# Interrogating the Deep Earth with USArray

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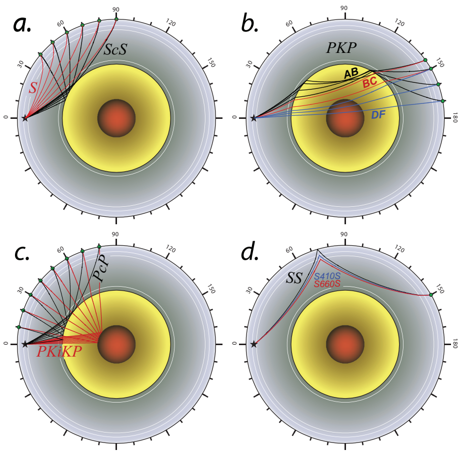
Investigating the deep, inaccessible realms within Earth is important since questions regarding the dynamics and evolution of the coupled crust-mantle and mantle-core systems cannot be answered without detailed knowledge of the interior. Active debate on a number of topics indicates that fundamental questions remain unresolved, such as the origin depth of mantle plumes that give rise to hot spot volcanism, the fate of subducted slabs, the properties of deep-mantle structures that appear related to large-scale mantle circulation, and the structure and evolution of the inner core.

Seismic methods currently provide the most detailed information on the interior. For decades, seismic tomography has depicted global mantle structure at relatively long wavelengths (e.g., lateral scales greater than a thousand km), and regional studies have revealed structures at shorter scales (less than 1000 km and in some cases hundreds of km). Limiting factors in the minimum resolvable scale length include the distance between seismic instruments (i.e., density of recorders) and the aperture or extent of the recording array.

## WHAT AND WHERE CAN USARRAY PROBE?

USArray offers unprecedented density and aperture, especially in combination with broadband stations from regional networks, PASSCAL experiments, and Flexible Array deployments. Thus, it is now possible to employ classic array methodologies that involve stacking seismic data, including wavefield migration, which were generally not feasible for deep Earth studies in the past. Subtle seismic phases that take long paths through the interior can now be utilized with much greater confidence, owing to the vast data abundance and sampling density which enhances coherent signal energy in stacking procedures.

A variety of seismic phases, such as *ScS, SS, PcP, PKiKP,* and *PKP*, are used at different epicentral distances to study Earth's interior. For example, *ScS* is usually compared to the direct *S* wave at epicentral distances between 65° and 80° to investigate fine-scale structure of the D″ layer. Thus, USArray data from deep focus earthquakes in Fiji-Tonga, South America, and the northwest Pacific can be analyzed to study D″ and the core mantle boundary structure beneath the central Pacific Ocean, Central America and the Caribbean, and Alaska including the northernmost Pacific.

