Direct detection of Western US sharp upper-mantle features with waveform complexity

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Abstract

A recent technique for processing array data searching for multipathing has been applied to USArray data [*Sun and Helmberger*, 2009]. A record can be decomposed by S(t) + A*S(t+ Δ_{LR}), where S(t) is the synthetics for a reference model. Time separation Δ_{LR} and amplitude ratio A are needed to obtain a useful cross-correlation between a simulated waveform and data. The travel time of the composite waveform relative to the reference model synthetics is defined as Δ_T. A simulated annealing algorithm is used to determine the parameters of Δ_{LR}, Δ_T and A. Whereas the conventional tomography yields a travel time correction (Δ_T), our analysis yields an extra parameters of Δ_{LR} which describe the waveform complexity. With the array, we can construct a mapping of the gradient of Δ_{LR} with complexity patterns. A horizontal structure will introduce the waveform complexity along the distance profile (in-plane multipathing). A azimuthally orientation Δ_{LR} pattern indicates a vertical structure with out-of-plane multipathing. Using such maps generated from artificial data we can easily recognize features produced by downwelling (DW) vs. upwelling (UW) and address their scale lengths.

In particular, we find a line of DW's along the Rock Mountain Front which have anomalies similar to those found along the La Ristra line. These Δ_{LR} anomalies are up to 8s, which corresponds to features extending down to the 600 km discontinuity with a 6% shear velocity increase. Such features appear to be produced by delamination caused by the sharp lateral temperature gradient [*Song and Helmberger*, 2007abc].

The Δ_{LR} patters for the Western US indicates a number of UW's, in which the Yellowstone is particularly obvious. The records for events from the southwestern and southeastern directions show generally simple waveform across the Yellowstone -Snake River Plain (SRP). For the event from the northeast, the stations along the western edge of SRP show strong waveform distortions, which indicate azimuthally multipathing occuring and a structure with sharp vertical wall beneath SRP.

Tomographic model of Western US

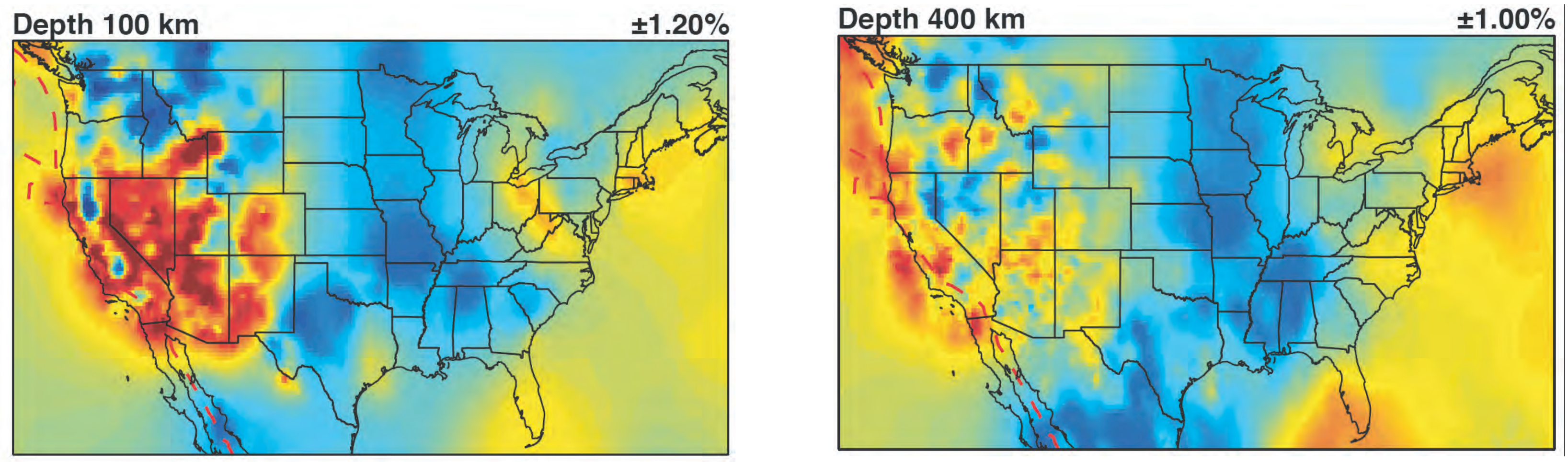


Figure 1. The P-wave tomographic model beneath Western US (from Burdick et al., 2009). It clearly displays the relatively slow western basin-and-range including Nevada, most of Arizona at depth dwon 200 km. Significant strips of slow velocities along the Snake River Plain (SRP) structure, the St. George lineament and Rio Grande Rift are detailed. Most of the features are gone at depth greater than 300 km suggesting relatively shallow mantle structure involvement in crustal tectonic feature. However, to model multi-pathing generally requires deeper structures.

