

A new method to invert seismic waveforms for 3-D Earth structure —Imaging the Lowermost Mantle under Central America—

1. Key Points

- ◆Development of a “big data” approach for directly inverting large data sets of seismic waveforms for 3-D earth structure
- ◆Obtained higher resolution 3-D images of the lowermost mantle (Note #1) under Central America than previous studies
- ◆Important information for understanding the Earth's dynamics and evolution

2. Summary

The Earth consists of the crust, mantle (Note #1), outer core and inner core (Note #2). The D" (pronounced “Dee double prime”) layer is the name given to the lowermost several hundred km of the mantle, directly below which is the molten outer core, which is composed primarily of iron. The temperature and chemical composition within D" vary rapidly as the distance to the core-mantle boundary (CMB) decreases. Data on material and energy flux in D" can provide important information for understanding the Earth's dynamics and evolution, but the three dimensional (3-D) structure of D" was not heretofore known with sufficiently high resolution. The present study, by Kenji Kawai (a visiting researcher at the University of Tokyo and Assistant Professor at the Tokyo Institute of Technology), Robert J. Geller (Professor at the University of Tokyo), and their co-workers, has developed a new method for direct inversion of seismic waveforms for high-resolution 3-D Earth structure. The study then applied the new inversion method to a large data set of seismic waveforms recorded at seismic stations in North America for earthquakes under South America to determine seismic structure in the lowermost mantle under Central America. The study found evidence for the existence of remnants of the subducted Farallon Plate (Note #3) in D" beneath Central America. This material was carried from the Earth's surface to D" by mantle convection. It is anticipated that the new data analysis method presented in this study can also be applied to data from many other regions to image D" on a global scale, thereby contributing to better understanding of the Earth's dynamics and evolution.

3. Details

In recent years as several seismological arrays (Note #4) have been installed, the volume of available high quality seismological waveform data has increased greatly, and expectations have been high that this will lead to better images of the Earth's internal structure. However, due to the difficulty of fully exploiting this large volume of new data using pre-existing data analysis methods, development of new methods became necessary.

The D" layer at the base of the lower mantle (Note #1) is the lower boundary for convection in the mantle and is a chemical boundary between the mantle and the outer core (Note #2), which is composed of liquid iron alloy. Obtaining clearer and more accurate

images of the structure of D" would provide important information on the Earth's dynamics and evolution.

Previous methods for analyzing seismic waveforms have shown the existence of laterally heterogeneous structure in D" on a scale of thousands of kilometers. However, it is not yet known whether the cause of these heterogeneities is thermal or chemical or some combination of the two. Research in the early and mid-2000s found that the main mineral making up the lower mantle, Mg-perovskite, undergoes a phase transition to a denser crystal structure, Mg-postperovskite, in D". Sharper images of Earth structure in D" could help to better understand the physics and chemistry of this region, but previous methods have a vertical resolution of only about 300-500km. Development of new data analysis methods that can provide finer scale resolution was thus essential.

The authors had previously developed and applied methods for directly inverting seismic waveform data (Note #5) to determine the vertical dependence of Earth structure in a particular region. In the present study they extend these methods to be able to invert for localized 3-D structure in a particular region. This "big data" approach makes it possible to objectively and quantitatively analyze all of the information in all of the observed waveforms together, and find evidence for fine scale features that cannot be clearly seen in any single individual waveform.

The present study analyzed a large volume of seismograms recorded at seismic stations in North America, primarily by the US-Array, for earthquakes under South America, thereby obtaining data for inferring the structure in D" (Figure 1). The authors then applied their new methods of waveform inversion to determine the S-wave velocity structure in the lowermost 400km of the mantle under Central America with a vertical discretization of 50km and a horizontal discretization of 5°. The model obtained by the inversion (Figures 2 and 3) shows a high velocity region with a lateral scale of 250 × 250 km surrounded by a low velocity region. The velocity contrast between the high velocity material and the surrounding lower velocity material increases with increasing depth.

