Detection of a Core Rigidity Zone beneath eastern Mexico: Constraints from ScP waveform modeling

Cal Poly Physics

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Abstract

An earthquake with epicenter in western Guatemala recorded at a tightly spaced 10 element seismometer array in western Nevada shows a ScP waveform indicative of a Core Rigidity Zone (CRZ) structure.

CRZ are regions of finite S-wave velocity just underneath the core-mantle boundary, and are thought to arise as "underside sedimentation" of light elements in the outer core. These light elements are collected and trapped under concave down topography of the core-mantle boundary.

One-dimensional forward modeling of the potential CRZ waveform is carried out for a set of models by varying (1) the CRZ thickness, (2) Shear-wave (Vs) velocity in the CRZ, and (3) the density reduction in the CRZ relative to the outermost core. P-wave velocity variations in the CRZ have little effect on the synthetic seismograms.

The best-fitting model is **(1) a 1.1 km thick CRZ, with (2) Vs = 1.8 km/s, and (3) a 10% density reduction within the CRZ.**

These results indicate a much thicker and higher velocity CRZ compared the results of Rost & Revenaugh 2001 where a CRZ was observed east of Australia.

The results from the small array in western Nevada are then compared to ScP signals from individual seismometer stations of the Transportable Array to determine the spatial extent of the CRZ signal.

The CRZ signal is spatially continuous beneath the coastline of eastern Mexico but fades to the west. Large amplitude post-cursory signal in the data may arise from wavefield focusing of reverberated CRZ phases by topography on the core-mantle boundary, but this hypothesis is not constrained by the present observed data.

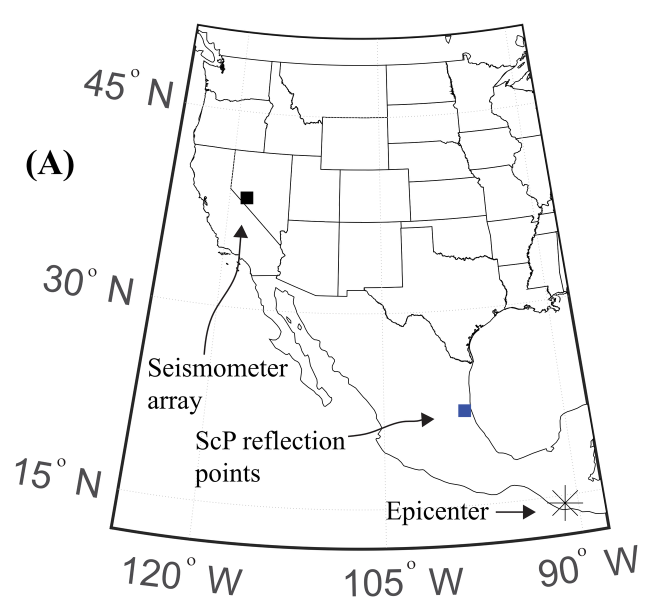
Figure 1. Event, ScP reflection points, array, and CRZ cartoon.

