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Time-dependence of Seismic Wave Speeds in Volcanic and Geothermal Systems

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ABSTRACT

That seismic wave speeds in geothermal systems might change with time is an expected consequence both of natural processes and of industrial activities such as fluid withdrawal and injection, and indeed detections of such changes have been reported, based on repeated microearthquake seismic tomography. Seismic tomography suffers, however, from limitations that cast doubt on some of these reports. Specifying a three-dimensional model of seismic wave speed in even a small volume requires at least thousands of parameter values, but because of the limited distribution of both earthquakes and seismometers, real data sets virtually never contain enough information. Seismic rays tend to occur in bundles that sample the Earth very unevenly, and standard inversion methods impose assumptions that result in structural features that mimic these bundles. Any changes in the ray distributions, such as those caused by seismicity variations, can therefore produce spurious apparent changes in the wave speeds.

It is possible to overcome this difficulty by simultaneously inverting data sets from different epochs, imposing constraints to minimize temporal and spatial variations. This strategy greatly reduces both complex structure and temporal variations that are not actually required by the data.

We report the results of applying program **tomo4d**, which uses this strategy, to seismic data from Mt. Etna, in Sicily (where strong temporal variations have been reported in the literature), Long Valley caldera, California, which is largely in a natural state, and the heavily exploited Coso geothermal area, California. For Coso, we studied in detail the epochs 1996-2006 and 2007-2012, determining V_P, V_S and V_P/V_S. In our presentation, we will report our latest results

1. INTRODUCTION

Because the elasticity of rocks depends on factors such as pressure, temperature, porosity, pore geometry, and pore-fluid compressibility and viscosity, it is to be expected that seismic wave speeds would vary with time as a result of tides, various geological processes, and human activities. Indeed, many investigators have reported detection of temporal changes using a variety of seismological methods (Julian and Foulger, 2010).

Information about temporal changes in seismic wave speeds could be of great value for understanding and possibly predicting earthquakes and volcanic eruptions and for monitoring industrial operations involving mineral and geothermal resources. For such purposes, three-dimensional (3D) images of temporal changes are needed, but obtaining reliable images of this kind is difficult. The geographical distribution of earthquake sources (and often of seismometers), and thus the spatial sampling provided by seismic rays, usually is suboptimal, changing with time, and beyond experimental control. Even if one keeps source and seismometer locations fixed (*e.g.* by using artificial sources), observational errors cannot be entirely avoided. For these reasons, inferred seismic wave speeds will generally vary with time even if the true wave speeds do not.

These difficulties arise from the practice of inverting data sets from different epochs independently. They can be largely avoided by inverting the data sets simultaneously while applying constraints to suppress temporal changes that are not actually required by the observations. Julian and Foulger (2010) presented a modified form of least-squares fitting that efficiently incorporates such constraints, and demonstrated its effectiveness using synthetic arrival-time data.

2. CONVENTIONAL SEISMIC TOMOGRAPHY

Despite the above-described limitations, some investigators have claimed to detect temporal changes using repeat seismic tomography.

2.1 The Geysers

Following initial investigations by Foulger *et al.* (1997), Gunasekera *et al.* (2003) conducted a systematic study of The Geysers geothermal field of northern California, applying the SIMUL program of Thurber (1993) to data from five epochs between 1991 and 1998. They found a strong systematic decrease in V_P/V_S at depths of 1 to 2 km, caused primarily by a decrease in V_P.

2.2 Mammoth Mountain, California

Long Valley caldera, in east-central California, and its surroundings have experienced ongoing rapid crustal deformation and continuous seismic unrest since 1978, including at least five earthquakes above magnitude 6 and, beginning in 1989, emissions of CO_2. These have caused extensive tree mortality around Mammoth Mountain, a lava-dome complex on the southwest edge of the caldera. Results of repeat tomography using data from earthquake swarms in 1989 and 1997 suggest that seismic wave speeds at shallow depths near Mammoth Mountain changed during this interval. This conclusion is subject to doubt for the reasons outlined in Section 1. Nevertheless, the spatial distribution of apparent changes correlates with locations of fumaroles, CO_2 springs, and areas of tree-kill in a way that is highly suggestive. We are currently analyzing the 1989 and 1997 seismic data using **tomo4d** to resolve whether the changes in structure reported earlier are real or not.

