Relative Microearthquake Locations at the Geysers

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ABSTRACT

Passive seismology has become widely used in geothermal, oil and shale gas areas to enhance the good management of resources by determination of the physical parameters of the reservoir, fluid flow paths, and the effects of reservoir engineering. In the case of well-designed networks, the dominant source of location error in geothermal areas is usually imperfectly known crustal structure. If induced seismicity is monitored, it can reveal details of the structure and physical parameters of the medium and changes in these parameters caused by production. In our study, we relocated seismic events associated with fluid injections in the NW Geysers geothermal area, over 270 days. We used relative location software, along with different velocity models. Our results show good agreement with injection operations.

1. INTRODUCTION

Microseismic monitoring is extensively used for detection of microseismic events induced by hydraulic fracture stimulation. This method is widely used especially in new geothermal, oil and shale gas areas to observe the seismicity and help to enhance the good management of sources by the determination of the physical parameters of the reservoir and mapping fluid flow paths. In addition, observing microseismic activity is useful to inform people who live around a production site about any seismic activity an operation caused and the effect on tectonic structures. In this study, we concentrated on the relation between microseismic events and injection of water from a well in the geothermal reservoir. There are many studies in regions of geothermal, shale gas and oil resources. We selected the Geysers Geothermal Field in California, USA. The Geysers has been the main electric power supplier for the region since 1960 (Barker et al., 1992). It is located between several northwest-trending right lateral strike-slip faults of the northern San Andreas fault system (Fig. 1). In addition to the right-lateral strike-slip faulting in the region there is shallow volcanism (Stanley et al., 1998).

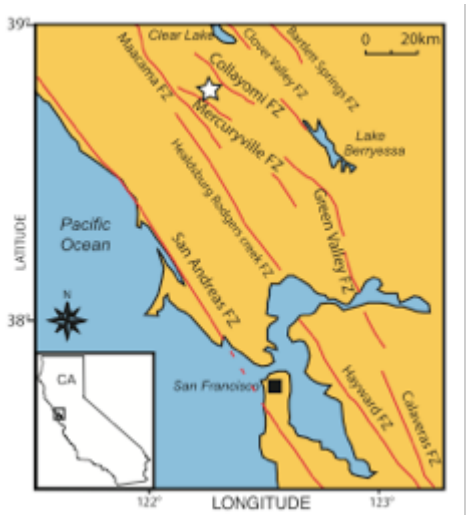


Figure 1: The Geysers geothermal field (Jeanne et al., 2014)

2. METHOD

Conventional hypocentre location methods, which are based on fitting arrival times of seismic waves observed at multiple seismometers, are subject to bias caused by the imperfectly known internal structure of the earth.

Modern high-resolution relative hypocentre location methods overcome this difficulty by fitting the differences in arrival times for pairs of earthquakes observed at individual seismometers. If the earthquakes in each pair are close together, the travel time anomalies nearly cancel one another out and the resulting errors in relative locations can be greatly reduced. This tactic has a disadvantage, however. Its reliance on time differences renders the results insensitive to absolute hypocentre locations. In geothermal applications, where the precise locations of structures are needed, for example to guide drilling, absolute location errors can be a serious problem.

The sensitivity of relative relocation methods to absolute position can be improved by exploiting a strength of the conventional location method, i.e., by taking some account of absolute arrival times. The relative hypocentre location program **hypocc** can

invert data sets that contain both differential and absolute arrival times. Including absolute times for one, or a small number of earthquakes, provides greatly improved absolute hypocentral accuracy without significantly degrading the ability of the method to resolve small-scale details.

hypocc includes many optimizations and improvements. It organizes seismic data in a mathematical graph, with each graph node representing an earthquake and graph edges connecting earthquakes for which accurate differential times are available. Determining absolute micro-earthquake locations depends upon the accuracy of models of the local wave-speed structure. Local wave-speed models are very important to elucidate the lithology and local geological structure and geothermal operations can cause changes in the wave speeds (Julian and Foulger, 2010).

