

Time-Dependent Tomography Using TOMO4D: Theoretical Advances and Early Applications

Najwa Mhana¹, Ceri Nunn^{1,2}, Bruce R. Julian¹, Gillian R. Foulger¹, and Andrew E. Sabin³

¹Dept. of Earth Sciences, Durham University, Durham DH1 3LE, United Kingdom

²now at Dept. of Earth and Environmental Sciences, Ludwig-Maximilians-Universität, Theresienstrasse 41, 80333 Munich, Germany

³U. S. Navy Geothermal Program Office, China Lake, CA 93555

najwa.mhanna@durham.ac.uk; ceri.nunn@gmail.com; b.r.julian@durham.ac.uk; g.r.foulger@durham.ac.uk; andrew.sabin@navy.mil

Keywords: Seismic tomography; temporal change; Coso; Etna; Long Valley caldera;

ABSTRACT

Detecting and measuring temporal changes in seismic wave speeds is difficult, because of the difficulty of exactly replicating experimental conditions and because of inevitable observational errors. Therefore, despite the potential value of such measurements for monitoring exploited geothermal reservoirs and active volcanoes, most reports of changes in wave speeds are of questionable reliability.

These difficulties can be greatly reduced by inverting data from different epochs simultaneously, imposing “regularization” constraints to minimize the differences between derived models. We report on the first applications of the seismic tomography program *tomo4d*, which uses this approach, to data from three areas: the exploited Coso geothermal area in southeastern California; the lightly exploited but seismically active Long Valley caldera in east-central California; and the highly active volcano Mount Etna, in Sicily. In all these cases, temporal variations that had been inferred from independent tomographic inversions of data from different epochs are not actually required by the data. The use of hypothesis testing approaches such as that embodied in *tomo4d* have great power to prevent us from being misled by the limited information content in virtually all seismic-tomography data.

1. INTRODUCTION

The mechanical properties of porous rocks depend, among other things, upon the properties of the pore fluids, and thus should change in response to geothermal exploitation and to natural causes. Indeed, strong and easily detectable changes in the seismic wave speeds reportedly occur at some heavily exploited geothermal fields, such as The Geysers in northern California (Gunasekera *et al.*, 2003), but at most fields and for natural processes, temporal changes are weak and difficult to identify with certainty.

Temporal changes in the structure of volcanic and geothermal areas have until now been investigated by applying conventional tomographic techniques to invert seismic wave arrival-time data for different epochs independently, and assuming that differences in the resulting models reflect real temporal variations. Unfortunately, however, changes between derived models are expected even if the structure did not actually change, due to differences in seismic ray distributions and to inevitable observational errors. Thus, it remains open to question whether weak changes in structure sometimes reported at volcanic and geothermal areas are real.

It is possible to overcome these difficulties by inverting data sets from different epochs simultaneously, imposing “regularization” constraints to minimize differences between derived models for different epochs. This approach requires solving systems of linear equations whose order is twice that required for independent inversion, but sparseness of the matrices involved makes possible optimizations that largely compensate for this disadvantage. In this paper, we use this approach, as implemented in the local-earthquake tomography program *tomo4d* (Julian and Foulger, 2010), to assess possible temporal changes at the exploited Coso geothermal area, eastern California, and at two volcanic areas, Long Valley caldera, California, and Mount Etna, Sicily.

The *tomo4d* program takes advantage of the sparse structure of the relevant equations to achieve significant computational efficiencies, and also incorporates significant improvements over previous local-earthquake tomography programs, for example performing true ray tracing through 3D structures (Julian and Gubbins, 1977). Tests using synthetic data verify that *tomo4d* suppresses artificial temporal variations in seismic-wave speed.

The difficulties with measuring temporal changes are consequences of the small amount of information contained in any real seismic data set compared with the information required to fully specify a useful three-dimensional model of Earth structure. There will always be an infinite number of significantly different 3D models that fit observations within their uncertainties, and examining particular tomographic models often sheds little light on structure and processes within the Earth. Our approach, of finding the smallest temporal changes consistent with observation, attempts to test hypotheses by falsifying possible models, as advocated by Tarantola (2006).

2. DATA ANALYSIS

2.1 Long Valley Caldera

Long Valley caldera, in eastern California, has experienced ongoing seismic activity since 1978, involving hundreds of thousands of microearthquakes and four events above magnitude 6. Repeated local-earthquake tomography using data from 1989 and 1997 conducted by Foulger *et al.* (2003) found possible evidence for a CO₂ reservoir that had been suggested by Julian *et al.* (1998) beneath Mammoth Mountain, in the form of an increase of up to 3% in the ratio, V_P/V_S , of the compressional- and shear-wave speeds.