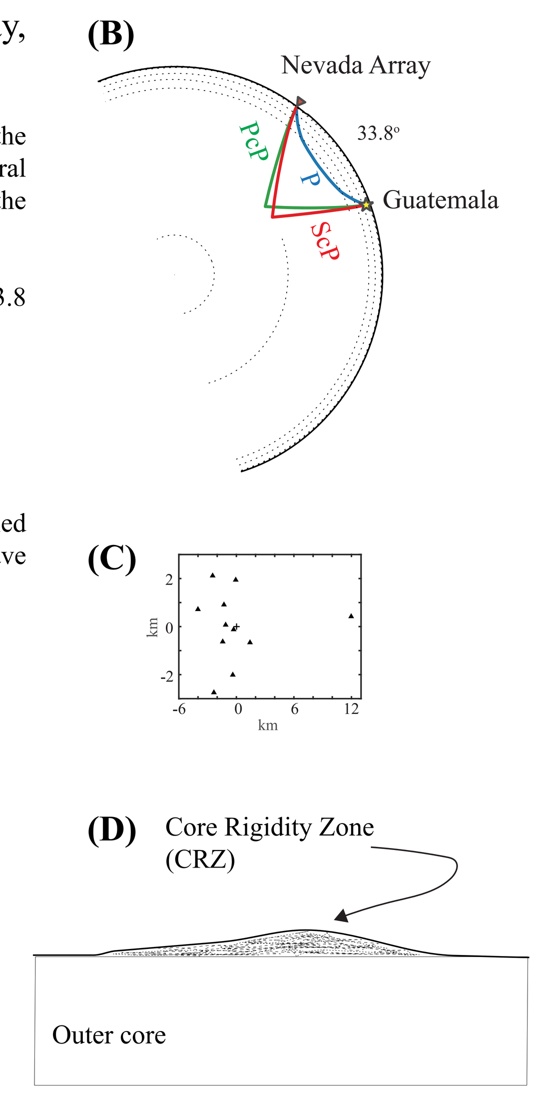
(A) Map of event (Mw 5.4), ScP reflection points on the core-mantle boundary beneath eastern Mexico, and general location of a 10 seismometer array in Nevada recording the event (http://ds.iris.edu/mda2/IM/).

(B) Raypaths of P, PcP, and ScP for epicentral distance of 33.8 degrees.

(C) Spatial detail of the 10 seismometer array in Nevada. Seismometers are from the International Miscellaneous Array.

(D) Cartoon of a CRZ at the core-mantle boundary. Speckled pattern represents a region of finite rigidity allowing S-wave propagation into a thin region of the outermost core.





