

INTRODUCTION

The purpose of this effort is to gather data on seismicity from the various project areas to supplement any existing seismic data as well as provide baseline and ongoing seismic data in the vicinity of the project that will be used to not only forecast induced seismicity activity but understand induced seismicity for mitigation and reservoir management. A main element in determining if induced seismicity will be at or below acceptable levels to the surrounding community is to determine the level of seismic activity that exists before the project starts. That is, how will the geothermal project modify existing "natural" seismicity? Depending upon the location of the project, data may only be available from regional seismic monitoring (10's of kilometers or more, distances between seismic monitoring stations). Experience up to now with most geothermal projects is that sensitivity to seismicity at low magnitude thresholds (magnitude 0 to 1 range) is necessary to determine the location of smaller active seismic zones. Regional monitoring, however, is usually only reliable in the magnitude 2.0 and above. Also, in most geothermal induced seismicity cases, the great majority of the seismicity is below the magnitude 2.0 level, (Majer 2007), thus it is important to know the base level of seismicity at the lower magnitudes. Once natural seismicity is determined these data are will also be useful for determining operational decisions such as directions of stress, source types (faulting types) and other characteristics that will be useful for designing the overall stimulation project. Last but not least, a minimum amount of information will be necessary to collect in order to perform initial screening steps, including some information on the frequency of occurrence of natural earthquakes that will be needed to estimate the potential impact on any nearby real-estate and industrial assets .

DESIGN CRITERIA FOR MONITORING

The seismic monitoring is designed to collect data that is not aliased in time or space in the vicinity of the potential geothermal project. This implies that one should start monitoring at least six months before anticipated injection with an array of instruments that has enough elements, sensitivity and aperture to capture seismicity in the volume at least twice the radius of the anticipated stimulated volume at magnitudes of as small as magnitude 1.0, and preferably magnitude zero The more sensitive the array the more detail will be collected on fault structure, seismicity rates, failure mechanisms and state of stress. These are all needed to not only model and forecast the seismicity, but also to design the injection rates and locations (also useful for designing production wells). Ongoing seismicity also indicates stress build up and release mechanisms that may be more easily triggered by fluid injection. Ideally, one would like as much bandwidth and dynamic range as possible but typical seismic networks for capturing seismicity in these types of applications are targeting the frequency range from a few hertz to several hundred hertz. Twenty four bit resolution is now common at these data rates and should be used. Borehole installations of wide bandwidth sensors are better than surface sensors in order to increase signal to noise ratios and capture small magnitude events which will increase resolution and location accuracy. The sensors (surface or borehole) should supply three component data in order to provide complete information on the failure mechanisms and wave propagation (compressional and shear waves) attributes as well as provide data for more precise locations.

The goal is to provide data such that the minimum processing can provide the location, magnitude and source mechanisms. More sophisticated analysis such as advanced location schemes (double difference, tomographic analysis for improved velocity models, moment tensor analysis and joint inversions, etc.) will probably be needed in the production phase of the projects but unlikely in the background monitoring phase. In order to achieve the above objectives for the DOE EGS geothermal projects (one or two injection wells, several production wells in a five kilometer or less diameter area), at least eight three component stations are distributed over and around each EGS area. Deep or larger projects would require more than eight stations. As the project advances and the seismicity is characterized more stations will be needed to “follow” and characterize the seismicity and utilize the seismicity for not only designing mitigation strategies but reservoir enhancement and management strategies. In certain instances it may be required to “infill” the main array with temporary stations in order to augment the data for such times as initial reservoir creation, or when one changes injection strategies. Last but not least, a consideration should be made weather to have continuous recording or triggered recording. In any case, especially in the injection phase, the data should be processed in close to real time for location and magnitude by examining a continuous stream of data.

The monitoring should be maintained throughout the injection activity to validate the engineering design of the injection (the fluid is going where it was designed to go), as well as, guide the operators on optimal injection volumes and rates. Background and local monitoring will also separate any natural seismicity from induced seismicity and provide a protection to the operators, as well as, make sure that the operators are adhering to local vibration standards. If one is in the vicinity of local communities, the local monitoring should also include less sensitive recorders that only record ground shaking that can be felt, i.e. a few strong motion recorders near any sensitive structures to record vibrations that may be problematic. It is also important to make the results of the local monitoring available to the public in as close to real time as feasible. The monitoring should be maintained at a comprehensive level at least as long as the life time of the project. Depending on the level of the seismicity after the EGS injections stop the seismicity monitoring can be discontinued.