To test this conjecture, and to look for other wave-speed changes that might have accompanied the ongoing seismic activity, we applied *tomo4d* to compare mid-1997, when a dense seismometer network was deployed temporarily, with the two-year period 2009-2010. We selected 276 well-recorded local earthquakes from the United States Geological Survey (USGS) catalogue for 2009-2010, with all events having at least 10 *P*-phase readings and 4 *S*-phase readings (Figure 1), and manually measured arrival times for these events from digital seismograms obtained from the Northern California Earthquake Data Center (NCEDC). We obtained 3727 *P*-phase and 1170 *S*-phase arrival times, with estimated precisions of ~ 0.01 s and ~ 0.03 s.

2009-2010

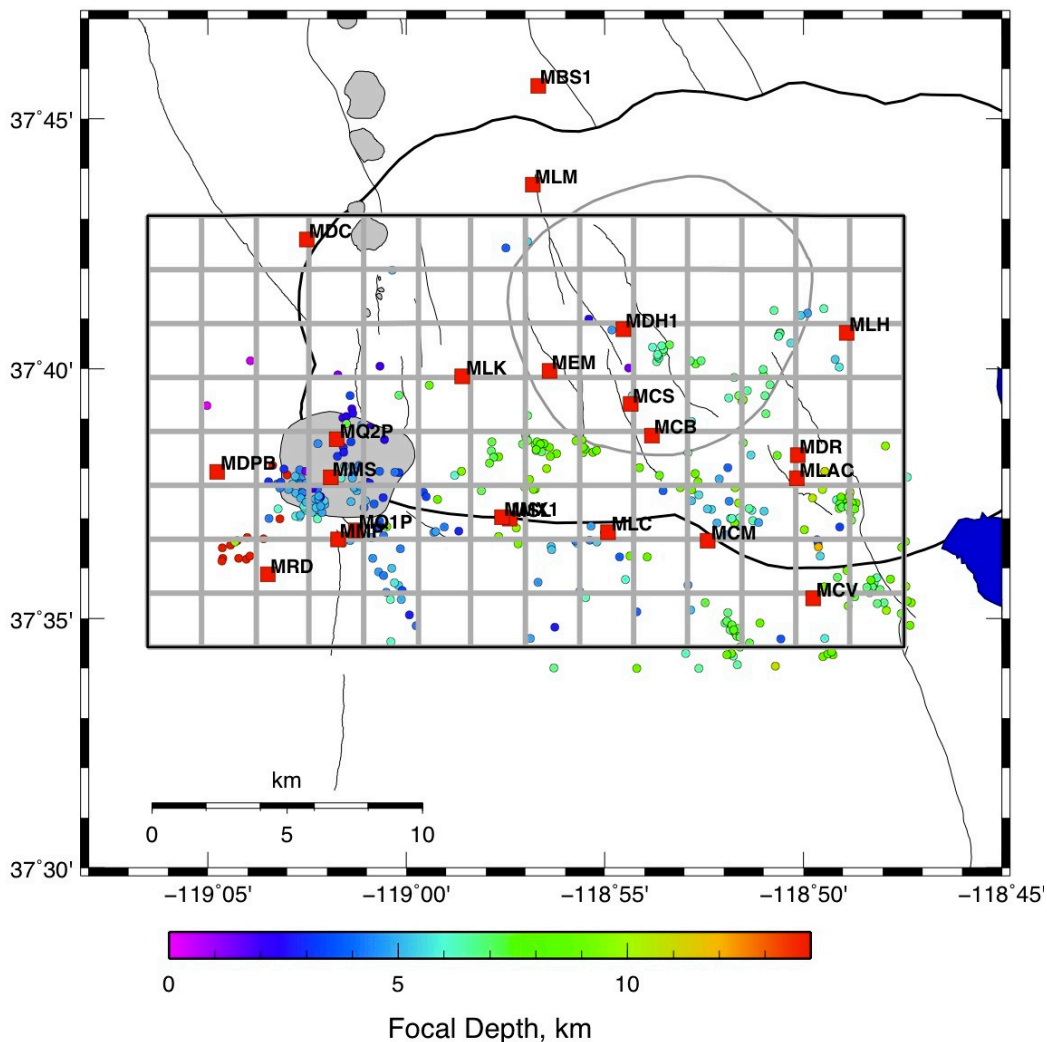


Figure 1: Map of central and western Long Valley caldera and vicinity, showing the 276 earthquakes analyzed for the period 2009–2010, color-coded by focal depth (locations from the USGS catalog), and the grid upon which the tomographic models are defined. Mammoth Mountain is shown in gray at left center, and Crowley Lake in blue at right. Black line: topographic caldera margin; heavy gray line: resurgent dome; thin gray lines: faults; red squares: seismometers.

We obtained much weaker structural changes between 1997 and 2009-2010 when inverting the data sets simultaneously using *tomo4d* than when inverting them independently using *simul2000A*. The apparent changes in the wave speeds exceed 5% for independent inversion, but are approximately 0.05% when using *tomo4d*. Similarly, the apparent changes in the wave-speed ratio V_P/V_S are about 100 times weaker when using *tomo4d* than with *simul2000A*. Because these apparent changes are so weak (less than one part in one thousand), their reality is doubtful.