In general high velocity regions have lower than average temperatures, and vice versa. The high velocity region found by this study can thus be interpreted as a part of the Farallon plate (Note #3) which has subducted to the lowermost mantle, and the surrounding low velocity as upsplashed hot material in the thermal boundary layer immediately above the CMB. The clear identification of the remnants of the subducted Farallon plate at the base of the mantle is an important constraint on mantle convection.

The new data analysis method developed by this study is a "big data" method in which all of the data are processed at one time to obtain the 3-D Earth model by systematically optimizing the fit between the observed and theoretical waveforms. It is thus a "black box" processing method where it is difficult to pinpoint the evidence for any one feature of the model in any specific feature of some particular seismogram. The authors therefore performed a variety of confirmatory tests to validate the model obtained by the inversion.

As discussed above, many hypotheses have been proposed to explain the heterogeneity in D". Since in some parts of D" the temperature is likely to be higher than the solidus (Note #6), it is likely that magma exists stably in those places. Thus not only the temperature but also the chemical composition of D" is likely to be heterogeneous. Remnants of the proto-

continents on which life on Earth first developed are likely to have been subducted to the CMB. Future applications of the data analysis methods developed by this study to D" in other regions has the potential to shed important new light on fundamental questions in Earth science.

4. Publication:

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5. Explanation of Technical Terms

Note #1 Mantle

The mantle, which is composed of solid silicate and other rocks, extends from the base of the Earth's crust to the core-mantle boundary (CMB) at a depth of about 2900km. The upper mantle extends from the base of the crust to a depth of about 660km, where there is a mineralogical phase transition (a change to a denser crystal structure); the lower mantle extends from a depth of about 660km to the CMB. The D" layer is the lowermost 300-400km of the lower mantle; its lower boundary is the CMB. D" is the lower boundary for cells of mantle convection, and the temperature in D" increases rapidly as the distance to the core-mantle boundary decreases. Research in the early and mid-2000s found that the main mineral making up the lower mantle, Mg-perovskite, undergoes a phase transition to a denser crystal structure, Mg-postperovskite, in D". As a result the bulk of the lower mantle is composed of Mg-perovskite and ferropericlase, but D" is composed of Mg-postperovskite and ferropericlase.

Note #2 Core

The Earth's core, which extends from the core-mantle boundary (CMB), at a depth of about 2900 km, to the Earth's center, is thought to be composed of an alloy of mainly iron, a significant fraction of nickel, and a small proportions of other elements. The outer core, which is liquid, extends from the CMB to a depth of about 5150km, while the solid inner core extends from a depth of about 5150km to the Earth's center. Convection in the outer core generates the Earth's magnetic field.

Note #3 Farallon Plate

50 million years ago, an oceanic plate, the Farallon Plate, was located between the Pacific Plate and North American Plate. The Farallon Plate has now been almost entirely subducted.

Note #4 Seismic Arrays

In recent years dense arrays of broad-band seismic stations are being installed in many locations (e.g., the American US-Array, Japan's Hi-net). Data from such arrays are extremely useful in studies that invert seismic waveforms for 3-D Earth structure.

Note #5 Waveform Inversion

Most previous studies of Earth structure first measured intermediate parameters such as arrival time of seismic body waves or phase velocity of surface waves, and then analyzed these intermediate parameters to infer Earth structure. In contrast, waveform inversion directly compares the theoretical and observed seismograms and systematically finds the Earth model that minimizes the misfit between theory and observations (subject to some regularization constraints to assure stability). The authors independently developed the methods and software for waveform inversion that were used in this study.

Note #6 Solidus

The temperature (for some given pressure) above which rocks start to melt.