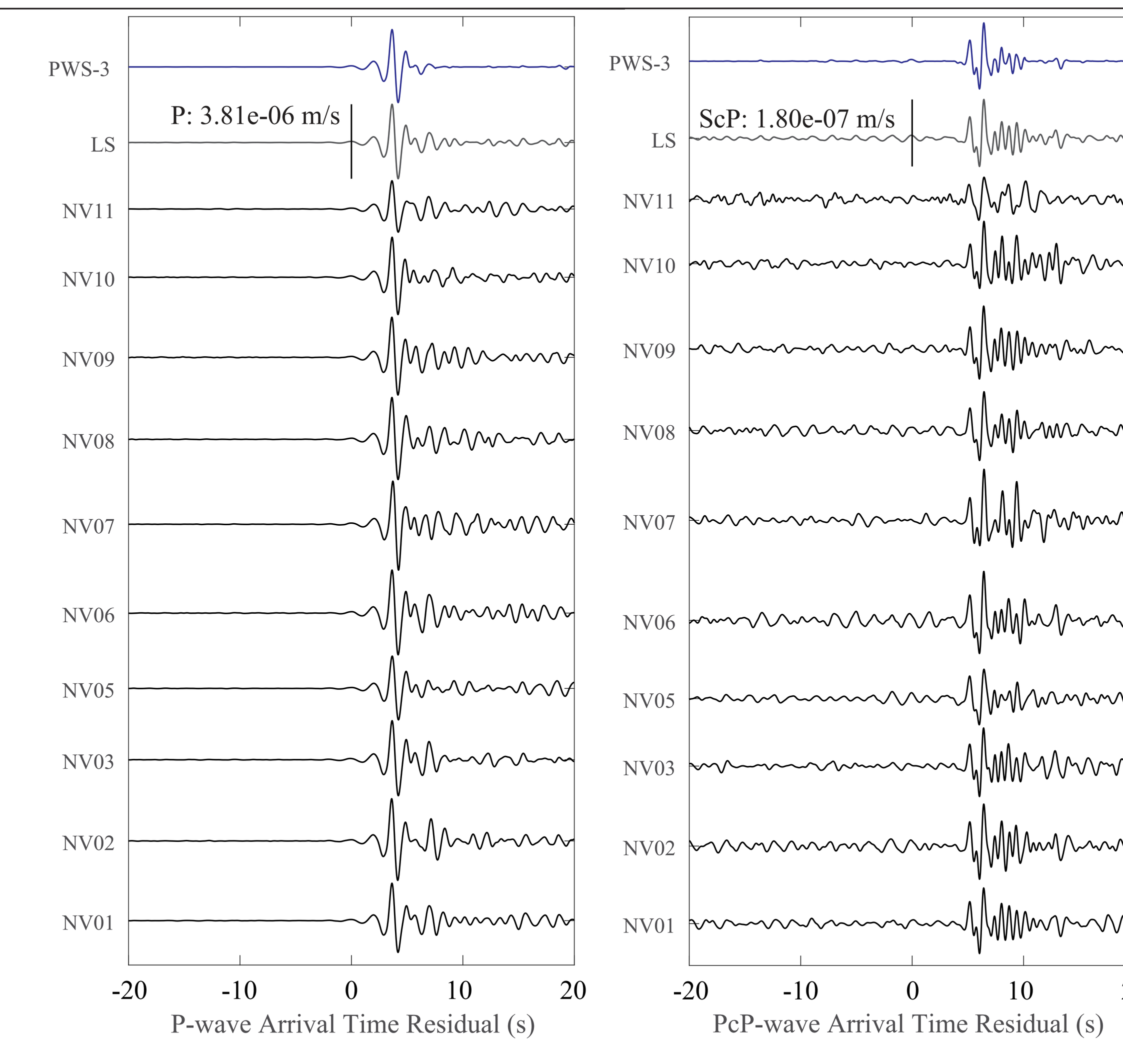


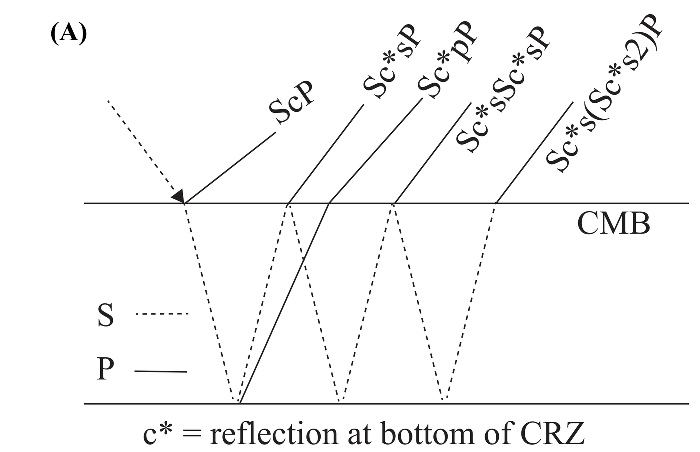
Figure 2. Event data at the Nevada Array.
Black seismograms are (left) P-wave arrivals and (right) ScP arrivals at each seismometer of the Nevada array aligned by cross-correlation.
Grey traces in both panels are the linear stack of the array data with peak-to-peak velocity amplitude noted.
Blue traces in both panels are phase-weighted stacks of the array data with exponent 3.
All data are bandpass filtered [0.5, 2] Hz.