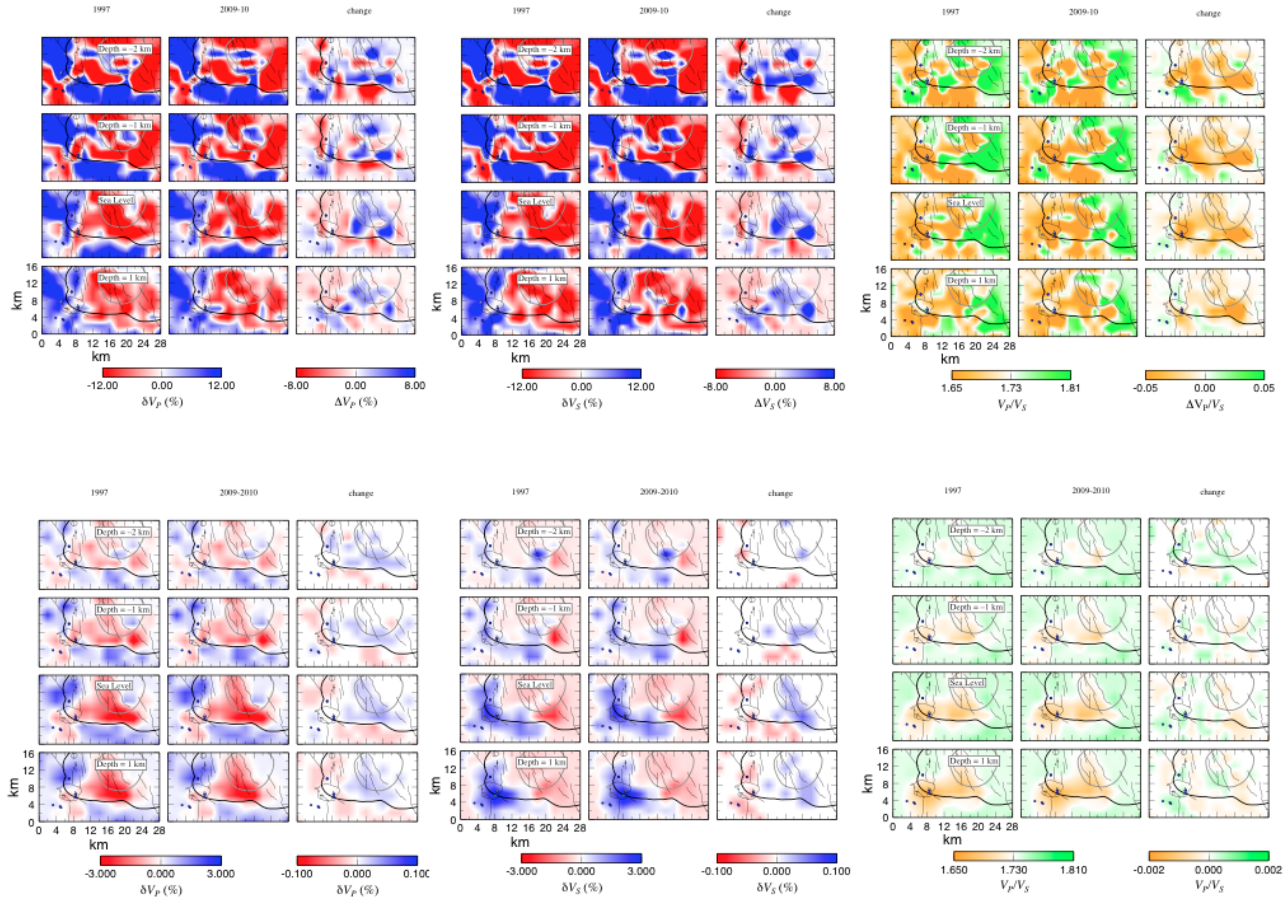


Figure 2: Changes in compressional-wave speed V_P (left), shear-wave speed V_S (middle), and the ratio V_P/V_S (right), at Long Valley caldera between 1997 and 2009-2010 at four depths (-2, -1, 0, 1 km below sea level) determined using *simul2000A* (top) and *tomo4d* (bottom). Note the differences in color scales. Changes inferred using *tomo4d* are about 100 times weaker than those from *simul2000A*.

2.2 Coso Geothermal Area

The commercially exploited Coso geothermal area, located near the southwestern corner of the Basin and Range Province in southeastern California, is an area of high microearthquake activity, both natural and induced. The geothermal field lies on the Naval Weapons Center, and the seismometer network operated by the Geothermal Program Office of the US Navy records thousands of earthquakes per year.

Foulger (2007) performed independent local-earthquake tomography inversions of high-quality subsets of data from each of the nine years 1996-2004, and found evidence of an irregular reduction of the wave-speed ratio V_P/V_S in about the upper 2 km within the geothermal field. Indeed, irregularities in the apparent temporal changes in V_P/V_S found in this study provided the primary motivation for developing and programming the *tomo4d* algorithm.