Waveform complexity along Rio Grande Rift zone

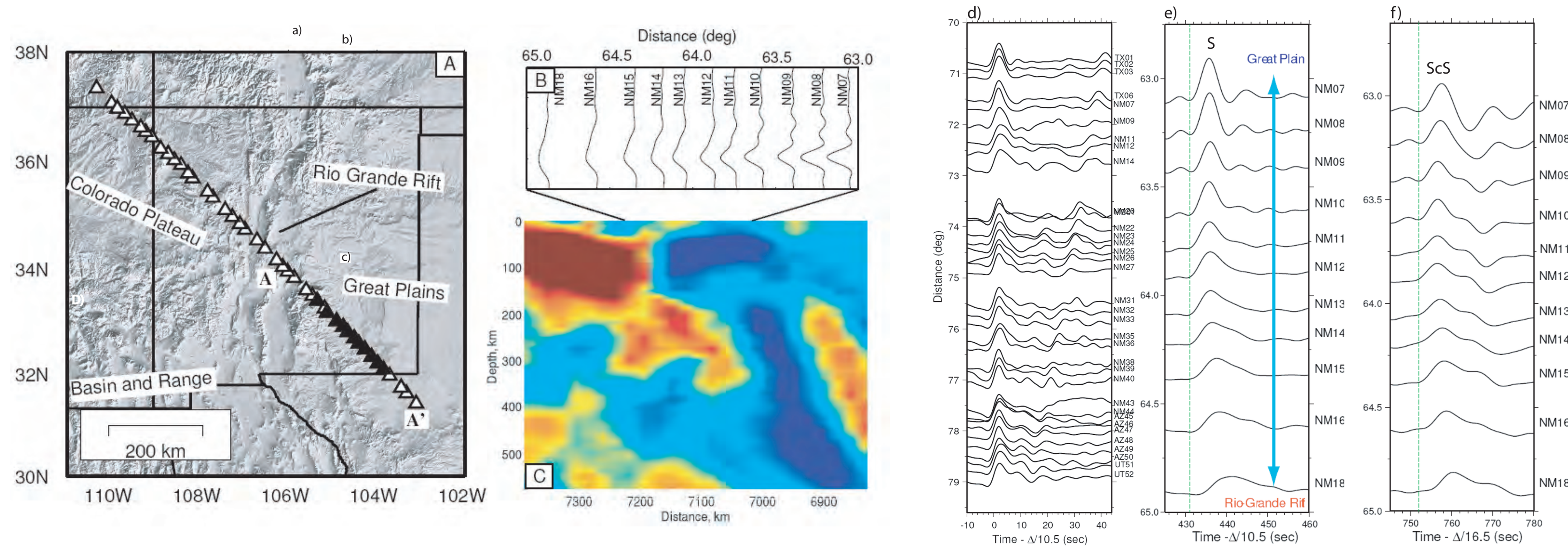


Figure 2. Multi-pathing example; a) Elevation map along with the LA RISTRA Transect (triangles) crossing the edge of the Great Plains, the Rio Grande Rift and the Colorado Plateau. b) Deconvolved S waveform section (event 990915) showing waveform distortion across the transition between the western Great Plains and the Rio Grande Rift (solid triangles in a)). Waveform broadening is present at stations towards the NW such as NM12-NM18. The S velocity section A-A' of model A [Song and Helmberger, 2007] extending down to 600 km is displayed in c). d) An example S wave record section (event 20000423) shows developed S waveform complexity from station NM07 to station NM14, which also occurs on the records for a closer event in e). The ScS complexity in f) appears at the same stations as the S in e), which indicates that the cause of the complex waveform is relatively shallow (upper mantle) since it affects both phases.