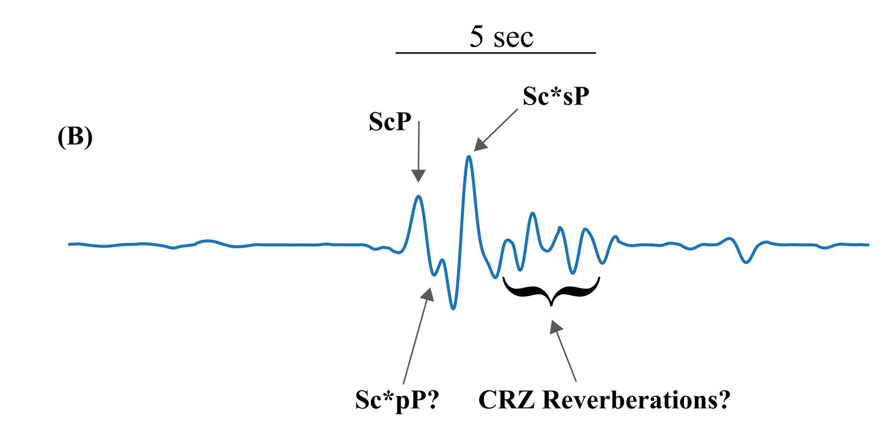
Figure 3. Core-rigidity zone (CRZ) phase arrivals and observed ScP wavelet.

(A) Selected possible phase arrivals from a core-rigidity zone. Two reverberated phases are shown as Sc*sSc*sP and Sc*s(Sc*s2)P. Upgoing P- and S-waves in the CRZ are denoted by lowercase letters: p, s.

(B) Phase-weighted stack of ScP at the NV array (exponent 3) with interpreted phase arrivals.

(C) Modified from Rost and Revenaugh, 2001. Comparison to CRZ observation east of Australia (Rost & Revenaugh, 2001). ScP, Sc*pP, and Sc*sP are similar. The present data contains larger amplitude post-cursors which are potentially generated from reverberations in the CRZ.





Waveform Modeling the Nevada Array Data

Modeling Procedure

Synthetic seismograms are calculated with ZRAYAMP software (asymptotic ray theory).

Outputs are convolved with the phase-weighted stacked P-wavelet. Synthetic seismograms are calculated for various core-rigidity zone (CRZ) thicknesses, S-wave velocity, and density reduction with the CRZ.

Results

Tradeoffs exist between S-wave velocity and CRZ thickness. P-wave velocity has no significant effect on the synthetic seismograms.

In a CRZ, the density should be reduced relative to the outermost core. Rost & Revenaugh (2010) found a 10% reduction in density in a 0.14 km thick CRZ with Vs = 0.7 km/s.

The best-fitting model in the present data is:

CRZ thickness: 1.1 km Vs = 1.8 km/s Density reduction: 10% (following Rost and Revenaugh 2001).

We note that the first two peaks can be fit with: CRZ thickness = 0.85 km and Vs = 1.4 km/s without a density reduction, and little effect on the amplitude of reverberated phases (Fig. 4C). Large amplitude post-cursors to ScP and Sc*sP are difficult to generate in a simple CRZ model.