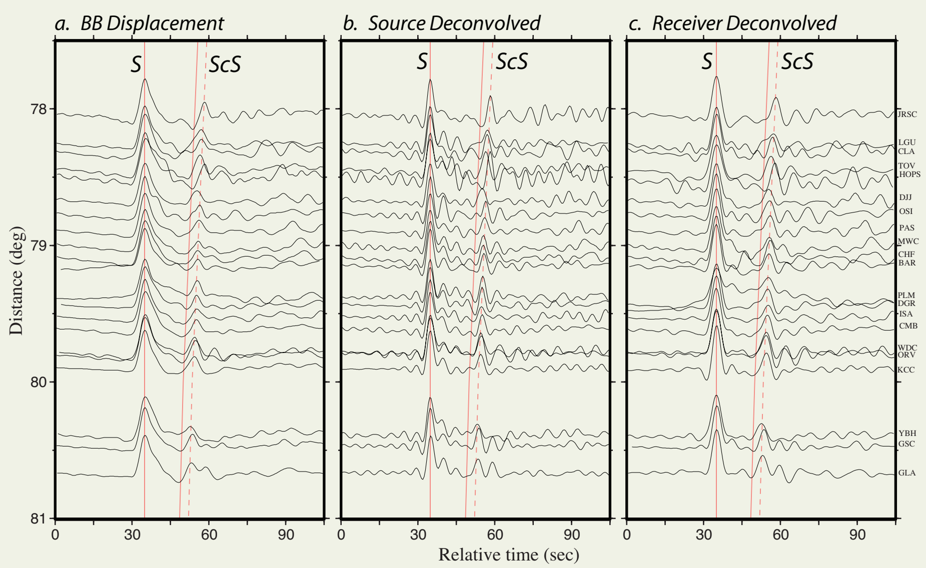



Different raypaths to USArray can be used as deep Earth probes only in restricted distance ranges from specific earthquake source regions, thus the deep interior will be sampled in disparate locations around the globe.

## WAVEFORMS FROM DIFFERENT EARTHQUAKES AND RECEIVERS

One challenge in USArray research of the deep interior involves combining data from different stages of the array. As the Transportable Array (TA) marches east, new earthquakes will be recorded with wave paths sampling slightly different deep Earth regions. The different regions sampled may distinctly (differently) alter the waveform. Isolation of contributions to signal complexity from the Earth structure we seek to model first requires estimation of possible contributions from the earthquake source and receiver structure.

Removal of source and receiver effects is not trivial and typically requires some form of deconvolution. If enough receivers record a given earthquake, then an empirical source wavelet can be constructed from stacking a reference phase recorded across the network. This can then be ➔




Transverse component of the direct *S* wave and the core-reflected *ScS* on 21 broadband seismometers in California from a deep Fiji earthquake on November 11, 2004, aligned in time and amplitude on the *S* wave. Solid red lines denote arrival time predictions from the PREM reference model; the dashed red line denotes approximate delayed arrival times of observed *ScS* indicating reduced deep mantle velocities beneath the central Pacific. Instrument deconvolved displacement is displayed in panel (a). Panel (b) shows the same data after deconvolution of an empirical source constructed from stacking the cleanest, narrowly windowed *ScS* pulses. This results in a narrower pulse width, but the deconvolution introduces slight ringing. However, abundant recordings at many California stations exist for Fiji-Tonga earthquakes and thus stacking recordings at each station permits estimation of empirical station responses. These are subsequently deconvolved from traces in (b), and shown in panel (c). Key points from this experiment are: (i) energy between *S* and *ScS* is commonly imaged as due to deep mantle reflectance, however, receiver structure and earthquake source must first be addressed; note the variability of such energy from panel (a) through (c); and (ii) in some cases, significant coda energy following *ScS* persists, but is not found after *S*, and is thus most likely due to deep mantle heterogeneity.

deconvolved from the data for that earthquake. Similarly, if enough earthquakes are recorded at a specific seismic station, the earthquake-deconvolved records at that station can be used in the same fashion – stacking a reference seismic phase, and applying a second deconvolution of the empirical station response.

The success of this approach depends on the data quantity and quality, for which there is no objective measure. Nonetheless, preliminary experiments using USArray data recordings from the Fiji-Tonga earthquakes are encouraging. The double-deconvolution approach results in more impulse and simpler waveforms. Experiments such as this one will likely be very important as the TA marches east, if subtle waveform features are to be confidently modeled.

## HANDLING ENORMOUS DATA SETS

The amount of USArray data available and appropriate for deep Earth studies is already well beyond that used in many past waveform studies. There is a natural tendency towards automated processing procedures to handle the copious data. But nearly any automation scheme can be defied by unexpected and interesting waveform or noise effects in data, resulting in averaging away, or worse, contaminating, the subtle sought-after waveform features, particularly at periods less than 10 s.