Records for USArray

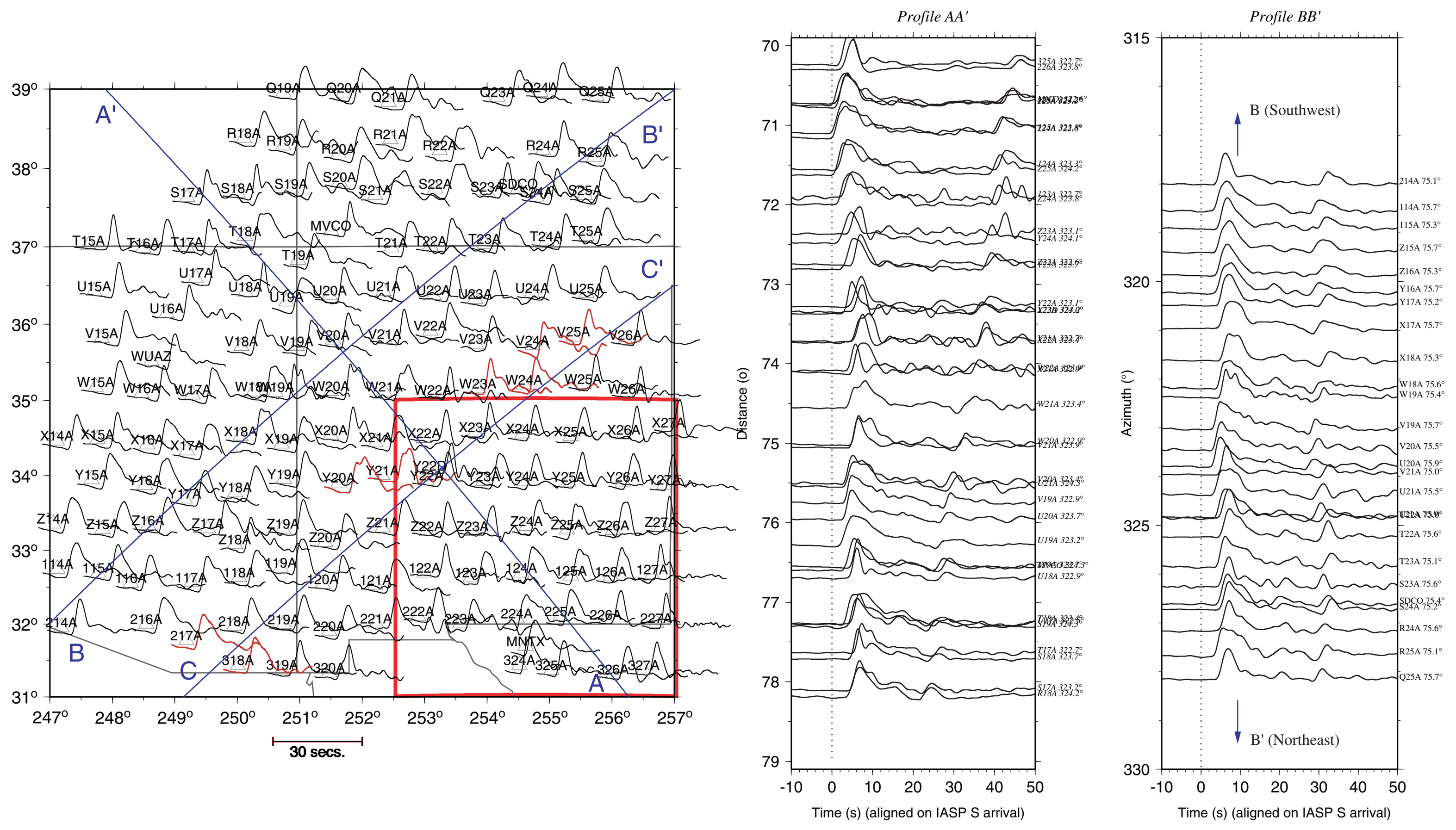


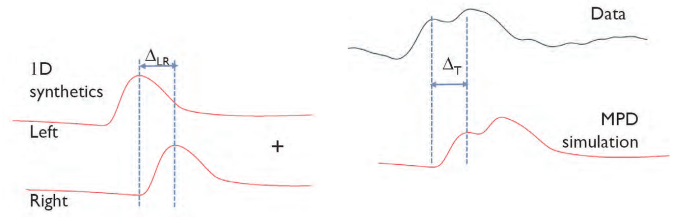
Figure 3. USArray records (direct S) for an a South American event (20080903). The records along profile AA' and BB' are plotted on the right. Some waveforms are simple and some are strongly distorted, which indicates the occurrence of the strong multi-pathing and upper-mantle structure (Fig. 2).