6. Materials

High resolution versions of the figures in this press release may be found at the following

URL: <http://www.s.u-tokyo.ac.jp/b/20140203g>

7. Figures

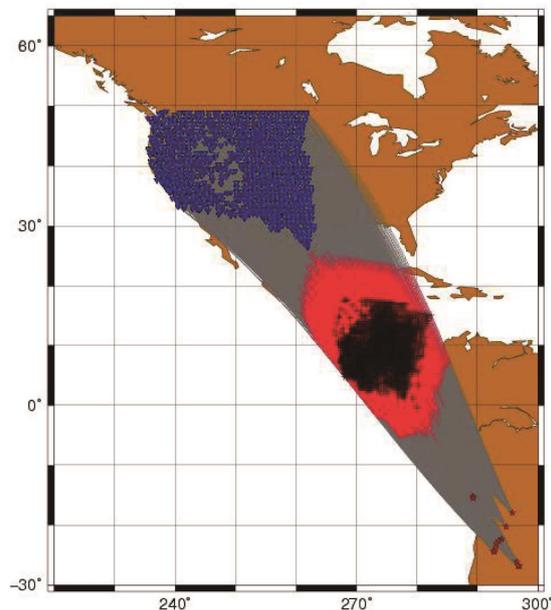


Figure 1. Earthquakes (stars) beneath South America and seismic stations (triangles) in North America, with great circle ray paths. Red shows the region beneath which D" is sampled.

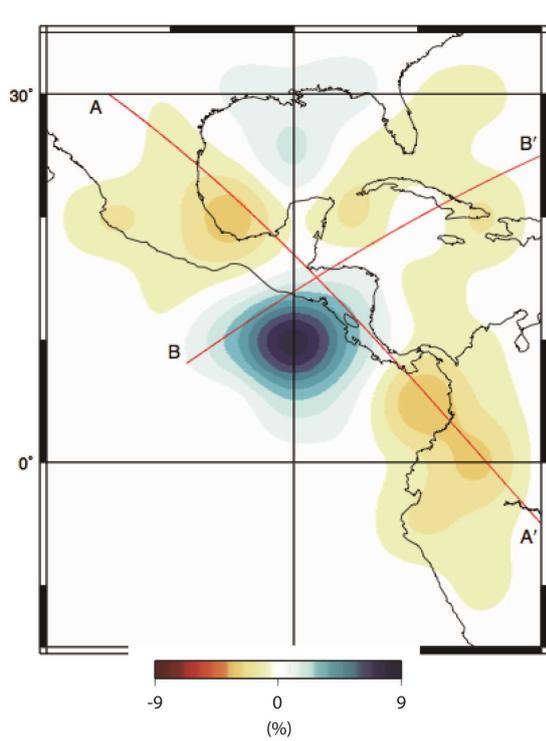


Figure 2. 3-D S-velocity structure (percentage difference with respect to the PREM reference model) inferred in the lowermost 50 km of D'' (i.e., directly above the CMB) beneath Central America.

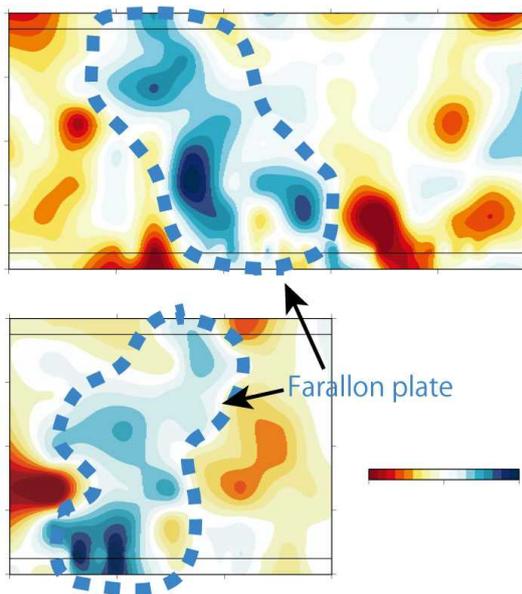


Figure 3. Cross sections of results of the inversion (percentage difference with respect to the PREM reference model) D'' beneath Central America. The locations of the cross-sections are shown in Fig. 2. A high velocity anomaly with a lateral scale of 250×250 km is surrounded by a low velocity anomaly. This can be interpreted as the subducted Farallon plate upsplashing hot material in the thermal boundary layer immediately above the core-mantle boundary.