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IMPROVED METHODS FOR MAPPING PERMEABILITY AND HEAT SOURCES IN GEOTHERMAL AREAS USING MICROEARTHQUAKE DATA

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ABSTRACT

Geothermal microearthquakes, and the seismic waves they generate, provide a rich source of information about physical processes associated with Enhanced Geothermal Systems (EGS) experiments and other geothermal operations. With support from the Dept. of Energy, we are developing several software packages to enhance the utility of microearthquake data in geothermal operations and EGS experiments. Two of these are:

1. Enhanced relative hypocenter location techniques. Relative relocations produce three-dimensional images showing in fine detail the geometry of microearthquake clusters, and thus failure zones. These images are valuable for diagnosing failure mechanisms and for identifying promising drilling targets, but they suffer from a fundamental weakness: they are relatively insensitive to absolute locations and generally yield cluster locations with excellent structural detail but poorly located as a whole.

   We are refining the hypocenter-location program **hypocc** to use both absolute and differential arrival times, in order to constrain the absolute locations of clusters in addition to the relative locations of the earthquakes in them. **hypocc** can use three-dimensional ray tracing to take full advantage of detailed information about local structure when it is available, and can also use simpler (e.g., one-dimensional) models for less well-constrained cases.

2. Local-earthquake tomography produces three-dimensional images of the seismic wave-speed structure that can delineate geothermal reservoirs and detect and measure temporal changes caused by geothermal operations. However, because waves from local earthquakes travel upward to surface or shallow-borehole seismometers, they provide no information about the deeper portions of geothermal reservoirs or the regions below them. An additional problem is that some geothermal areas are only weakly seismogenic, and provide few data useful for tomographic inversion.

   We are extending the local-earthquake tomography program **tomo4d** [Julian and Foulger, 2009] to use data from regional earthquakes (out to distances of a few hundred kilometers) as well as from local earthquakes. Waves from regional earthquakes pass beneath geothermal areas, and using them can provide more accurate and complete models, including the deeper portions of reservoirs and the underlying heat sources.

METHODS

Absolute Microearthquake Locations

Conventional hypocenter-location methods, which are based on fitting the arrival times of seismic waves observed at multiple seismometers, are subject to bias caused by the imperfectly known internal structure of the Earth. Furthermore, this bias differs from event to event because of differences in the station suites that record different events. The resulting errors in computed locations obscure the details of hypocenter distributions and render them of little use for inferring the geometry of failure zones.

Modern high-resolution relative hypocenter location methods overcome this difficulty by fitting the *differences* in the arrival times for pairs of earthquakes as 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 one serious disadvantage, however–its reliance on time differences renders the results insensitive to absolute hypocenter locations. Thus, structures may be sharply defined by the earthquake relocations but there may be significant errors in the position of the structure as a whole. In geothermal applications, where the precise locations of structures are needed, for example to guide drilling, absolute location errors can thus 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. We have extended the relative hypocenter-location program **hypocc** [Julian, in preparation] in this way. The new program 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.

The new program **hypocc** additionally incorporates 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. This organization is economical, both in terms of memory usage (thousands of times more economical than conventional matrix representations) and computational speed. Furthermore, there is no duplication of storage or of computational labor when several (typically about ten) differential times involve the same event, seismometer, and seismic phase. Adding the ability to treat absolute arrival times required modifying the graph-node data structures to accept absolute arrival times, designing new input formats for these data, and modifying the functions that access the data and perform numerical computations.

Tomographic Images of Geothermal Areas

Determining absolute micro-earthquake locations using the method described above depends critically upon the accuracy of models of the local wave-speed structure. Furthermore, local wave-speed models are of direct importance for elucidating lithology and local geological structure and because geothermal operations can cause measurable changes in the wave speeds. The only practical method currently available for obtaining accurate three-dimensional models for geothermal areas is local-earthquake tomography. Some information can be obtained by dense, three-dimensional seismic reflection surveying, but that technique is expensive and insensitive to absolute wave speeds.

Local-earthquake tomography, as conventionally applied to geothermal areas, currently suffers from two serious problems:

1. It relies on local earthquakes: Unexploited geothermal areas may have low levels of natural seismic activity, so available data often are inadequate for resolving structure;

2. Local-earthquake tomography cannot resolve structure below the (typically shallow) local earthquakes: No rays to near-surface seismometers sample beneath the earthquakes. Thus no information is available about this region, which typically includes the geothermal reservoir itself and the heat source (Figure 1).

We are solving both of these problems by extending the local-earthquake tomography program **tomo4d** [Julian and Foulger, 2009] to use data from regional earthquakes (out to distances of a few hundred kilometers) in addition to local earthquakes. Figure 1 illustrates the ray paths involved. Rays from regional earthquakes by themselves can provide useful sampling of local structure. Moreover, these rays pass beneath the local earthquakes, so using both data types can provide information about the deep reservoir and potentially about the heat source.

A complication of using regional earthquakes arises because their travel times depend upon the structure outside the local volume of interest, as well as the structure within it. This effect, if not properly accounted for, will lead to spurious local wave-speed anomalies. We prevent this by simultaneously solving for extra parameters that describe the orientations and shapes of the wave fronts impinging on the local volume. In the simplest case, these might describe the orientation and arrival time of a simple plane wave, or they could also include descriptions of the wave-front curvature. Formally, this procedure is similar to solving for hypocenter locations in local-earthquake tomography.