Multi-path Detector (MPD)

$$V(r,z,t) = O_L * G_R^2(\Delta_l) + O_D * G_R^2(\Delta_d) + O_L * G_L^2(\Delta_l) + O_D * G_L^2(\Delta_d)$$

Focus on short period

$$V(t) = O * G_R^2(\Delta_l) + O * G_L^2(\Delta_l)$$



Δ_{LR}: Describing how strong the effect of multi-pathing is.
Δ_T: Time delay related to a reference 1D model (PREM etc).

The displacement wavefield by adding non-great circle path contributions. If we focus on short periods, we can only treat the left and right aspects of the field. With the Multi-path Detector (MPD) [Sun et al., 2009], we recover two timing delays. One associated with the shift between the left and the right branches (Δ_{LR}), and the other between the entire simulation relative to the reference model or total delay (Δ_T). The differential times generated from a 2-D array can then be used to construct the spatial gradient of these delays.

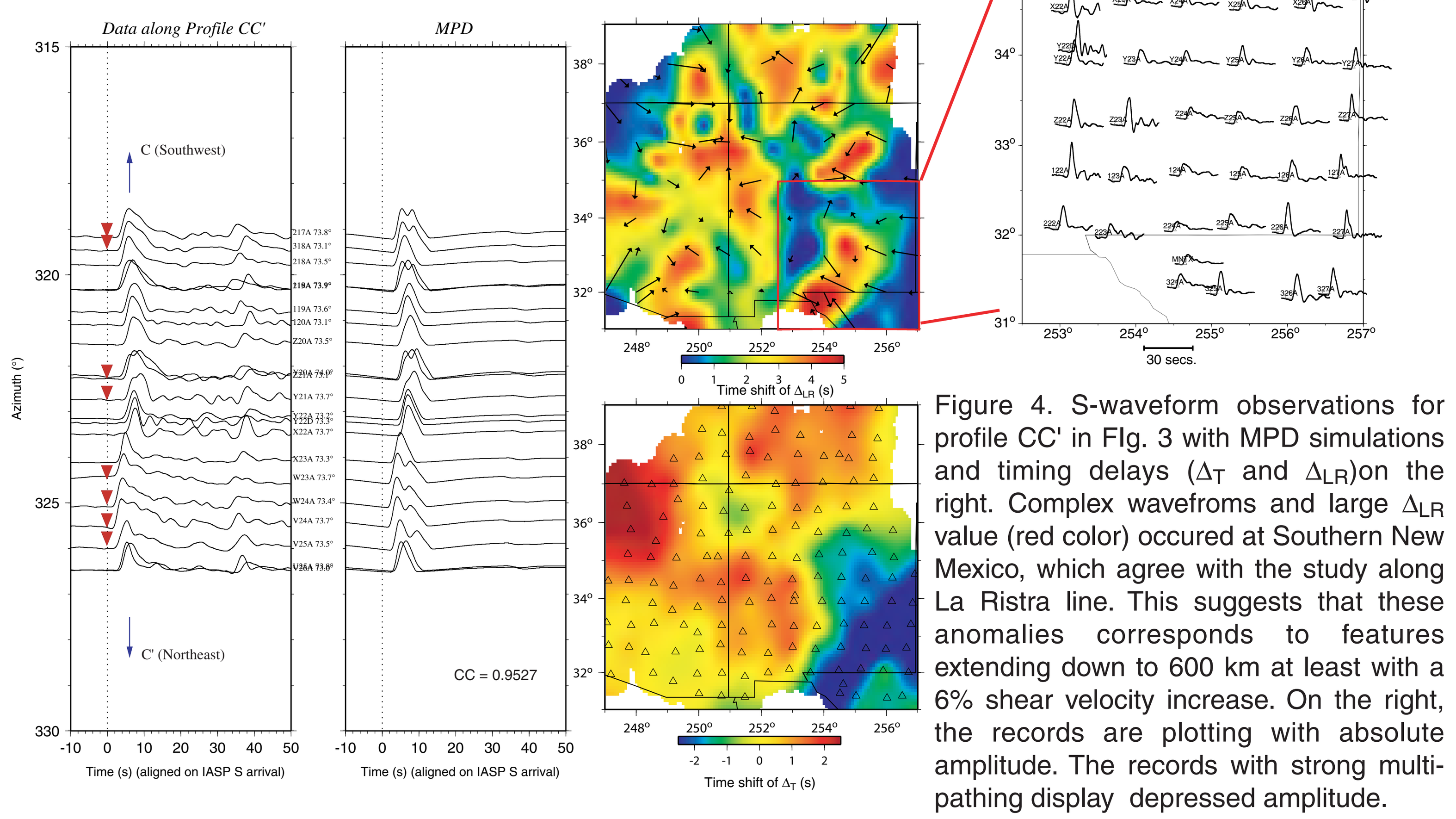
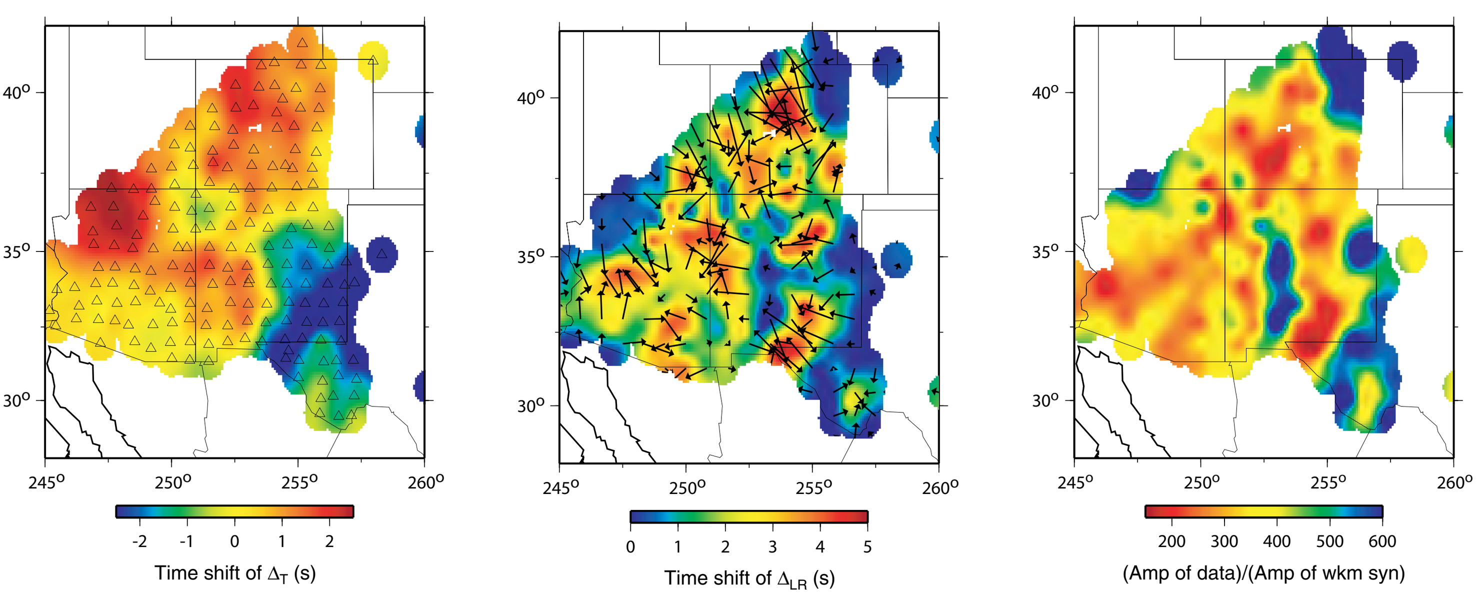


