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GEOTHERMAL SEISMOLOGY: THE STATE OF THE ART

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ABSTRACT

Injecting fluid into crustal rocks for purposes such as engineering geothermal systems and sequestering CO_2 often has, as a side effect, the stimulation of seismic activity. Understanding the physical processes involved is important for controlling the maximum size of such earthquakes, and limiting the damage that they might cause. At the same time, the seismic waves from induced earthquakes provide a rich source of potentially high-resolution information about these physical processes. Many recent seismological developments, such as the moment-tensor source representation, high-resolution relative hypocenter-determination, and time-dependent seismic tomography, have greatly advanced our ability to extract this information from seismograms, particularly when different result types (*e.g.* moment tensors and hypocenter locations) are interpreted jointly. Many challenges still remain, however.

Confidence assessments for derived quantities are essential components of any scientific investigation. Methods for computing confidence regions for moment-tensor source mechanisms have not been available until recently, and are still a rapidly developing subject, especially for very small (micro-) earthquakes. Most common hypocenter-location computer programs use methods that involve highly unrealistic assumptions about the sources of errors, *e.g.*, that the crustal velocity structure is perfectly known, and produce confidence regions that are too optimistic by an order of magnitude. In truth, hypocenter location errors are dominated by real geophysical travel-time anomalies, not seismogram-reading errors. Methods based on stochastic modeling of wave-speed variations in the Earth can greatly improve both estimated hypocenters and estimated hypocentral confidence regions.

The three-dimensional seismic-wave speed structure can delineate geothermal reservoirs, and temporal changes in wave speeds can be used to monitor changes in pore-fluid pressure within them. Local microearthquakes in geothermal areas, however, are shallow, and cannot be used to determine structure at great depth. We have extended tomographic methods to combine data from local and regional earthquakes. In cases where suitable seismicity exists, this extension will enable us to measure wave speeds, and their temporal changes, within the deep parts of reservoirs and the heat sources beneath them. This work is resulting in important steps toward making microearthquake studies a practical industrial tool for planning, guiding, and managing industrial reservoir fluid injection.

FLUID INJECTIONS IN CRUSTAL ROCKS

Energy related operations increasingly rely on injecting fluid into rock formations. “Fracking” to increase permeability in gas shale formations has in particular become widespread in recent years. There are now several case histories of fracking causing earthquakes that are troublesome to local populations, including events up to M ~ 4. Managing induced earthquakes that are strong enough to be felt at the surface is essential to the future of that industry, to CO_2 sequestration, and to creating Engineered Geothermal Reservoirs (EGS) [Cladouhos *et al.*, 2010; Majer *et al.*, 2007].

One approach to the problem is to conduct injection in areas distant from significant population centers. This is possible where reservoirs and resources are remote. Many desirable targets are not remote, however, and if exploitation is to go ahead, methods are needed for keeping the size of the largest earthquakes down. This is a challenging problem, because earthquakes are naturally fractal. Large numbers of small earthquakes are inevitably accompanied by the occasional larger event, a distribution of size that is fundamental to the earthquake phenomenon.

The maximum size of earthquake that occurs in an area is related to the maximum length of faults in the activated volume. However, all local areas are part of larger regions, and local changes in stress diffuse freely out into neighboring areas. Both the local and regional geological situation is thus relevant to the seismic response to a fluid injection.

In order to progress in this field, a body of case histories is required, and this is rapidly accumulating. In addition to improving our understanding of the physical processes involved, it is clear that a good understanding of the regional geology and its long-term seismic history is imperative, as well as suitable operational planning to assess risk potential and to deal with events as they unfold.

EARTHQUAKES AS A GEOPHYSICAL TOOL

In addition to being potentially troublesome, earthquakes are extremely useful for studying reservoirs and prospects. Diverse approaches exist to utilize seismic waves, and improved specialized techniques are currently under development. These include:

- accurately locating earthquakes, which can reveal where injected fluids flowed and where permeability was increased,
- calculating source mechanisms, which can reveal the nature of the new cracks and faults created and activated, and
- calculating the structure of the prospect using methods such as seismic tomography. If conducted repeatedly in time, this method can also reveal if and how reservoir structure evolved in response to exploitation.

Realistic assessment of errors is critical to producing serviceable results. This is a neglected aspect of traditional earthquake seismology, because accurate error assessment has typically not been particularly important to tectonic-oriented research goals. Now, earthquake locations may be required to guide drilling strategies, and results that are reliable to an accuracy of a few meters are needed.