STATUS OF SEISMIC MONITORING

As of January 20, 2011 LBNL is receiving real time triggered data from four different sites, (The Geysers, California, Brady's Hot Springs, Nevada, Desert Peak, Nevada and Raft River, Idaho). There are also arrays of stations recording continuous data that LBNL periodically collects from New York, Canyon, Nevada and Newberry Caldera, Oregon. These latter two arrays do not have internet access , thus the lack of real time access. All arrays are at least eight stations and up to 30 stations (The Geysers) with three component recording. The recording electronics are collecting data at 24 bits and 500 samples/sec. An example of the real time data display is shown in figure 1.

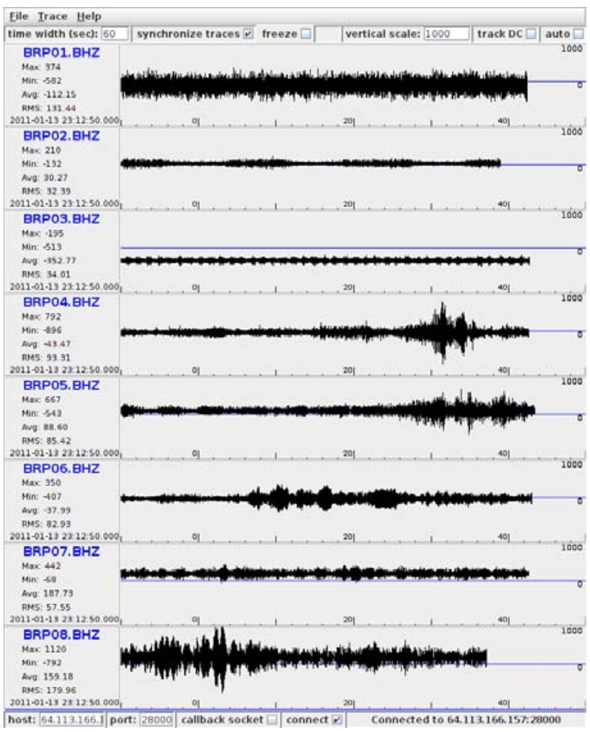

Figure 1: An example of waveform monitoring from the Brady's Hot springs array

This is an example of what the operator looks at in real time from the sites linked to internet. This image shows all of the desired traces in real time from the Brady's Hot springs eight stations (vertical component, but all twenty four traces can also be viewed) In addition to these six arrays, there are two "temporary arrays". One at The Geysers of five stations deployed around the EGS injection well, and one at Desert Peak of six stations also deployed close in around the EGS injection well. Both of these temporary arrays were deployed to gather data during the initial ESG injection. The details of the instrumentation is shown in Table 1.

Table 1: Specifications of seismic instrumentation at the DOE/Industry EGS sites.

Site	Injection Start	Seismic Stations (Perm)	Seismic Stations (Temp)	Monitoring Start
Desert Peak, NV	SEP, 2010	(9)3-C, 4.5 hz 500 s/sec, 3 (b)	(6) 3-C, 2.0 hz surface (c)	2008
Brady's Hot Springs, NV	Spring, 2011	(8) 3-C, 8.0 hz 500 s/sec, 7 (b)	(5) 3-C, 4.5 hz Surface (c)	6/2010
Raft River, ID	Spring/ Summer, 2011	(8) 3-C, 4.5 hz 500 s/sec	(15) 3-C 4.5 hz, Surface (c) 3 Shallow Arrays	8/2010
New York Canyon, NV	Summer/ Fall,2011		(8) 3-C 4.5 hz (c)	7/2010
The Geyser's, CA	JAN, 2011	(30) 3-C, 4.5 hz 500 s/sec	(5) 3-C 4.5 hz 500 s/sec (c)	2003 (perm) 10/2010
Newberry Caldera, OR	Summer/ Fall, 2011		(7) 3-C 4.5 hz 500 s/sec, 1 (b)	10/2010