Following procedures similar to those of *Foulger (2007)*, in this study we processed data for the years 2007, 2008, 2010 and 2012, using both *simul2000A* and *tomo4d*. Figure 3 shows the event locations for 2008 and 2012, and Figure 4 shows the corresponding wave-speed models and inferred temporal changes.

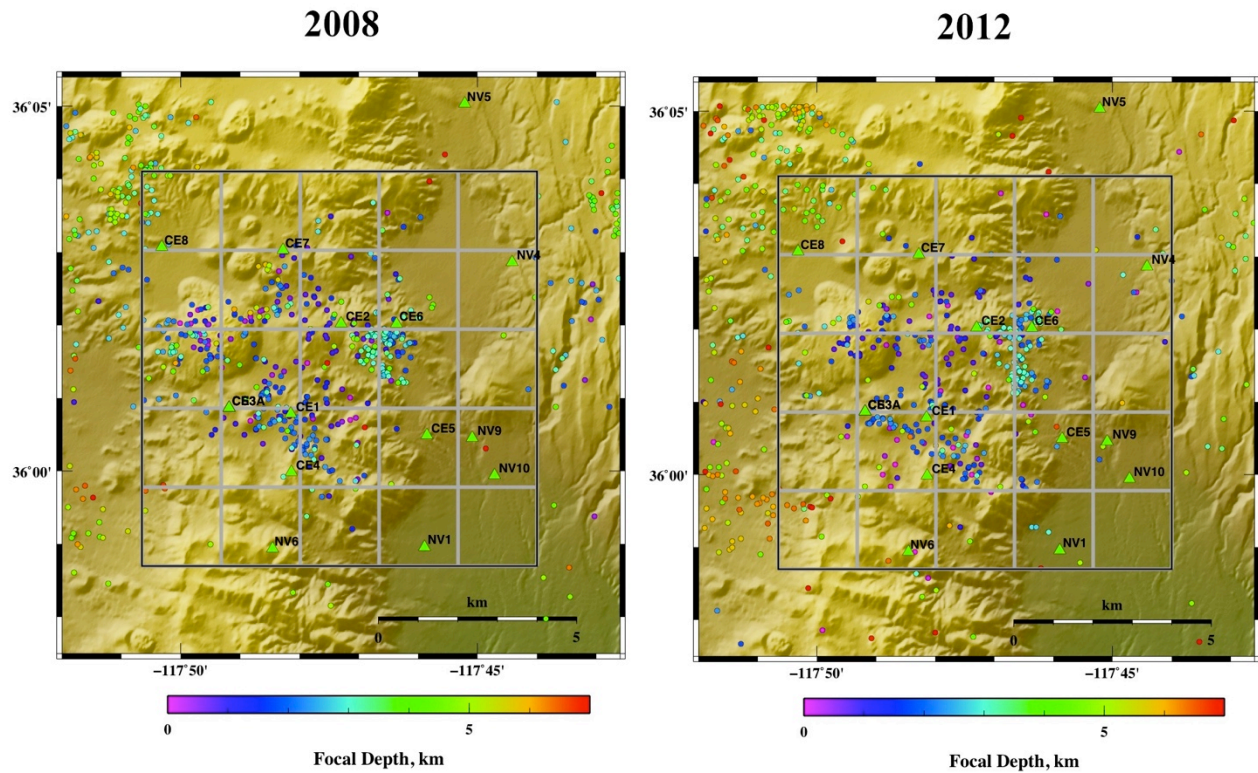


Figure 3: Shaded-relief maps of the Coso geothermal area, showing earthquakes analyzed for the years 2008 (570 events) and 2012 (504 events), color-coded by focal depth, and the 10 km by 10 km by 8 km grid upon which the tomographic models are defined. Green triangles: Seismometers of the US Navy network.

The spatial patterns of wave-speed variation in the models generated by the two programs are vaguely similar, but those from *tomo4d* are less than about half as strong. Even more strikingly, the temporal variations in the *tomo4d* results are about two orders of magnitude weaker than those obtained by independent inversions using *simul2000A* and there is little or no resemblance between the patterns from the two methods. Evidently, temporal variations in the seismic wave speeds are less than about 0.1% in magnitude, and those in V_p/V_s are less than about 0.001 in magnitude. The much larger changes inferred from independent *simul2000A* inversions are entirely spurious.