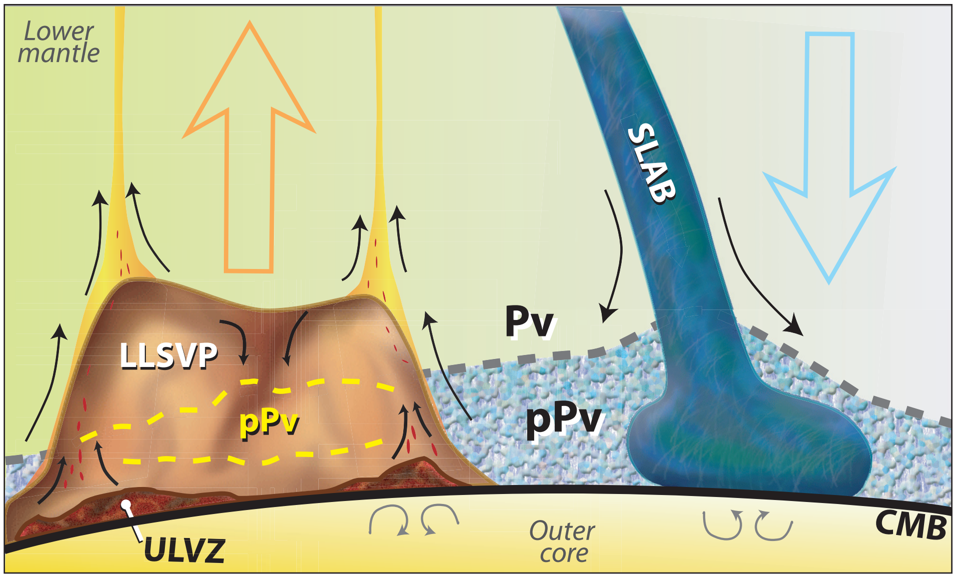
By spending slightly extra time to preview records, greater confidence is gained in results. Most automation approaches are easily adaptable for outreach and sharing, and this is facilitated by common freeware such as IRIS's data collection tools (*http://www.iris.edu/data/data.htm*), Seismic Analysis Code (*http://www.llnl.gov/sac*), the TauP Toolkit (*http://www.seis.sc.edu/software/TauP*), and Generic Mapping Tools, *GMT* (*http://gmt.soest.hawaii.edu*).

## DEEP EARTH TARGETS WITH USARRAY

There is no shortage of attempts to unravel Earth's enigmatic interior (e.g., any of the recent monographs in *Further Reading*). Recent studies paint a picture of an extremely complex boundary layer at the base of the mantle that rivals Earth's surface boundary layer in implied chemical, structural, and dynamical behavior diversity. Some key structural components recently suggested for the base of the mantle includes chemically distinct piles, a phase transition from Mg-Si perovskite to a "post-perovskite" structure, ultra-low velocity zones, anisotropy, and strong heterogeneity. While debate is still active on most of these features, they have been related to important whole mantle processes, such as plume initiation and a resting place for subducted slabs.

Higher up in the mantle, similar complexities and questions exist. For example, fine layering above the 410 km discontinuity, topography of the 410 and 660 phase boundaries, and heterogeneities and/or scattering in the transition zone and below, are all actively pursued and relate to important chemical and dynamical questions. Essential questions remain concerning the detailed structure of the outer and inner cores. With its unparalleled data volume and geographical coverage, USArray is uniquely suited to advance our knowledge on all these topics.

Large uncertainties still exist in deep Earth research due to long seismic wave paths and lateral averaging through the very structures we seek to image. USArray presents an opportunity for seismologists to work with researchers from other disciplines including geochemistry, geodynamics, and mineral physics. A multidisciplinary approach reduces the solution space of viable models and, increasingly, results from those disciplines guide our seismological research goals and interpretations.




Ancient subducted oceanic lithosphere (slab) may descend to the CMB in large-scale downwellings. The lowest few hundred km of the mantle is predicted to have a phase transformation from perovskite (*Pv*) to a post-perovskite (*pPv*) structure, which explains past evidence for a D″ discontinuity. Large, low shear velocity provinces (LLSVP), as seen in tomographic images, may be chemically distinct piles, whose sides guide upwelling motions and mantle plume initiation. *pPv* may be present in the piles, with the possibility of a second (deeper) phase transition back to *Pv* due to the large temperature increase in the thermal boundary within the LLSVP. Thin ultra-low velocity zones (ULVZ) with possible origin of partially molten material should be geographically correlated with these hottest zones.


## ACKNOWLEDGEMENTS

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## FOR FURTHER READING


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