(b) = borehole site (most 100 ft)
(c) = continuous monitoring

In addition to the data collection LBNL is also developing a suite of programs to provide real-time seismic monitoring at Enhanced Geothermal Systems (EGS) field sites with remote access, thus allowing control and analysis from offsite. During the actual initial EGS injections real time plotting in three dimensions will be required to aid in the overall analysis by the operators to determine if the injections are performing as designed, both for reservoir creation and staying within the acceptable limits of induced seismicity. The system is built on the existing LBNL framework, which includes detection of signal-to-noise surges ('triggers'), time association of incoming continuous waveform data, and real-time waveform display of desired sensors from all recording stations. 'Triggered' data is then sent to an LBNL server in batched form where it is picked, located, and a moment magnitude calculation is obtained. The majority of triggered events have too few pickable records to obtain reliable locations, but thresholds are set especially low to allow the highest number of locations, with appropriate pick weighting conveying the reliability of the solution. All triggers, as well as all events located within the stimulation study area, are summarized and displayed in an automatically-generated seismicity report, sent every day at midnight (GMT time) to members of an email list associated with the project. Additionally, events that are located within the stimulation study area are added to self-updating remote and local 3-D interactive plots of the area. An example of the plots are shown in figure 2 and 3.

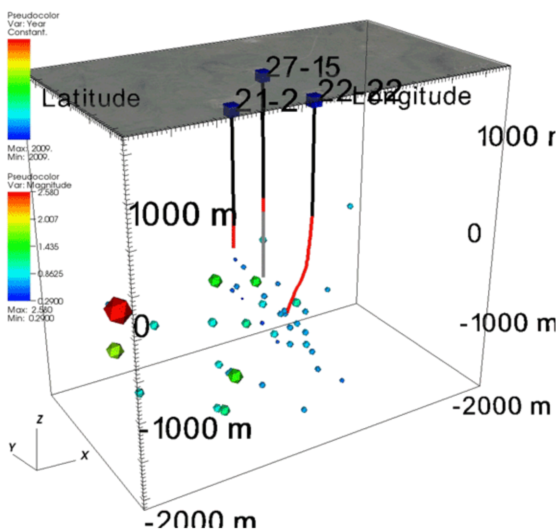

Figure 2: 3-D view Seismicity from 2007 to September 2010 prior to injection at Desert Peak, Nevada.

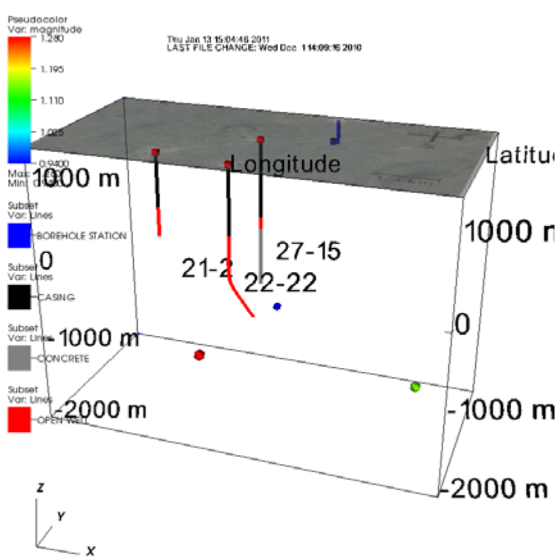

Figure 3: 3-D view Seismicity from September 2010 until January 2011 after injection at Desert Peak, Nevada.

Figure 2 shows the seismicity from April, 2007 until September of 2010 in a 3-D study box around the 27-15 injection well just prior to injection start at the EGS Desert Peak, Nevada. Figure 3 shows the seismicity from the start of injection until the end of December 2010. These plots are instantaneously updated with new events, and allow operators, monitoring teams, and researchers to interact with the stimulation area and to compare hypocentral locations with nearby wells, towns, geologic features, and recognizable surface characteristics. Any members of the dataset that conform to a more rigorous set of quality criteria are used for ongoing 3-D tomographic inversion to increase location accuracy and explore changing velocity structure in the region. In EGS deployments such as the Geysers, where upwards of 4,000 locatable events each month, 3-D seismic features occur can be produced on a monthly basis.