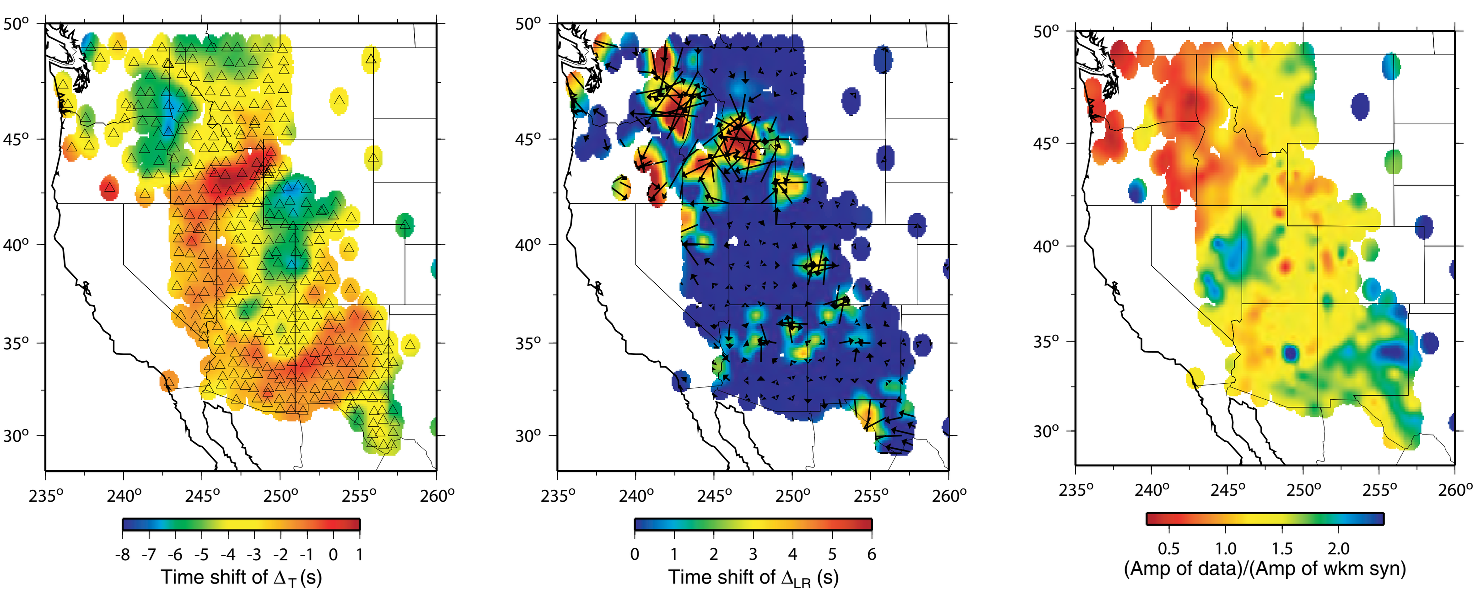
Figure 4. S-waveform observations for profile CC' in FIg. 3 with MPD simulations and timing delays (Δ_T and Δ_{LR})on the right. Complex wavefroms and large Δ_{LR} value (red color) occured at Southern New Mexico, which agree with the study along La Ristra line. This suggests that these anomalies corresponds to features extending down to 600 km at least with a 6% shear velocity increase. On the right, the records are plotting with absolute amplitude. The records with strong multi-pathing display depressed amplitude.