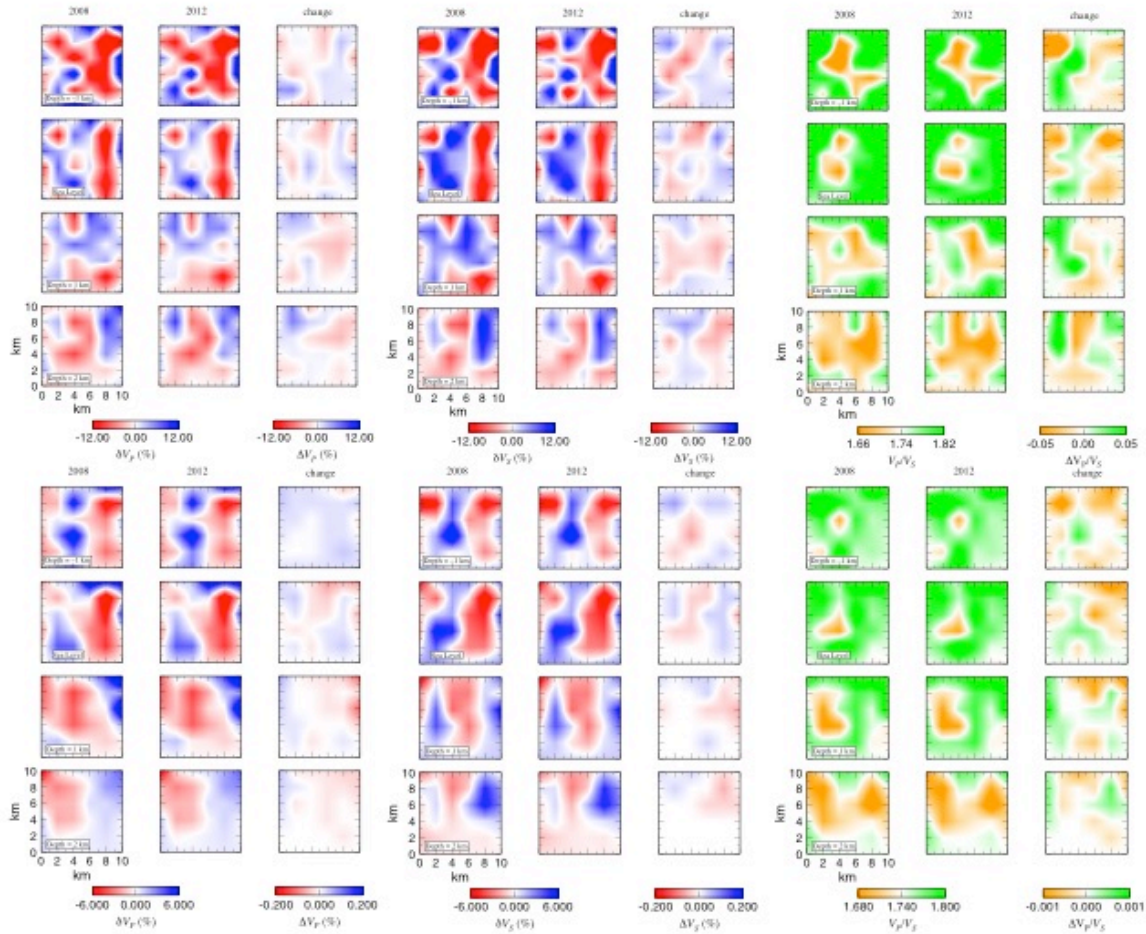


Figure 4: Apparent changes in compressional-wave speed V_P (left), shear-wave speed V_S (middle), and the ratio V_P/V_S (right), at the Coso geothermal area between 2008 and 2012 at four depths (-2, -1, 0, 1 km below sea level), determined using *simul2000A* (top) and *tomo4d* (bottom). Note the differences in color scales.

2.3 Mount Etna

Mount Etna is a highly active and potentially dangerous basaltic stratovolcano that rises about 3350 m above sea level on the east coast of Sicily (Figure 5), close to the city of Catania. Patanè *et al.* (2006) applied repeated local-earthquake tomography to arrival-time data from a local seismometer network obtained before, during, and after a flank eruption that occurred from October 2002 to January 2003, and concluded that during the eruptive phase the wave-speed ratio V_P/V_S increased from 1.74 to 1.82 (> 4%) throughout a volume with dimensions of several kilometers.

