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MAPPING DEEP STRUCTURE IN GEOTHERMAL AREAS USING LOCAL AND REGIONAL MICROEARTHQUAKE DATA

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ABSTRACT

Tomographic study of volcanic and geothermal areas has always been limited by the absence of local microearthquakes at depth, a result of the same high temperatures that make these areas interesting and important. Seismic ray coverage is limited to the volume above the deepest earthquakes, and this circumstance excludes study of the deeper parts of geothermal reservoirs and their heat sources. An additional problem is that some geothermal areas, particularly ones not under exploitation, are only weakly seismogenic and provide few data useful for tomographic inversion.

These limitations can be overcome by using seismic-wave arrival times from regional earthquakes (ones at distances of a few tens to hundreds of kilometers) in addition to those from any local events available (those within the volume being studied). Waves from regional events penetrate to mid-crustal to upper-mantle depths and propagate upward through the region under study.

A difficulty arises with using regional data, however, because of unknown travel-time variations that may have been introduced by propagation over long distances between the earthquakes and the local region of study. This difficulty is similar to that imposed by ignorance of the hypocentral locations of local earthquakes, and can be solved by a similar mathematical approach: solving simultaneously for parameters describing the geometry of the incoming wave front and for the local three-dimensional structure. In fact, regional earthquakes offer advantages over local events because they require the addition of fewer extra unknowns (3 per event vs. 4) and because it can be presumed that incoming wave directions from earthquakes near one another will be similar. Offsetting these advantages are the requirement that regional seismic activity must exist and the fact that regional seismic waves often are relatively weak. We are currently developing new software – Combined Local- and Regional-Earthquake Tomography (**CLARET**) – that is based on this new approach. It uses local and regional earthquake data to determine three-dimensional structure and its variation with time.

INTRODUCTION

The problem

Accurate local wave-speed models for geothermal areas are useful for a variety of reasons. For example, determining absolute microearthquake locations depends critically upon model accuracy [Foulger *et al.*, 1997; Foulger *et al.*, 2003; Julian *et al.*, 2010]. The quality of source mechanisms is also dependent on the quality of the crustal model [Foulger & Julian, 1993; Julian & Foulger, 1996]. Three-dimensional models can also provide valuable structural information about the prospect, the reservoir, and its evolution with time during exploitation [Gunasekera *et al.*, 2003; Julian *et al.*, 1996]. Both production and reinjection associated with commercial exploitation, and also natural processes, can cause temporal changes in the wave speeds [Foulger *et al.*, 1997; Foulger *et al.*, 2003; Gunasekera *et al.*, 2003]. Structural models are also important because wave-speed anomalies can delineate the locations and shapes of geothermal reservoirs [Julian *et al.*, 1996].

The only practical method currently available for obtaining accurate three-dimensional wave-speed models for geothermal areas is local-earthquake tomography. In theory, some information can be obtained by dense, three-dimensional seismic reflection surveying, but these techniques are expensive and insensitive to absolute wave speeds.

Seismic tomography, however, currently suffers from two serious problems:

- Local earthquakes are needed: Unexploited geothermal areas frequently have low levels of seismic activity so data adequate for estimating structure are often not available;
- The technique cannot resolve structure below the local earthquakes: No rays from local earthquakes to near-surface seismometers pass below the local earthquake cloud. Thus no information is available about the deeper part of the area of interest, which typically includes the reservoir itself, and the heat source (Figure 1).

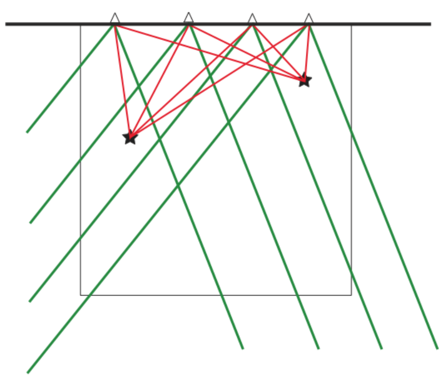

Figure 1: Schematic diagram of the seismic ray coverage from different kinds of earthquakes. Heavy horizontal line: Earth's surface; Triangles: Seismometers; Square: outline of a volume of interest such as a 10-km-thick geothermal area; Stars: Local earthquakes. Rays from local earthquakes (red lines) provide no coverage below the seismically active volume (and of course require that local seismicity occurs). Rays from more distant (regional) earthquakes (green lines) sample almost the entire volume of interest, even in the absence of local seismicity.