MPD patterns for Western US

South Amreican event (20080903)



Iceland event (20080529)



Kuril Island event (20080804)

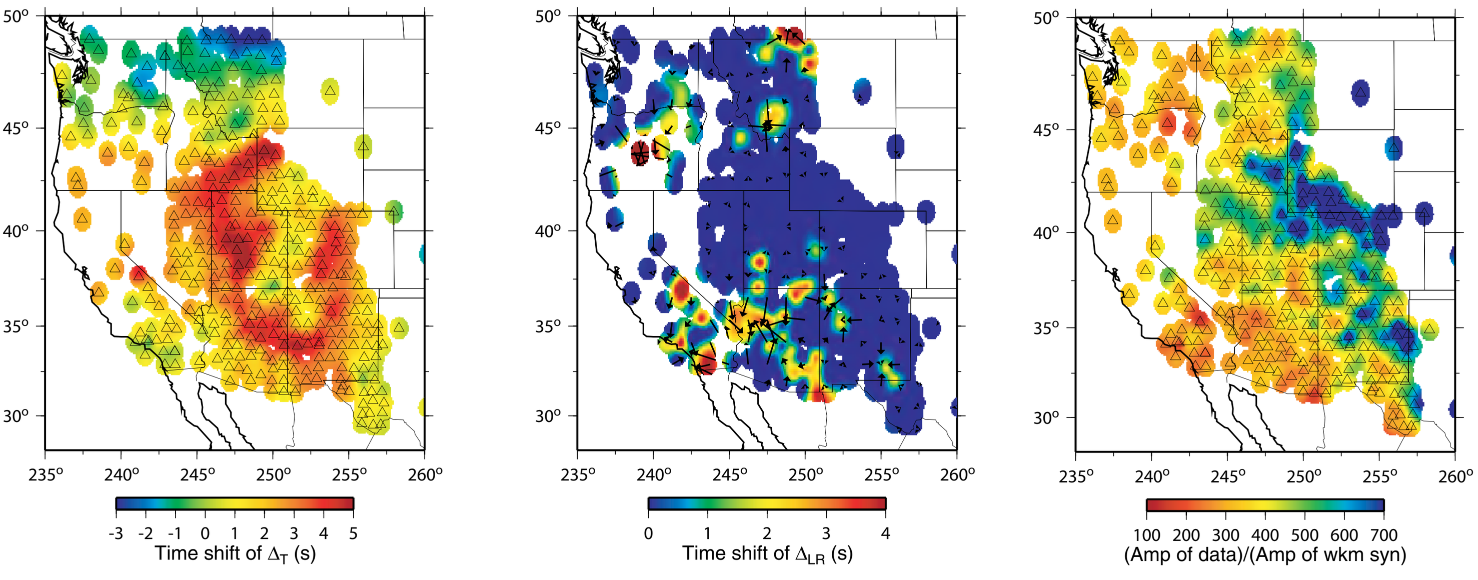


Figure 5. Δ_T, Δ_{LR}, and amplitude (A) pattterns for different events recorded by USArray. These are all teleseismic events. The Δ_T patterns agree well with the tomographic result (Figure 1).The multi-pathing pattern (Δ_{LR}) show highly azimuthal dependence. For South American events, strong multi-pathing occurs along the Rocky Mountain Front. But these regions also show weak multi-pathing when the events come from the north. The azimuthal dependence indicates that the multi-pathing is highly directional. The preferred strong multi-pathing for the event from the South suggests that the anomalies in the upper mantle dip to the south, which give the strongest multi-pathing when rays sample the dipping structure. Another two regions with strong multi-pathing are the Snake River Plain (SNR) and Western Idaho. The third column displays the amplitude ratio of S arrival between data and calculated synthetics with WKM method. The amplitude ratio map correlates with the DLR pattern very well. The amplitude of the record in strong multi-pathing regions is 3~4 times less than the normal region.

High Velocity vs. Low Velocity

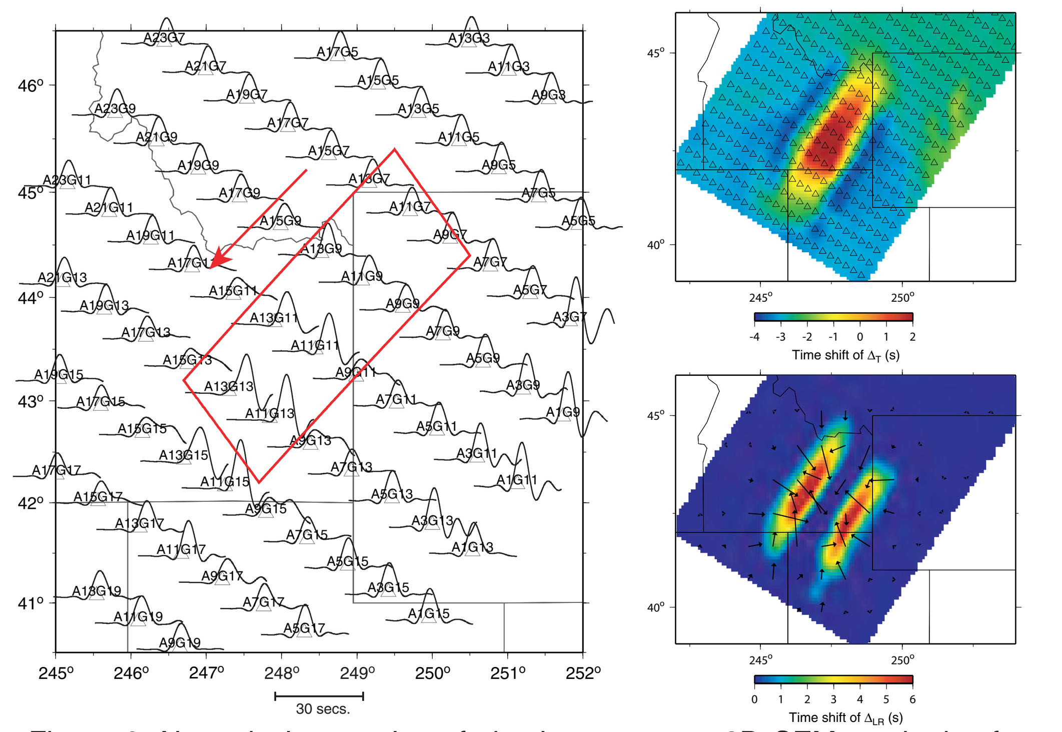


Figure 6. Numerical examples of simple structures; 3D SEM synthetics for a box structure, which extended from 100 to 400 km with -8% shear velocity perturbation for the Iceland Event geometry. Note the increase of S amplitude when sampling the middle of the structure although those waveforms are simple. Multi-pathing occurs along the two edges, which indicate strong azimuthally multi-pathing.