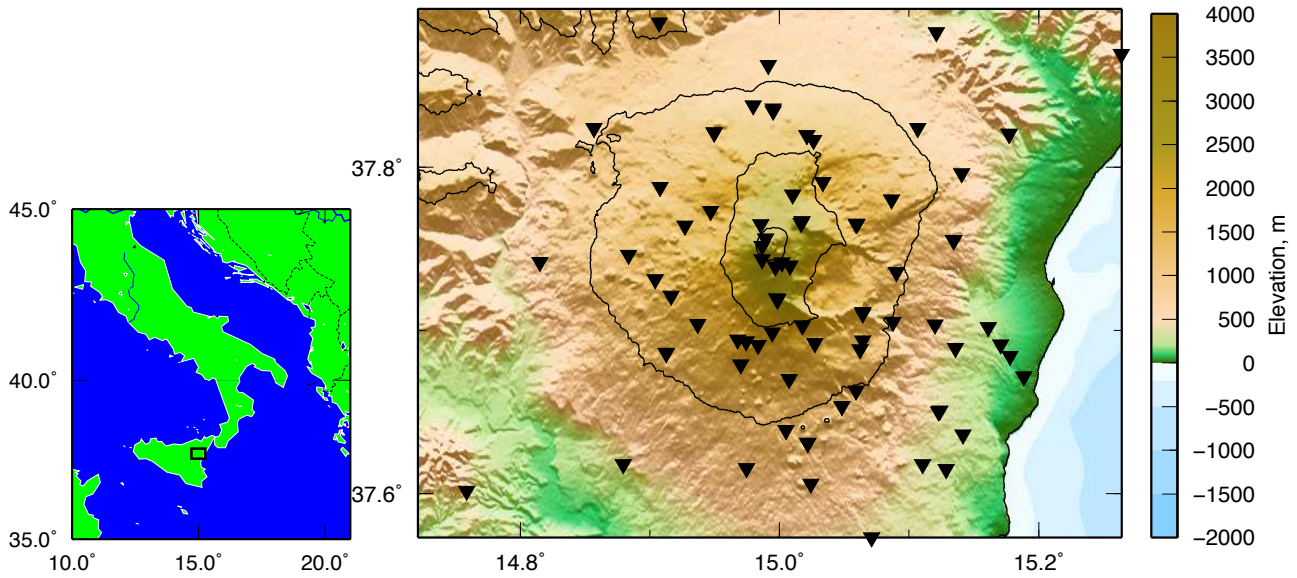


Figure 5. Left) Map of Italy showing the location of the study area (black box). Right) Shaded topographic map of Etna. Black triangles: Seismometer locations; black lines: Topographic contours (interval 1000 m). During the study period, some of the seismometers were moved.

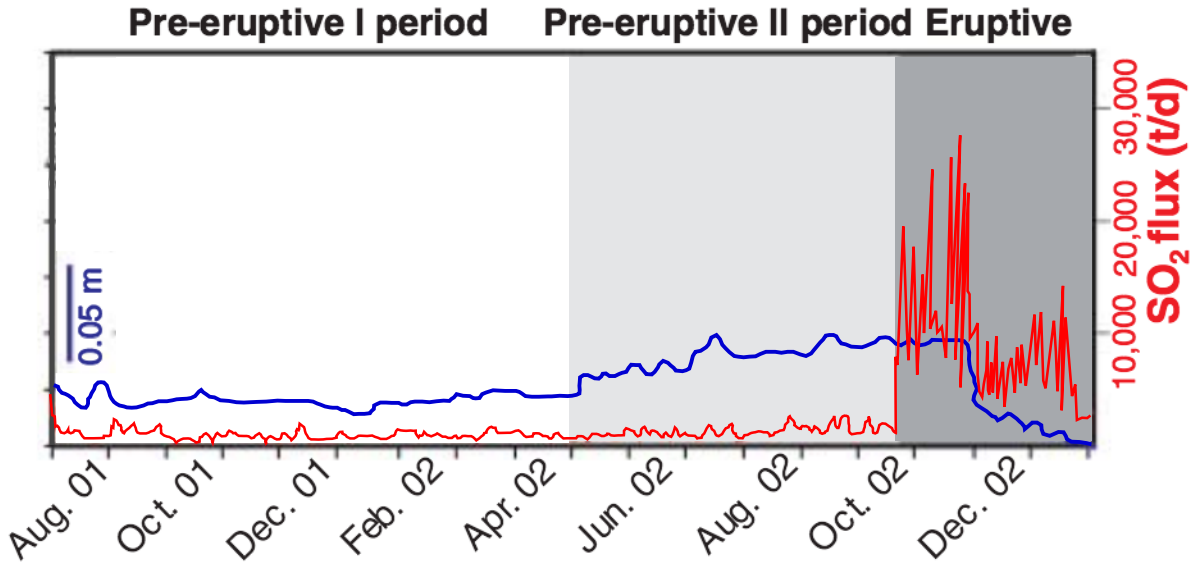


Figure 6. Blue: Geodetic deformation (changes in the length of an ~18-km baseline) on the SW side of Mt. Etna measured using GPS; Red: SO₂ flux at Mt. Etna from August 2001 through January 2003. Both after Patanè *et al.* (2006).

To test whether temporal changes were actually required, we re-analyzed the Etna arrival-time data using *tomo4d*. We used data from 80 seismic stations from the permanent and temporary networks (Fig. 5) operated by the Mount Etna Istituto Nazionale di Geofisica e Vulcanologia–Sezione di Catania (INGV-CT). Of these stations, 45 had three-component digital seismometers, 22 had single-component digital seismometers, and the remainder had three-component analog seismometers. The model was defined on a 48-km (EW) by 36-km (NS) by 12-km (vertical) grid, with nodes spaced by 4 km horizontally and 2 km vertically.