Well-determined moment tensors provide information on the orientation of principal stress axes, the orientations of fault and crack planes, and the occurence or absence of crack opening. Simple fault-plane solutions have major inherent limitations and cannot provide the required information.

Three-dimensional structure obtained from seismic tomography may be useful for understanding the geology of a reservoir, and also for spatially monitoring reservoir depletion. The results may assist production and reinjection decision-making. Thus, uncertainties, including those resulting from inter-epoch variations in earthquake source locations, and the existence of un-sampled regions, need to be managed.

Earthquake Locations

Traditional earthquake seismology has under-emphasized error assessment, and commonly used earthquake location software may yield the familiar diffuse "dots in a box"-type product which has limited utility for operational decision-making. In order to generate locations of useful quality, more powerful techniques must be used, and errors must be rigorously assessed. This includes taking account of uncertainties in the crustal model used.

Geometrically strong seismometer networks are necessary. In the case of near-surface networks, well-calibrated, three-component sensors should be deployed in dense arrays surrounding anticipated epicentral areas and extending to distances of about twice the anticipated hypocentral depths. Such arrays will yield strong geometric control on the hypocenters. Techniques exist for optimizing station locations, taking into account local crustal structure [Foulger & Julian, 2011; Julian *et al.*, 2009; Miller *et al.*, 1998] (Figure 1). Sensors should ideally be deployed in shallow boreholes. This enhances the signal-to-noise ratio by placing the sensors away from surface noise and beneath loose near-surface deposits that scatter seismic waves.

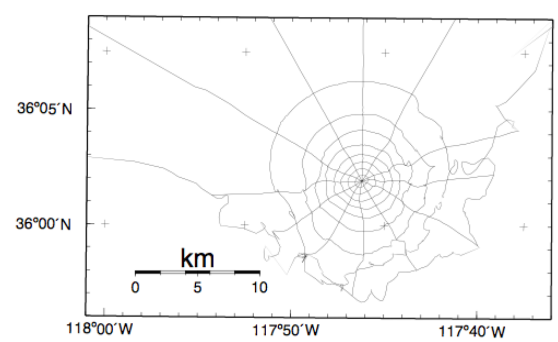

Figure 1: Map showing the surface projection of seismic rays from the upper focal hemisphere of an earthquake 3 km deep at a geothermal field, computed using a three-dimensional crustal model. The pattern of emergence of rays at the surface can be used to guide optimal distribution of seismic stations [from Foulger & Julian, 2011].

Where borehole sensor strings are used, ideally multiple wells should be instrumented, because a single linear string of sensors is a geometrically weak configuration. Unfortunately, deploying multiple strings is often prohibitively expensive.

The choice of whether to use a near-surface network or a borehole sensor string is typically guided by the anticipated size of induced earthquakes, coupled with surface noise conditions. Where earthquakes are expected to be extremely small (less than M~0), or noise is high, a near-surface network may not record usable data. On the other hand, such a network is inherently geometrically stronger, easier to calibrate for the purpose of calculating moment tensors, and less expensive to deploy. It is likely to be the best choice for situations where the induced earthquakes are expected to be larger than M~0 or so. Experiments deploying both types of sensor array would be desirable.

With geometrically strong networks, the major source of hypocentral error is usually ignorance of the crustal structure [*e.g.*, Maxwell, 2009]. Random errors associated with inaccuracies in timing and arrival-time measurements may cause a few tens of meters of location error, but the systematic errors that result from unknowns crustal structure can easily be hundreds of meters. This problem may be addressed in a number of ways. Initial starting models obtained, *e.g.*, using explosion seismology, may be improved by one-dimensional inversions of arrival times to obtain both locations and wave-speed models [*e.g.*, Kissling, 1995]. The resulting improvements in the crustal model may reduce earthquake location errors by a few percent. Additional gains may be achieved by calculating full three-dimensional crustal models using seismic tomography [*e.g.*, Arnott & Foulger, 1994; Foulger & Toomey, 1989; Foulger & Arnott, 1993; Foulger *et al.*, 1995a; Foulger *et al.*, 1995b; Julian *et al.*, 1996; Ross *et al.*, 1999]. However, tomographic models typically are accurate only on a comparatively large scale of 1 to 2 km. Inhomogeneities on smaller scales are not resolvable, butmay still introduce significant hypocentral errors.