Since 2003 there have been over 273,000 triggers (5 stations recording an event in a 1 second window). Figure 4 shows the seismicity in 2009 and 2010 at The Geysers geothermal area. Plotted are the "high quality" events (with more than eight stations triggering).

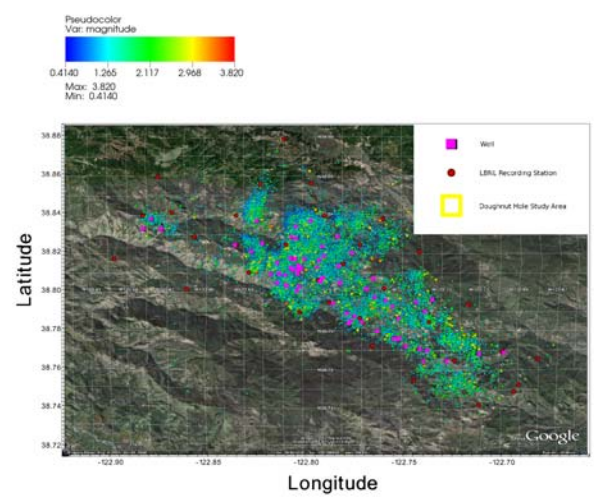

Figure 4: The Geysers seismicity from 2009 to January 2011. Plotted are 32,000 high quality events (at least 8 stations triggering per event).

There are 32,000 events on this plot, 20,000 in 2010. The increase in seismicity is due to improved detection, not seismicity increase. As a comparison, figure 5 shows 87,000 high quality events since 2003 to the present (out of the 273,000 triggers).

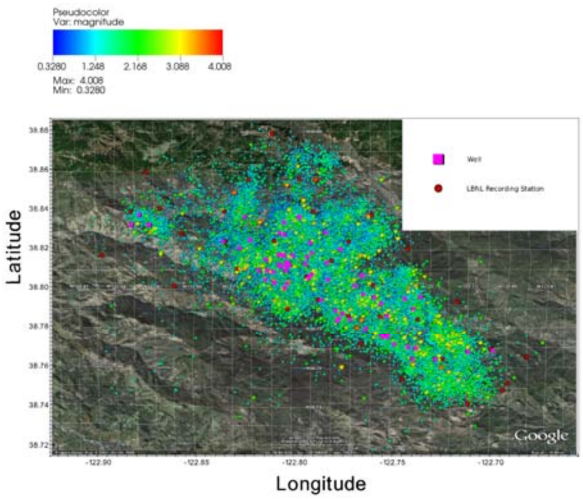

Figure 5: The Geysers seismicity from 2003 to January 2011. Plotted are 87,000 high quality events (at least 8 stations triggering per event)

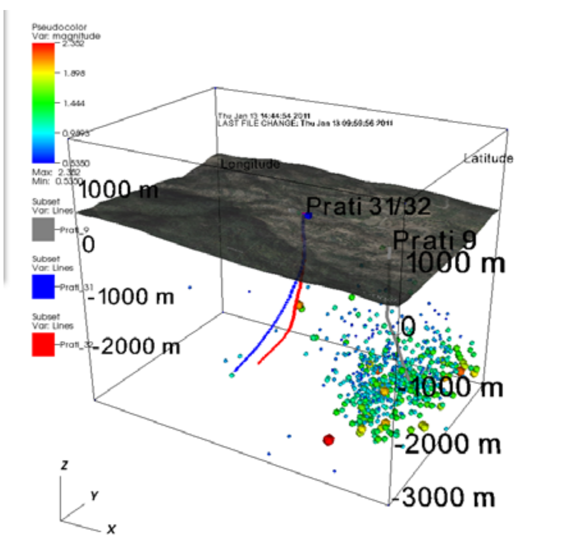

Figure 6: Seismicity in a 3-D volume around the EGS injection well Prati 31/32 (injection to start in early 2011) for December 2010. Injection is currently occurring in Prati 9.

Figure 6 shows the seismicity in a 3-D volume around The Geysers EGS injection well Prati 31/32 (injection to start in early 2011) for December 2010. Injection is currently occurring in Prati 9.