We separated the earthquakes into three groups based on the divisions of the eruptive cycle used by Patanè *et al.* (Fig. 6). Because the current version of *tomo4d* treats only two epochs at a time, we performed two inversions, each of which compared one of the two “pre-eruptive” periods with the “eruptive” period. Figures 7 and 8 show the results of the inversion that used “pre-eruptive period I”. (Results for “pre-eruptive period II” are similar.) Independent inversions using *simull2000A* indicated temporal variations in V_P of more than 5% and in V_P/V_S of more than 0.03. Inverting data from both periods simultaneously, however, *tomo4d* was able to fit the observed times with essentially no temporal changes in the wave speeds.

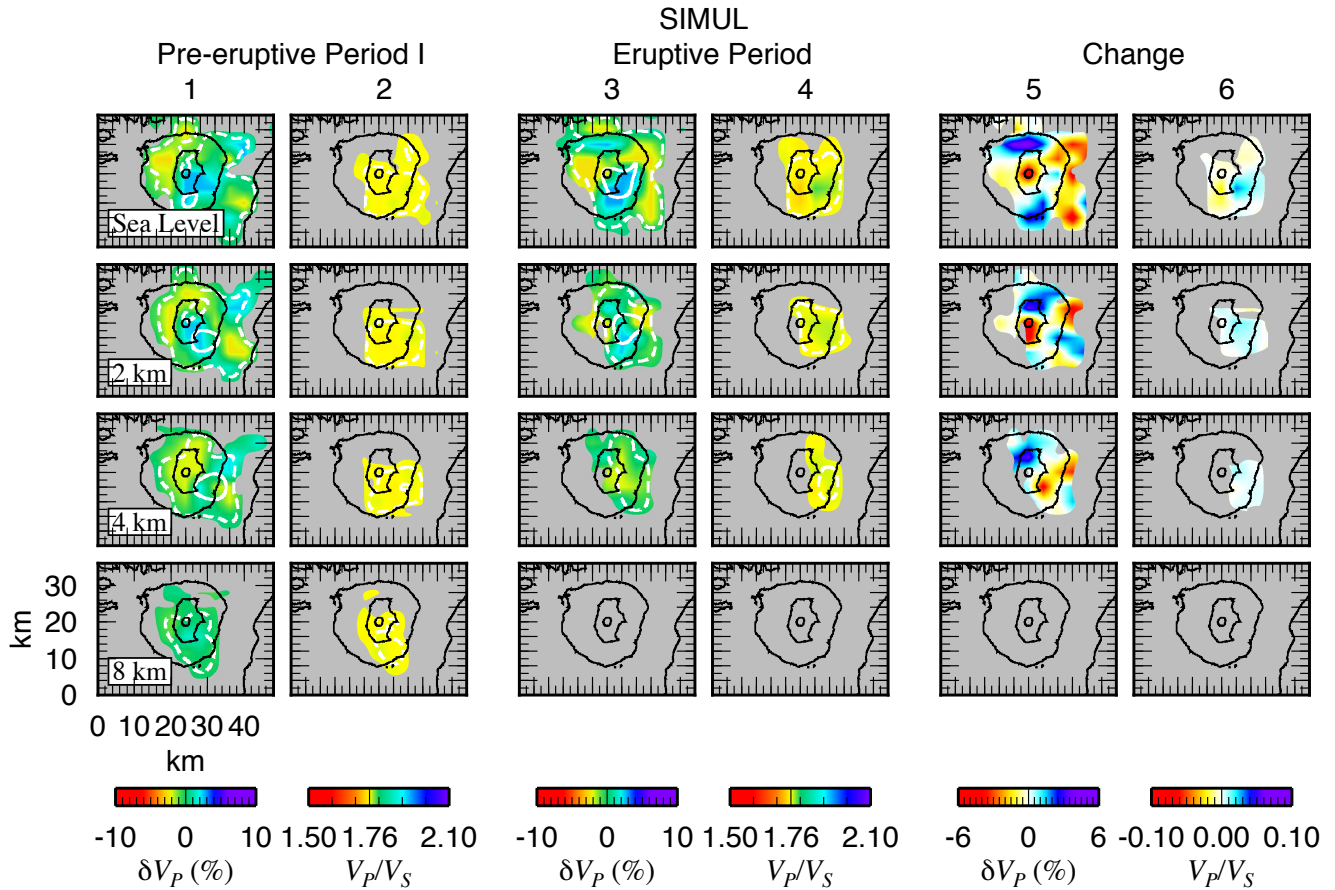


Figure 7. Maps of compressional-wave speed V_P (columns 1, 3) and wave-speed ratio V_P/V_S (columns 2, 4) at four different depths, as determined by independent *simul2000A* tomographic inversion of data from the earliest (left) and latest (middle) periods shown in Figure 6. Right: The differences between V_P (column 5) and V_P/V_S (column 6) values in the models for the two periods (*i.e.* the apparent temporal change). The maps cover the same area as that shown in Figure 5 (right). Heavy black line: coastline; lighter black lines: topographic contours (interval 1000 m); Gray: areas lacking adequate seismic ray coverage.