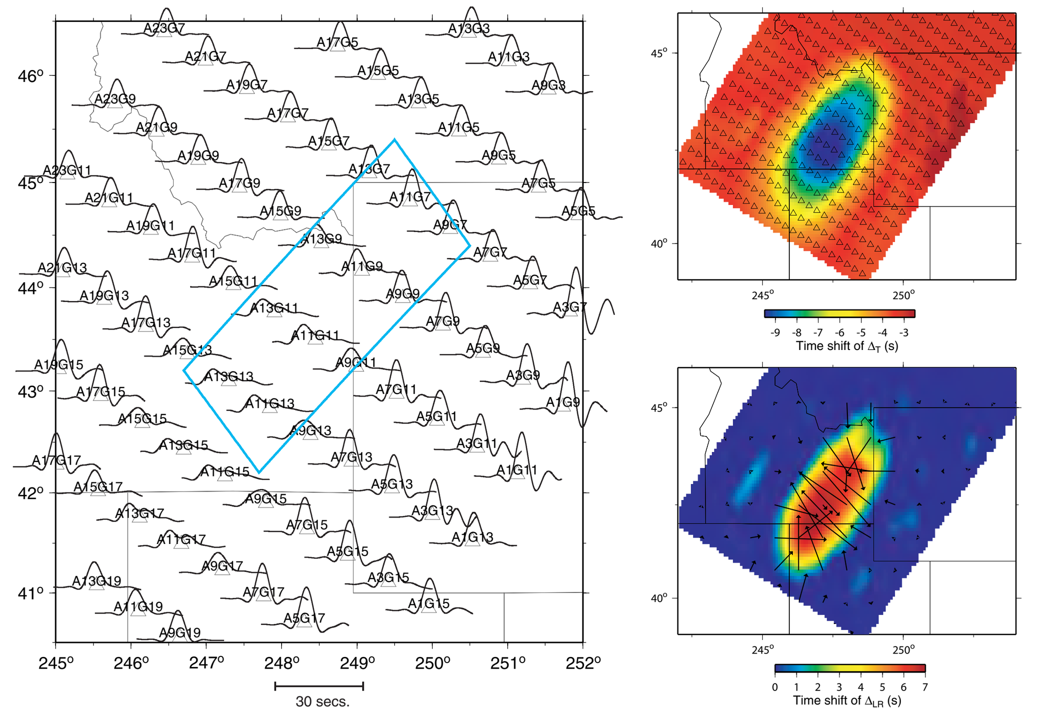


Figure 7. The same geometry as that in Fig. 6 but with 8% shear velocity perturbation inside the box. There are noticeable amplitude decreases when sampling the middle of the anomaly.

Yellowstone anomaly

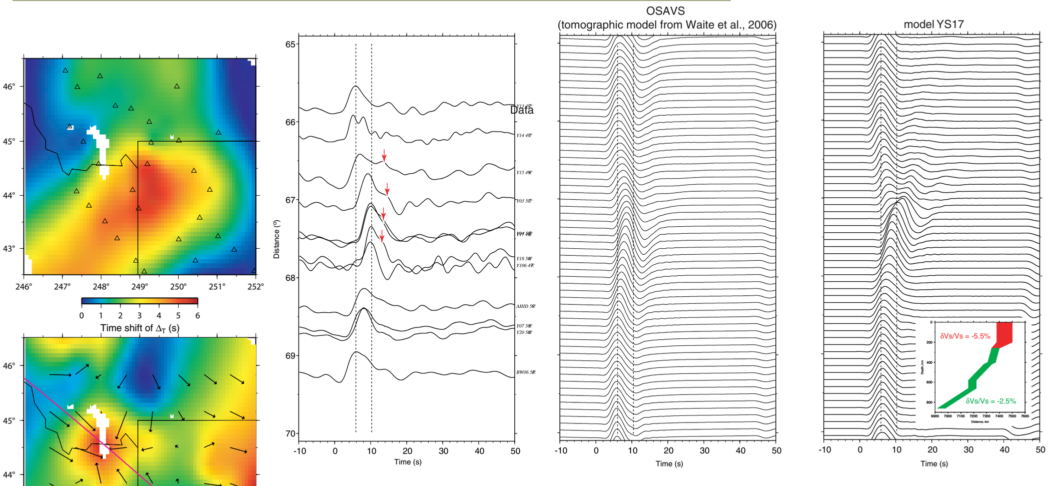


Figure 8. MPD patterns of direct S for a Japan event recorded by stations Yellowstone. To generate such a pattern, a plume-like low velocity structure as in model YS17 is needed, which can predict the later second arrivals as in data [Sun et al., 2009].