2.3 Mount Etna, Sicily

On the basis of repeated local-earthquake tomography of Mt. Etna, Patanè et al. (2005) reported decreases of about 5% in the seismic wave-speed ratio V_P/V_S during a large flank eruption in late 2002 and early 2003, compared to two intervals spanning the previous year. The affected regions, the south-central and northeast portions of the volcanic edifice, were surprisingly large, with volumes of the order of 10 to 20 km^3 (dimensions of about 4 km horizontally and 1 km vertically). The reality of these changes is open to question, however, because of the sparseness and time variability of the earthquake distribution, particularly around the northeastern anomaly. We are currently applying **tomo4d** to the 2002-2003 seismic data from Mt. Etna to resolve this question.

3. TOMO4D METHOD

In their simplest form, seismic tomography methods seek to minimize an *objective function*

$$\frac{1}{N}\chi^2 = \frac{1}{N}\sum_{DATA}\left(\frac{t_{OBS} - t_{CALC}}{\sigma}\right)^2, \tag{1}$$

that quantifies the quality of the fit to the observed data. Here t_{OBS} and t_{CALC} are the observed and calculated seismic-phase arrival times and σ is the standard error of one observation. Because seismic data sets virtually never contain enough information to completely specify a three-dimensional Earth model, it is usually necessary to add to the objective function terms such as

$$\frac{1}{V}\int_V (\Delta v)^2 dV, \tag{2}$$

where Δv is the per-iteration perturbation to the seismic-wave speed in the model and V is volume. Such additive terms attempt to make the model similar to an assumed starting model, or to make the model approximately homogeneous, or smooth, etc.

In "four dimensional" (time-dependent) tomography we face a similar difficulty of having incomplete data, which we handle similarly by adding to the objective function another term,

$$\frac{1}{V}\int_V (\Delta\delta v)^2 dV, \tag{3}$$

to minimize temporal change. Here δv is the inter-epoch change in the wave speed in the model and Δδv is its change per iteration.

Inverting two datasets simultaneously for two models doubles the order of the system of linearized equations that we must solve numerically, which would seem superficially to require eight times the computational labor. Julian and Foulger (2010) give an algorithm that takes advantage of the sparse structure of the equations to greatly reduce the required additional labor.

3. COSO GEOTHERMAL AREA

The Coso geothermal area is located on the Naval Weapons Center of the US Navy, near the southwestern corner of the Basin and Range Province, in southeastern California (Figure 1). It is commercially exploited to generate electrical power, and is an area of intense microearthquake activity. A local seismometer network operated by the Navy's Geothermal Program Office records thousands of earthquakes per year.

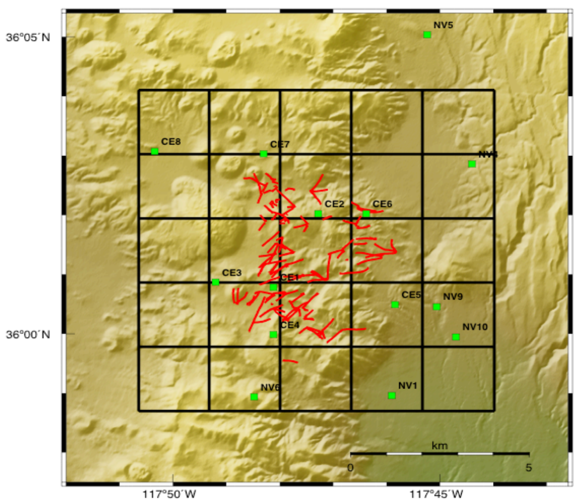

Figure 1: Map of the Coso geothermal area. Red lines: Surface traces of geothermal boreholes; Green squares: Seismometers operated by the US Navy; Black lines: Surface projection of the 10 km × 10 km spatial grid upon which seismic wave-speed models are defined. Grid nodes are spaced 2km apart horizontally and 1 km vertically.

Foulger (2007) studied the Coso field using the same method that Gunasekera *et al.* (2003) had successfully applied to The Geysers, performing independent tomographic inversions of high-quality sets of *P*- and *S*-phase arrival-time data from each of the nine years 1996-2004. The results provided evidence for an irregular reduction of the wave-speed ratio V_P/V_S in the upper 2 km of the geothermal field, but lacked consistency from year to year, undermining confidence in the results and motivating development of the **tomo4d** algorithm.

Figure 2 shows the results of applying **tomo4d** to detect possible temporal changes in seismic wave speeds over the five-year period from 2007 to 2012, for which the seismic data are of high quality. The first step in this process was to combine the 2007 and 2012 data and to invert them to obtain a model of V_P and V_S. The wave speeds in this model vary spatially by about 10% and have a formal precision of about 0.1%. The earthquake hypocenters are determined to within a few tens of meters. We then used this as the starting model for another tomographic inversion, to determine whether a significant improvement could be obtained by allowing differences between the models for 2007 and 2012. The results indicate temporal changes in the wave speeds, and their ratio, of the order of 0.1%. Of particular note is an increase in the ratio V_P/V_S in the upper km or two beneath the "east flank", northeast of the center of the model area. This observation lends support to previous observations, based on repeat-tomography analysis, that the east flank behaves differently from the rest of the geothermal system.