In lower-yield EGS sites with sparse seismic density patterns dominated by primarily low-magnitude events, such as Desert Peak, NV, the tomographic component of the real-time monitoring is not particularly illuminating. The magnitude threshold for the system is inherently Mw ~ 0.5, with events of lower magnitudes not showing up at enough stations to obtain a reliable location.

DATA ACCESS

In early 2011seismic data from the EGS sites and projects will be transferred to The Northern California Earthquake Data Center (NCEDC). NCEDC was established in 1991 and is operated by the Berkeley Seismological Laboratory (BSL) at the University of California, Berkeley. This joint project of the BSL and the Menlo Park office of the United States Geological Survey (USGS) serves as an on-line archive and user resource for parametric and digital waveform data from geophysical networks located primarily in northern and central California. The NCEDC has been accessible to the user community through the Internet since mid-1992. The Data Center holdings include both continuous time series and event waveform gathers. As data storage has become less expensive, the NCEDC has extended their holdings of continuous recording to include to data from short period stations and borehole stations with high sample rates.

The foundation of the software system is an Oracle database in which both event and waveform information is stored. In the DOE project, a “DOE Database” will be created for event parameters and waveform pointers. Event parameters will be ingested into the database, with pointers to their corresponding waveform gathers. Three copies of all waveforms will be archived, one in online RAIDS, one in an online tape library, and an offsite and offline copy on tape.

In addition the data will be archived in close to real time and open to public access at the Northern California Earthquake Data Center. With this system interested parties, both in-field and remote, are given a window into EGS study areas, and can use monitoring results to guide stimulation and to interact with the community.

All event and waveform data from this DOE/LBNL project will be freely available to the public. *Events*: Using existing tools, the NCEDC will provide a web interface to search the DOE/LBNL event catalogs, allowing parametric data to be extracted in a variety of common formats (see

http://www.ncedc.org/ncedc/catalog-search.html). The output formats include a standard 80 character, one line summary; two types of output related to the location program hypoinverse; output in KML for display in Google Earth; and output as CSV or comma-separated-variables for use in spreadsheet programs like Excel. Event searches are possible by any combination of *time window*, *geographical area* (described as a latitude/longitude rectangle, an annulus or a polygon), *depth range*, and *magnitude range*. As part of this project, the capability of searching by one or more *network codes* will be added. Thus, one could request "all events from the geothermal networks of magnitude 3 and greater" or, one could request "all events from the Geysers networks of magnitude 3 and greater. If desired and funded, additional search possibilities may be implemented. BSL will not provide a cross-reference between events from the DOE/LBNL catalog and events from the Northern California (NCEMC) catalog. *Waveforms*: Waveforms will be available through a variety of standard tools (see http://www.ncedc.org/data_access.html, http://www.ncedc.org/news/2004.11.11.fissures.html).

Currently, event waveform gathers are available from the NCEDC for Northern California earthquakes, but the request mechanism is a separate tool from the catalog search. During the first year of this project, we will develop and implement a tool which will provide a better and more automatic connection between the catalog search and request for corresponding waveform data. One hurdle to overcome in the development of such a tool is a way to deal with requests for very large amounts of data (many events) at once. In addition to being indexed by event ID, all waveforms from the DOE/LBNL networks will be available through the standard NCEDC time series request tools by SNCL and time. *Assembled Datasets:* Assembled datasets One of a kind data sets such as VSP or surface seismic, or reprocessed data sets of earthquakes, will be available as downloadable packages via ftp at the NCEDC. They will be indexed by date and geothermal area. When a brief description is provided it will also be posted.

SUMMARY

Seismic monitoring has been commenced at six DOE EGS sites. Where internet access is available the monitoring is in real time. If no internet access is available the data are recorded continuously In most cases data will be available well before the EGS injection begin or as soon as a project site is selected. The data coverage is comprehensive enough to allow complete coverage in time and space of background seismicity down to at least magnitude 1.0 and wide enough to cover an area at least twice as large as the anticipated the largest created reservoir over the project life time. The monitoring should be maintained for the lifetime of the project and possibly longer depending on seismicity created and volume affected. Data will be put in a NCDEC public data base operated by the Berkeley Seismological Lab at UC Berkeley.

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