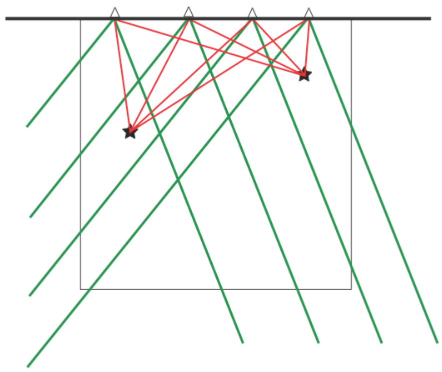

Figure 1: Schematic diagram of seismic ray coverage from different kinds of earthquakes. Heavy horizontal line: Earth's surface; Triangles: Seismometers; Square: volume of interest such as a geothermal area; Stars: Local earthquakes. Rays from local earthquakes (red lines) provide no coverage below the seismically active volume (and require local seismicity). Rays from more distant (regional) earthquakes (green lines) sample the entire volume of interest, even in the absence of local seismicity.

APPLICATIONS

Absolute Microearthquake Locations

The new **hypocc** program was tested on earthquakes from the Coso geothermal area, California (Figure 2). A month of earthquakes that occurred prior to an injection in well 34-9RD2 were used. They illustrate well both the problem and the successful solution.

Well 34-9RD2 was redrilled in 2005 with the plan of stimulating it at ~ 2,700 m depth. During drilling, major circulation-loss zones were encountered and total mud loss occurred near the targeted maximum drilling depth. This resulted in complete loss of circulation while injecting water at rates up to 20 l/s. A vigorous swam of earthquakes was induced by this unplanned event which thus constituted a somewhat unconventional EGS stimulation. Details of this injection event and the associated seismicity have been reported previously [Julian *et al.*, 2007; Julian *et al.*, 2009a; Julian *et al.*, 2009b].

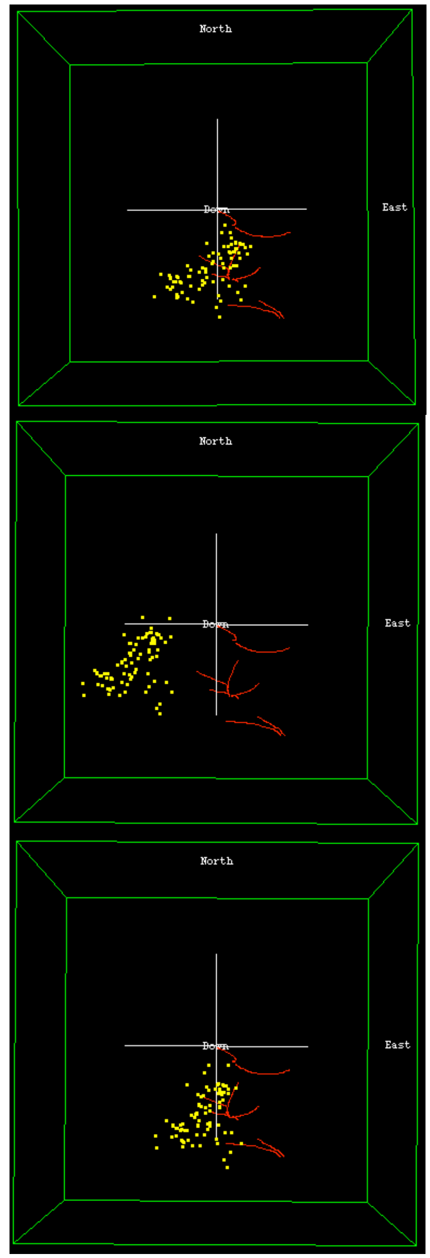

Figure 2: Relatively relocated earthquakes for the month of February 2005. The earthquakes studied occurred in the vicinity of well 34-9RD2, which was stimulated the following month. Top: Original relocations, after 3 iterations of hypocc; middle: relocations after 9 iterations. The earthquake cluster has migrated ~ 500 m to the NW; bottom: same as middle panel but including in the data the absolute arrival times of one well-recorded earthquake, weakly weighted.

The earthquakes before, during and after the injection event were relatively relocated using **hypocc**. The relocation process produced maximum clustering after 3 iterations (Figure 2, top panel). Nevertheless, if the program is allowed to continue iterating, the earthquake cluster progressively migrates west (Figure 2, middle panel). This behavior probably results from the progressive accumulation of small errors under conditions of almost no constraint on the earthquake absolute locations. Including the absolute arrival times of one well-recorded earthquake, essentially eliminates this problem, resulting in the earthquake cluster remaining close to its original position (Figure 2, bottom panel).

Tomographic Images of Geothermal Areas

Work on the new software will begin during 2010 and we anticipate that the program will be available for alpha testing during 2011. We would be interested in hearing from anyone who anticipates having a data set suitable for processing using this new software.

REFERENCES

Julian, B. R. (in preparation), hypocc: "A Program for Computing High-Resolution Relative Earthquake Locations", *Rep., U.S. Geological Survey Open-File Report*.

Julian, B. R., and G. R. Foulger (2009), "Time-dependent tomography", *Geophys. J. Int.*, submitted.

Julian, B. R., G. R. Foulger, and F. Monastero (2007), "Microearthquake moment tensors from the Coso Geothermal area", paper presented at Thirty-Second Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, January 22-24.

Julian, B. R., G. R. Foulger, and F. Monastero (2009a), "Seismic monitoring of EGS stimulation tests at the Coso geothermal field, California, using microearthquake locations and moment tensors", paper presented at Thirty-Fourth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 9-11.

Julian, B. R., G. R. Foulger, F. C. Monastero, and S. Bjornstad (2009b), "Imaging Hydraulic Fractures in a Geothermal Reservoir", *Geophys. Res. Lett.*, submitted.