There is only one method currently available that can remove almost all location errors, and that is to use calibration explosions to determine accurate travel-times of waves from the anticipated source volume to the seismometer sites. This may be done either by firing a single explosion in a borehole near the expected hypocentral volume, or by deploying a seismometer downhole and firing explosions at each planned surface-seismometer site. The measured travel times provide corrections that, when applied to earthquake arrival times, remove the effect of errors in the crustal model.

The relative locations of earthquakes in a single cluster can be further reduced by relative–location methods [*e.g.*, Waldhauser & Ellsworth, 2000]. These techniques can spectacularly improve the resolution of fine details of seismogenic structures such as faults that may comprise desirable drilling targets [*e.g.*, De Meersman *et al.*, 2009; Jansky *et al.*, 2009; Julian *et al.*, 2010]. Relative location methods cannot improve the absolute accuracy in locating an entire earthquake cluster, however, and may even degrade it because standard relative location programs do not strongly constrain absolute locations.

Assessment of location uncertainty

Least-squares fitting of seismic-wave arrival times is the commonest method of locating earthquakes. Implicit in the least-squares method is the assumption that errors in the data are normally distributed. For the linearized location problem, the derived parameters will then be normally distributed and their joint confidence regions will be hyperellipsoids. If the data errors are statistically independent, and their relative magnitudes are known, then their values can be estimated from the quality of the least-squares fit obtained.

The hypocentral confidence regions computed by most commonly used earthquake-location programs, however, are unrealistic as a result of two frequently made but incorrect assumptions: 1) that hypocentral errors are caused entirely by seismogram-reading errors, and 2) that the errors for different observations are statistically independent. These assumptions offer major computational advantages that were important in the past when computers were smaller and slower than they are today. The $m \times m$ covariance matrix $\boldsymbol{S}$ of the observational errors becomes diagonal, with just m independent elements (where m is the number of observations). Inverting $\boldsymbol{S}$ then becomes trivial. Nevertheless, these computational advantages are no longer very important because much more powerful computers are now commonly available.

In reality, imperfectly known crustal structure introduces uncertainties much larger than seismogram-picking errors. Structure-related errors are furthermore highly correlated. Ray paths from an earthquake to stations close to one another are similar and are similarly affected by structural heterogeneities. In such cases, hypocenter-location programs commonly minimize arrival-time residuals by “mis-locating” earthquakes. This mislocation produces deceptively good fits to the arrival-time data, and yields unrealistically small computed confidence regions (Figure 2).

One approach to this problem is to assume *a priori* standard errors for the data, and to choose values that are large enough to account for both the reading errors and travel-time uncertainties [Julian, 1973]. The covariance matrix is still diagonal, so negligible extra computational effort is required. This tactic is not ideal, as it enlarges the sizes of the computed confidence regions but does not change their shapes. An improved strategy is to use a stochastic model of travel-time anomalies caused by Earth heterogeneity. This approach can greatly improve hypocentral estimates and computed confidence regions [Foulger & Julian, 2011].

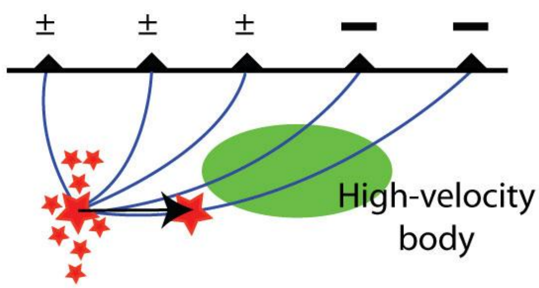

Figure 2: Unknown heterogeneities in crustal structure can cause major hypocentral mis-location. This schematic shows how a high-velocity body can cause an earthquake hypocenter to be located too far to the right because location programs try to minimize the root-mean-square of the residuals (indicated by ± and -).

Source mechanisms

Determining the source mechanisms of earthquakes induced by fluid injections is important for revealing the mechanism of failure and the orientation of principle stress axes. Accurate source mechanisms, in particular when they are interpreted jointly with other data such as "mini-frac" data, borehole televiewer data, and relative hypocenter locations, can enhance understanding of failure mechanics [*e.g.*, Foulger *et al.*, 2004; Julian *et al.*, 2010].