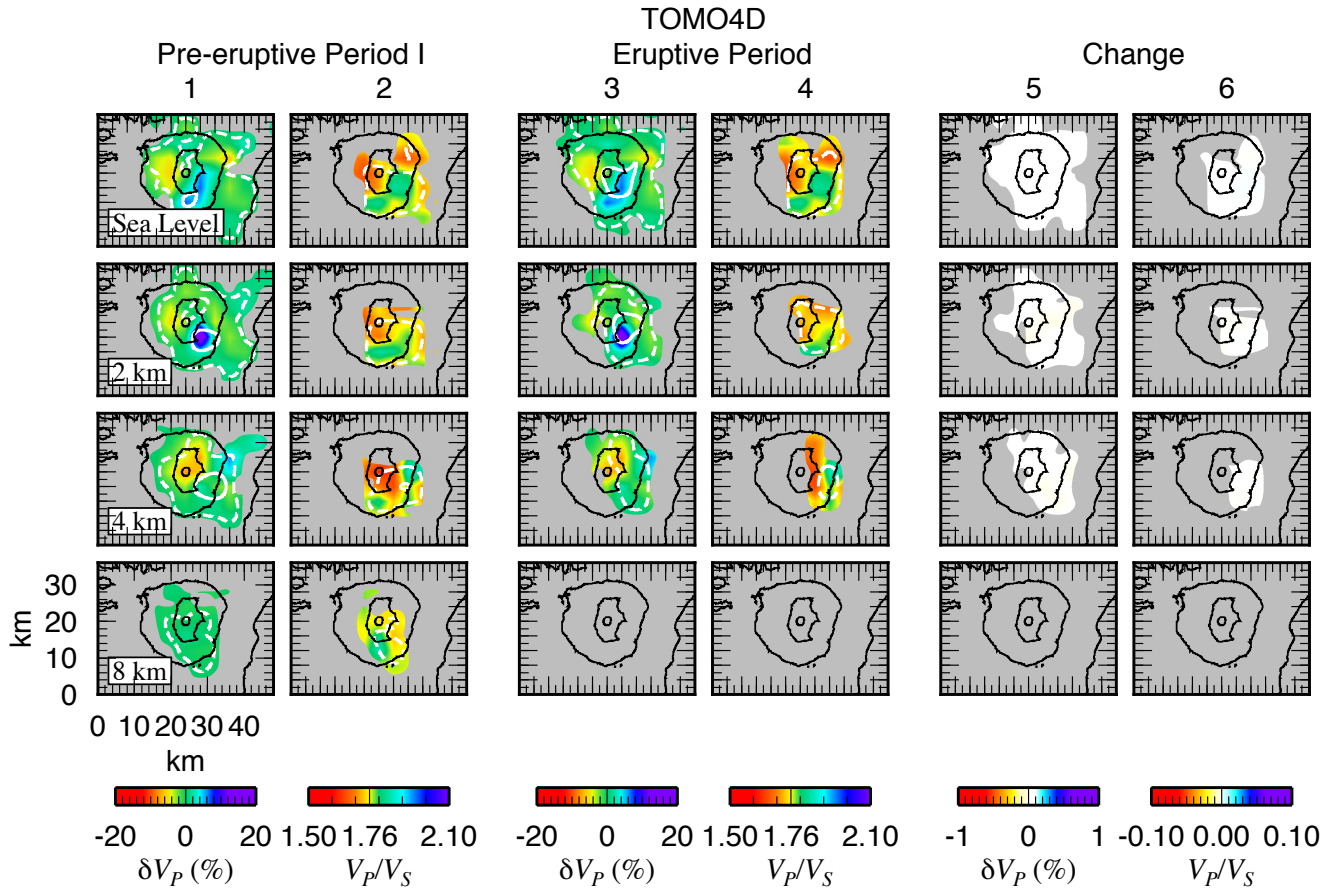


Figure 8. Similar to Figure 7, showing models determined in this study, by inverting data for the two time periods jointly using *tomo4d*. The apparent temporal change has almost completely vanished. Note the differences in color scales compared to Figure 7.

3. CONCLUSION

In the three cases analyzed here, it is possible, by inverting data from separate epochs simultaneously, to fit observed arrival-time data satisfactorily without hypothesizing temporal changes in the seismic wave speeds. Apparent wave-speed changes as large as 10-15% that result from analyzing data from different epochs independently are not required by the data.

The approach embodied in *tomo4d*, of inverting data from multiple epochs simultaneously, improves our ability to resolve temporal changes by about two orders of magnitude. The general philosophy underlying this approach, of using seismic tomography to test hypotheses (in this case, of temporal variations), rather than to produce models, shows great promise in a range of Earth-science applications extending far beyond those considered in this study.

ACKNOWLEDGEMENTS

C. N. was funded by the MEDiterranean SUPersite Volcanoes FP7 project (grant number 308665). We thank Domenico Patanè and Graziella Barberi from I.N.G.V. – Catania for kindly providing the revised and verified arrival-time data for Mount Etna.

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