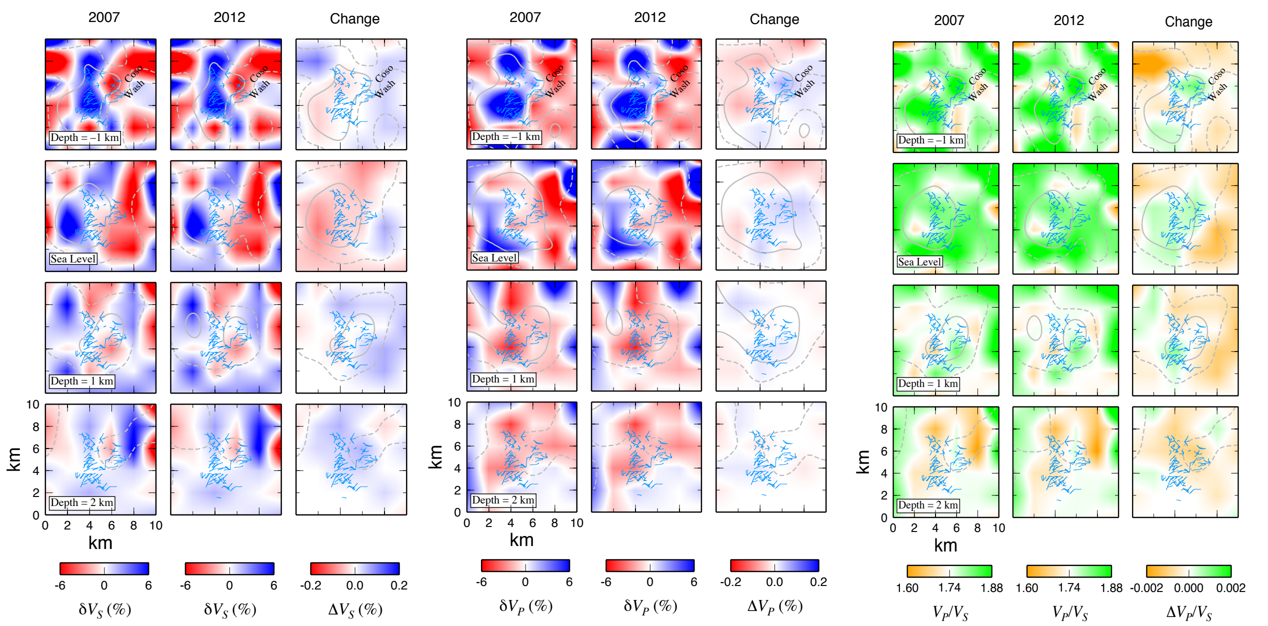

Figure 2: Models of the seismic-wave speeds at Coso for the years 2007 and 2012. The area plotted is that of the tomography grid shown in Figure 1. The ground surface at Coso is about 1 km above sea level, so the uppermost maps correspond to the near-surface. Left: Shear-wave speed V_S; Center: Compressional-wave speed V_P; Right: Wave-speed ratio V_P/V_S. The symbol δ indicates the departure from the mean value at each depth; the symbol Δ indicates temporal (between-epoch) variation.

CONCLUSIONS

Temporal changes in seismic-wave speeds, both natural and human-induced, occur in volcanic and geothermal systems, and can provide information valuable for hazard analysis and for managing geothermal exploitation. Unfortunately though, seismic tomography is subject to significant errors caused by inadequate sampling of Earth structure by available seismic rays. Consequently, temporal changes in seismicity patterns and other factors can easily be mistaken as evidence for temporal changes in Earth structure. Tomographic methods can be adapted to deal with this problem by inverting data sets from multiple epochs simultaneously, applying constraints to minimize temporal variations in derived models.

We are currently applying such a method, **tomo4d**, to seismic data from several geothermal and volcanic areas, including the Coso geothermal area and Long Valley caldera in eastern California, and Mt. Etna, Sicily.

At Coso, the results of this analysis confirm the conclusions of earlier studies that the wave-speed ratio V_P/V_S decreased at shallow depths beneath the Coso east flank between 2007 and 2012.

Preliminary analysis indicates that any changes in seismic-wave speeds at Mt. Etna during the 2002-2003 flank eruption were much weaker than has been suggested on the basis of simple repeat tomography.

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