Both of these problems can be solved by extending an existing local-earthquake tomography program **dtomo** [Julian & Foulger, 2010] to use data from regional earthquakes (out to distances of a few hundred kilometers) as well as local earthquakes. Figure 1 illustrates ray paths from local and regional earthquakes. Rays from regional earthquakes provide useful sampling of local structure. Moreover, these rays pass through volumes not sampled by local earthquakes, so using both data types when possible can provide even more accurate and complete models, extending into the deep reservoir and potentially into the geothermal heat source.

METHOD

Setting up the problem

Local-earthquake tomography involves numerically computing ray paths that connect specified points, representing hypocenters and seismometers, that lie within the local region under study. Perturbations to the hypocenter locations and origin times are then among the unknown quantities sought in the inversion procedure.

Incorporating regional earthquake data into local-earthquake tomography requires extending the two-point seismic ray-tracing problem to handle mixed boundary conditions at the ends of the rays. For these events, the major portions of the ray paths lie outside the local region, in places where the structure may be known poorly, if at all. This unknown structure affects the orientations, shapes, and arrival times of incoming wave fronts.

We can represent these effects by a few parameters (three, in the case of a plane-wave representation, for example), which we seek to determine in much the same way as we do the hypocentral coordinates of local events. This approach requires that rays must be traced from the (unknown) points where they enter the local volume of interest to the seismometers. At its entry point, each ray is specified by a one-parameter constraint on its position (the value of the depth, for example) and two angles specifying the ray direction. As is the case for local earthquakes, three spatial coordinates specify the known position of the other (seismometer) end of the ray.

Generalized Boundary Conditions

Julian and Gubbins [1977] presented an efficient and accurate numerical method for solving two-point ray-tracing problems, which they called the *bending* method. It involves assuming a path connecting two desired end points and then perturbing this path iteratively until it satisfies Fermat's Principle of stationary time. An extension of the method, which they described but did not implement, uses generalized boundary conditions of the form

$$\mathbf{F}\xi + \mathbf{G}\dot{\xi} = \mathbf{h}$$

at each end of a ray. Here

$$\xi \equiv \begin{bmatrix} \delta x \\ \delta y \\ \delta z \end{bmatrix},$$

where δx, δy, and δz are the components of the perturbation to the path, a dot indicates differentiation with respect to the parameter representing position along the ray (proportional to arc length), and $\mathbf{F}$, $\mathbf{G}$, and $\mathbf{h}$ are two 3×3 matrices and a 3-component vector specified by the user. In this formalism, fixed-position boundary conditions would correspond to $\mathbf{F} = \mathbf{I}$, the 3×3 identity matrix, $\mathbf{G} = \mathbf{0}$, and $\mathbf{h} = \mathbf{0}$, although it is simpler to handle this case by omitting the two points at the ends of the ray from the perturbation computation.

For computing rays from regional earthquakes we require a boundary condition in which the depth and the ray direction are fixed, $\delta\dot{x} = \delta\dot{y} = \delta z = 0$, corresponding to the choices

$$\mathbf{F} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \mathbf{G} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \text{and } \mathbf{h} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}.$$

The initial path has the z component and the derivatives $\dot{x}$ and $\dot{y}$ set to the desired values at one end; the boundary condition prevents these values from changing as the ray is bent.

The bending method requires solution of a system of linear equations with a banded coefficient matrix. This banded structure is important, because it reduces the computation labor required from $O(n^3)$ to $O(n)$, where n is the number of points used to specify a ray path. The finite-difference representation of the generalized boundary conditions destroys the banded structure of the matrix, and requires that Gaussian elimination be used to restore the needed structure before the boundary conditions are inserted into the matrix.

The initial path must be chosen carefully, because the desired ray angle is often nearly horizontal. Straight-line paths, although usually adequate for fixed-endpoint boundary conditions, would often result in paths to regional events that are far from the actual ray, and would impede, or even prevent, convergence of the iteration. We take the initial paths to be circular arcs appropriate to the estimated vertical gradient of the wave speed in the area.

Software components

The ray-tracing software we have developed consists of two components:

- **bend3d**, an object-oriented set of functions appropriate for general use, and
- **bendray**, a command-level interface, also useable as a test harness.

bend3d and **bendray** incorporate the generalized boundary condition described above. They contain functions to make initial guesses for the ray path when mixed boundary conditions are given.

FUTURE WORK

At the time of writing, the new tomography program is approaching completion. Completion is scheduled for Spring 2011. At that stage, the software will be applied to real datasets. We would be interested in hearing from anyone who has a dataset suitable for testing the new method.

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