Assessment of source mechanism uncertainty

In order to allow for crack-opening and -closing components, the source mechanisms must be expressed as 6-component moment tensors, and not as simple, traditional fault-plane solutions. Determining confidence bounds for such expressions is not straightforward because the errors in wave polarities and amplitudes used to determine moment tensors map in a complicated manner into the results. To date, only a few moment-tensor results have included any kind of error analysis [Baig & Urbancic, 2010; Baker & Young, 1997; Dreger *et al.*, 2008; Šílený *et al.*, 2009; Trifu *et al.*, 2000].

We extended the linear-programming method of Julian and Foulger [1994] to compute moment tensor confidence regions. The approach we use is to find the minimum value of an objective function that measures the L1 norm of the residuals between the observed and computed polarities and amplitude ratios. We then constrain this objective function to lie below a somewhat larger value chosen on the basis of *a priori* estimates of measurement uncertainty and move the solution in six-dimensional moment-tensor space in various specified directions as far as the constraint allows. In this way, we obtain a suite of solutions that fit the data adequately [Foulger & Julian, 2011; Julian & Foulger, 2009].

Results from several geothermal areas in Iceland, Indonesia, and California show that moment-tensor confidence regions often, but not always, are elongated along a trend between the +Dipole and –Dipole points on the source-type plot (Figure 3). This mirrors a systematic trend frequently found for geothermal earthquakes, and our results suggest that part of this trend may thus be an artifact of measurement error. Further work is required to fully understand how much of the observed trend is real and how much may be attributed to error. For this, good assessments of uncertainty are vital.

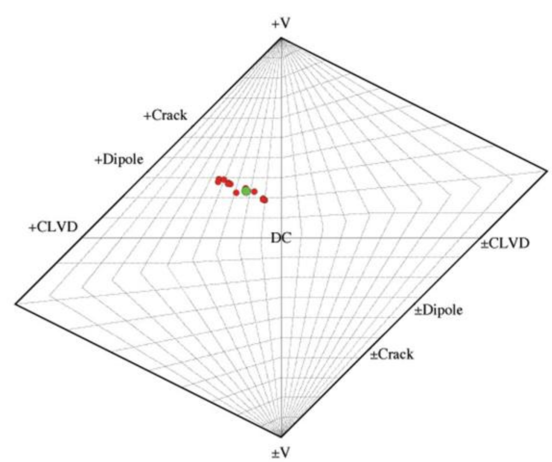

Figure 3: An example of the confidence region for the source type of a geothermal microearthquake. Green symbol: best-fit solution; red symbols: other acceptable solutions that delineate the confidence region [from Julian & Foulger, 2009].

Imaging geothermal reservoirs using earthquake tomography

A high-quality crustal structure is important, not only for accurate derivation of locations and source mechanisms, but also for understanding local geological structure and its possible change with time in response to operations. Three-dimensional crustal models can be obtained with local-earthquake tomography [*e.g.*, Foulger, 1988; Julian *et al.*, 1996].

An inconvenient shortcoming of local-earthquake tomography applied to geothermal targets is that the earthquakes are usually confined to the exploited part of the reservoir. This is generally the shallower parts, and certainly above the heat source. It would be useful to be able to extend images deeper, to include the underlying heat source. In order to do this, we have developed a general earthquake tomography program, **tomo4d** [Julian & Foulger, 2010].

tomo4d was originally written to provide an improved technique for time-dependent tomography. Traditional methods of determining changes in structure with time involve inverting travel-time data from different epochs independently, and differencing the results [*e.g.*, Gunasekera, 2001]. This is unsatisfactory because a) different results are expected from year to year even in the absence of structural change, simply because different sets of earthquakes are used, and b) there is no mechanism for calculating confidence levels accurately.

tomo4d inverts two epochs simultaneously for changes in structure that are required by the data, and is thus able to handle numerically both the problem of different sets of earthquakes, and the task of determining confidence levels.

We have extended **tomo4d** to include also rays from regional earthquakes, typically out to distances of a few hundred kilometers. These approach seismic networks after penetrating larger depths beneath the recording network (Figure 4). Including these rays enables structure beneath the seismogenic part of the reservoir to be determined. Structure can also be determined where there is a low level of earthquake activity in the reservoir, if regional earthquakes are recorded.