Hypocentral locations are arguably the most fundamental information about earthquakes. Nevertheless, hypocenters are often surprisingly poorly determined. Even when earthquakes actually lie on planar structures, computed hypocenters typically show only diffuse "dots in a box," and have limited ability to reveal geological features such as faults that may be important drilling targets. Furthermore, derived hypocenters are often subject to significant systematic biases, causing clouds of locations to be displaced from their true positions. The problem for the end user may be exacerbated where independently computed locations differ by more than the stated formal errors. This inconsistency results from the errors being calculated incorrectly, ignoring what is often the major contributor to the error budget, which is uncertainty about crustal structure. As a result, there is an urgent requirement for tools that produce locations that are not only accurate, but also have realistic error estimates.

In the case of well-designed networks, the dominant source of location error in geothermal areas is usually imperfectly known crustal structure (e.g., Maxwell, 2009). Whereas random errors associated with timing and arrival-time measurements may result in a few tens of meters of error in locations, the systematic errors that result from poor knowledge of crustal structure may be several times larger. There are several ways of reducing this problem. Initial, 1D models are generally obtained using controlled-source seismology. To penetrate to several kilometres depth in refraction experiments, profiles several tens of kilometres long, and relatively large explosions are needed. Sophisticated experiments involving many profiles and multiple explosions are necessary to acquire spatially extensive, 3D crustal models from such work. In oil and gas reservoirs, sophisticated 3D seismic reflection surveys are sometimes done to obtain accurate crustal structure information, but this is rarely done in geothermal areas.

One-dimensional inversions are conducted of arrival times from blasts (explosions for which the origin time is not measured), explosions (explosions for which the origin time is measured) and earthquakes, to calculate the 1D crustal model that minimizes the root-mean-square misfit of the arrival-time measurements (e.g., Kissling, 1995). Locating earthquakes using 1D models improved in this way may reduce location errors by a few percent.

If earthquakes are well distributed beneath a seismometer network, it may be possible to use local-scale seismic tomography to determine a 3D crustal model. Seismic tomography has been successfully applied to several exploited volcanic and geothermal areas (Foulger and Toomey, 1989; Foulger and Arnott, 1993; Arnott and Foulger, 1994; Foulger et al., 1995a, 1995b; Julian et al., 1996; Ross et al., 1999). In such areas, it is not uncommon for wave speeds to vary laterally on a scale of kilometers by more than 10%. The resulting traveltime anomalies may then be an order of magnitude larger than measurement errors and dominate the hypocentral-location error budget. Significant errors may also be introduced into moment tensor solutions if this affect is not accounted for (Foulger and Julian, 1993). Tomographic inversions typically solve for corrected hypocenter locations, in addition to a 3D crustal model. Locating local earthquakes using such a model can greatly reduce these errors. In practice, only errors resulting from inhomogeneities on the scale of structural parameterization are reduced. This is typically 1–2 km at best.

Relative hypocenter location methods can greatly reduce the errors in location between individual earthquakes in a cluster, thereby improving the resolution of seismically active structures (e.g., De Meersman et al., 2009; Jansky et al., 2009). It is important to realize that the absolute location of the entire cluster is not improved by this method, only the errors in the differences between earthquake locations. Relative location methods use, for each seismic station, the differences in arrival times of waves from closely spaced earthquakes. For such earthquakes, the biases caused by imperfectly modelled geological structure along the raypaths are almost identical. They thus nearly cancel out when arrival times are differenced, and the variations in arrival times remaining are largely a result of true, small variations in location between the earthquakes (Waldhauser and Ellsworth, 2000). The relative location method can be applied to arrival times obtained using any method, including automatic measurements, hand-measurements, and arrival times improved by waveform cross-correlation. Waveform cross-correlation is most helpful where waveforms are similar, and may be included automatically in the relative-location process. The results of relatively locating events in a tight cluster can be a spectacular improvement in the clarity of delineated structures — a move from "dots in a box" to "faults in a box" (Julian et al., 2010b).

3. APPLICATION

We selected The Geysers geothermal area in the United States to study the relationship between water injection and seismicity. We searched the catalogue for the past 20 years seismicity in the region. Figure 2 shows the numbers of earthquakes for the past 20 years in the region.