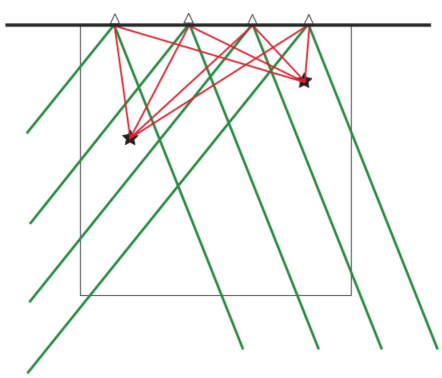

Figure 4: Schematic of seismic ray coverage from local and regional earthquakes. Triangles: seismic stations. Rays from local earthquakes (red lines) provide no deep coverage. Rays from regional earthquakes (green lines) can provide deeper information.

We are currently testing **tomo4d** on synthetic data. To this end, we developed software to generate pseudo-random three-dimensional wave-speed models. The geometry and the statistical properties of models generated may be varied by setting parameters such as the strength of the wave-speed heterogeneities and their correlation distances. An example is shown in Figure 5.

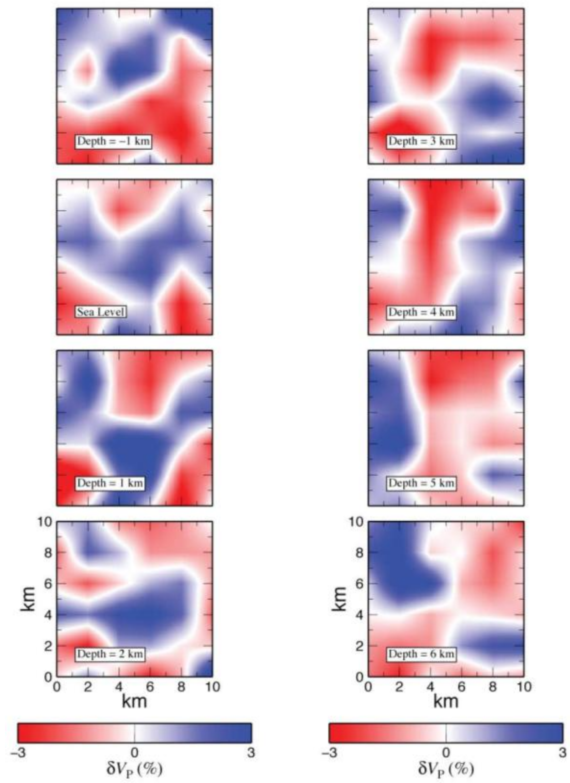

Figure 5: Maps showing variations in the compressional-wave speed V_P at different depths in a synthetic model. The standard deviation of V_P is taken to be 0.1 km/s, the horizontal correlation distances a_x and a_y are 2 km, and the vertical correlation distance a_z is 1 km.

In addition to crustal structure, the quality of seismic-tomography data sets, in particular the distribution of seismic sources, is also important. We developed software to generate synthetic data sets with a variety of source locations and ray directions. An example is shown in Figure 6.

CLOSING REMARKS

Seismicity in geothermal areas, in particular that induced by fluid injections, presents both challenges and opportunities. It is important to manage, because it represents a potential hazard, and one that may not be well understood by the general public, especially in areas not prone to natural seismicity.

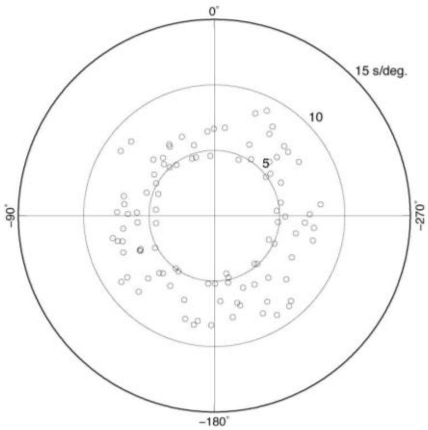

Figure 6: A synthetic pseudo-random distribution of the incidence directions of 100 P-phase rays from distant earthquakes, represented as points in two-dimensional slowness space. P phases are most easily useable for seismic tomography between epicentral distances of about 26˚ and 98˚, so only events within this distance range are plotted.

If well monitored, such seismicity produces a remarkably versatile type of data that can reveal details about several aspects of the structure and dynamics of geothermal prospects. These include the locations of injected fluid pathways, the mode of fault motion, the structure of the reservoir and, potentially, the location and structure of the underlying heat source.

Traditional earthquake-processing techniques and software are not optimal for these problems, not least because they do not provide realistic error estimates. Developing suitable techniques, that can provide results to the desired accuracy, along with correct error assessment, and software is a major task for the present decade, and one that is currently progressing rapidly.

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