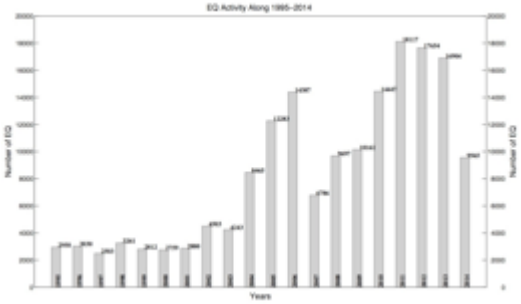


Figure 2: The numbers of earthquakes in the Geysers area for the last 20 years

In the Geysers geothermal area, there are many electric power plants and injection wells. We selected a sample area in the north-western Geysers for a period of 270 days seismic activity recorded during an injection for a specific project in the area (Fig. 3).

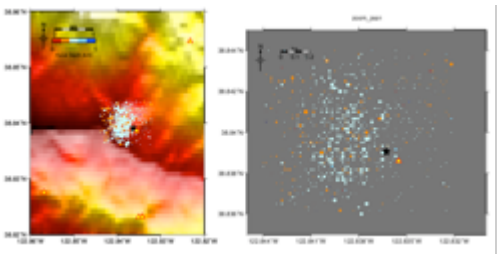


Figure 3: Data used for this study. The maps show all seismic activity along the injection period in the left panel and seismic events near the injection well in the right panel

The injection operation was conducted October 6, 2011 to August 8, 2012. The earthquake locations and phase readings were taken from the Northern California Earthquake Data Centre. Figure 4 shows the distribution of events as regards focal depth and magnitude along the injection time-line. The magnitude and depth of the events vary in the range M 0.1 to 2.5 and from 0 to 5 km respectively. The magnitude of the largest event in the injection period was M 2.46.

We relocated the seismic events using **hypocc** (Julian 2010). For this process, *P*- and *S*-wave phase readings were downloaded from the NCEDC website. We used two 1-D velocity models (Eberhart-Philips and Oppenheimer, 1984). Table 1 shows the 1-D velocity model parameters.

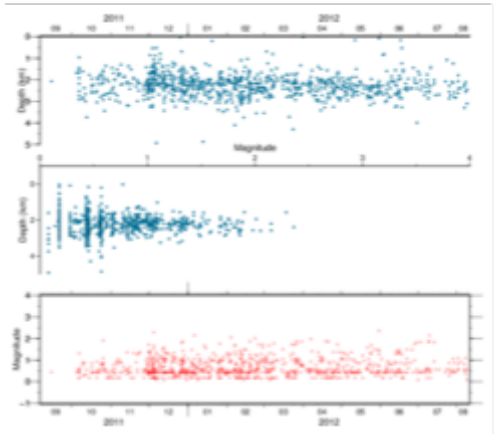


Figure 4: The distribution of the seismic events around the injection well regarding focal depth and magnitude, along the injection

Table 1: Used 1-D velocity models

Model 1			Model 2		
D(km)	Vp(km/s)	Vs(km/s)	D(km)	Vp(km/s)	Vs(km/s)
1.50	4.43	2.46	0.50	4.35	2.51
1.50	5.12	2.84	0.50	4.55	2.56
1.25	5.47	3.04	1.00	4.95	2.78
1.75	5.58	3.10	1.00	5.37	3.05
2.00	5.62	3.12	1.00	5.71	3.29
7.00	5.85	3.26	1.00	5.76	3.36
10.0	6.80	3.78	1.00	5.81	3.42
200.0	6.80	3.78	2.00	5.82	3.49
			2.00	5.82	3.49
			200.0	5.82	3.49

We investigated the number of iterations needed to optimize the relative locations. Figure 5 shows relatively located events for the different iterations. The location of the earthquake cluster as a whole migrates laterally with increasing number of iterations.

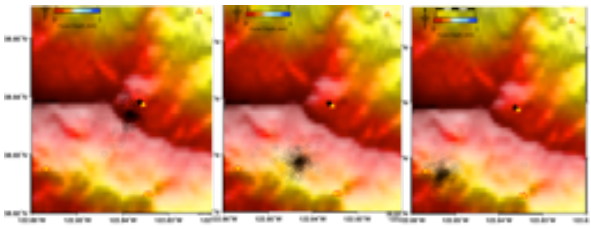


Figure 5: Left to right: Distribution of the relatively located events with 3, 10 and 30 iterations

As previously mentioned in the method section, **hypocc** offers the option of using absolute times along with time differences and can thereby optimize the relocation procedure. This is important for the commercial operation sites. Figure 6 compares the distribution of the relocated events for 10 iterations considering absolute times.

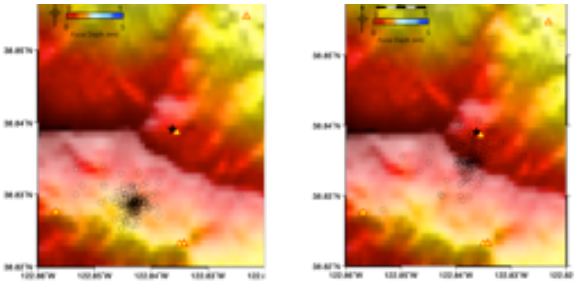


Figure 6. Distribution of the relocated events with 10 iterations with (right panel) and without (left panel) absolute times

For the sensitive relocation procedure, selection of the crustal velocity model is of vital importance. We tried the relocation procedure with two-velocity models. Figure 7 compares the effect of the velocity model relocations.

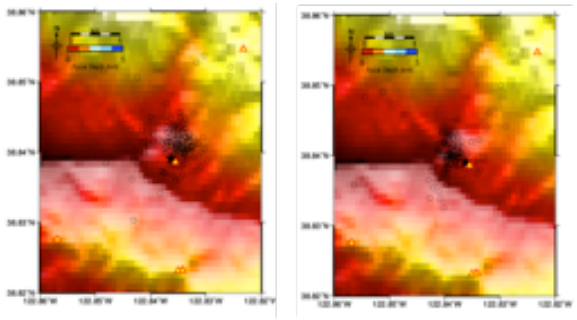


Figure 7. The effect of the velocity model on relocations. The map in the right panel was produced with a 1-D velocity model for the Geysers area

4. RESULTS AND CONCLUSIONS

We used microearthquakes to define pathways along an injection of cold water in the north-west Geysers. We used earthquake data recorded by the local network and made available via their website. We used the relocation program **hypocc**. Figure 8 shows 3-D images of the microearthquakes that were relocated using **hypocc**. Seismicity in geothermal areas induced by fluid injections provides valuable information that can help manage hazard in regions with natural seismicity. If induced seismicity is monitored, it can reveal details of the structure and physical parameters of the medium and changes in these parameters caused by production. These include the locations of the injected fluid pathways, the mode of fault motion, and the structure of the reservoir and location of the heat source. Traditional earthquake processing techniques and software are inadequate for these problems. The technique and software that are used in this study were developed for this specific reason.

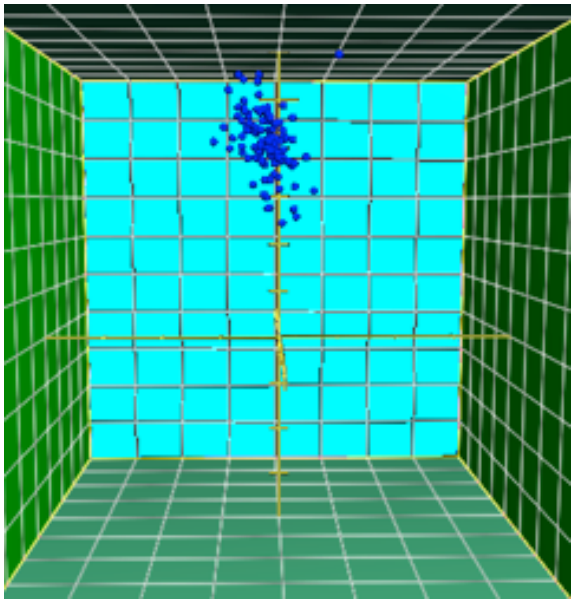


Figure 8. Distribution of the relocated events in 3-D view

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