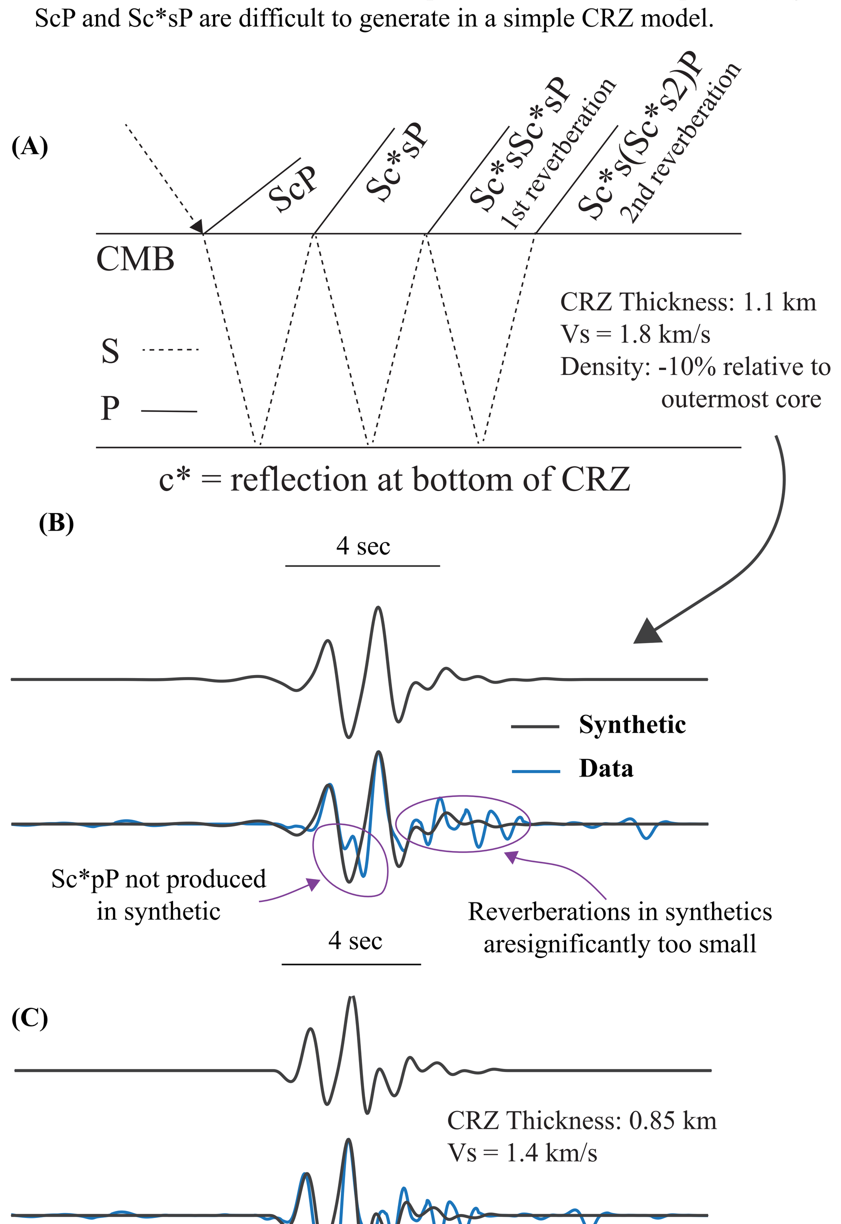


Figure 4. Primary and reverberated phases in a CRZ and Observations.

(A) Primary and (two) reverberations in a CRZ.

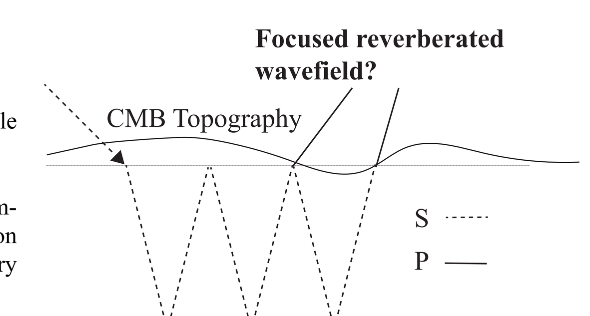
(B) Best-fitting CRZ model. Reverberations in the data are large, but CRZ models incorporating reverberations can not match the amplitude.

(C) A CRZ model without a density drop in the CRZ. Reverberation amplitudes are slightly larger, but a density decrease is needed in a CRZ to be physically correct.

Figure 5. Core-mantle boundary topography.

Modeling reverberations in the synthetic data does produce visible reverberations.

Amplitude of the modeled reverberations are about 50% of the amplitude of the first reverberation in the data. This amplitude variation may be attainable by present constraints on core-mantle boundary topography of up to 4 km on wavelengths of < 300 km.



Observations of ScP waveforms at the Transportable Array

To constrain the spatial extent of the CRZ structure, 392 individual seismometers of the Transportable Array were examined that recorded this event.

Single station sites are not modeled, but are simply visually assessed for similarity to the observed and stacked ScP (reference) wavefrom at the Nevada Array.

ScP waveforms are assigned four "quality categories" (Figure 6).

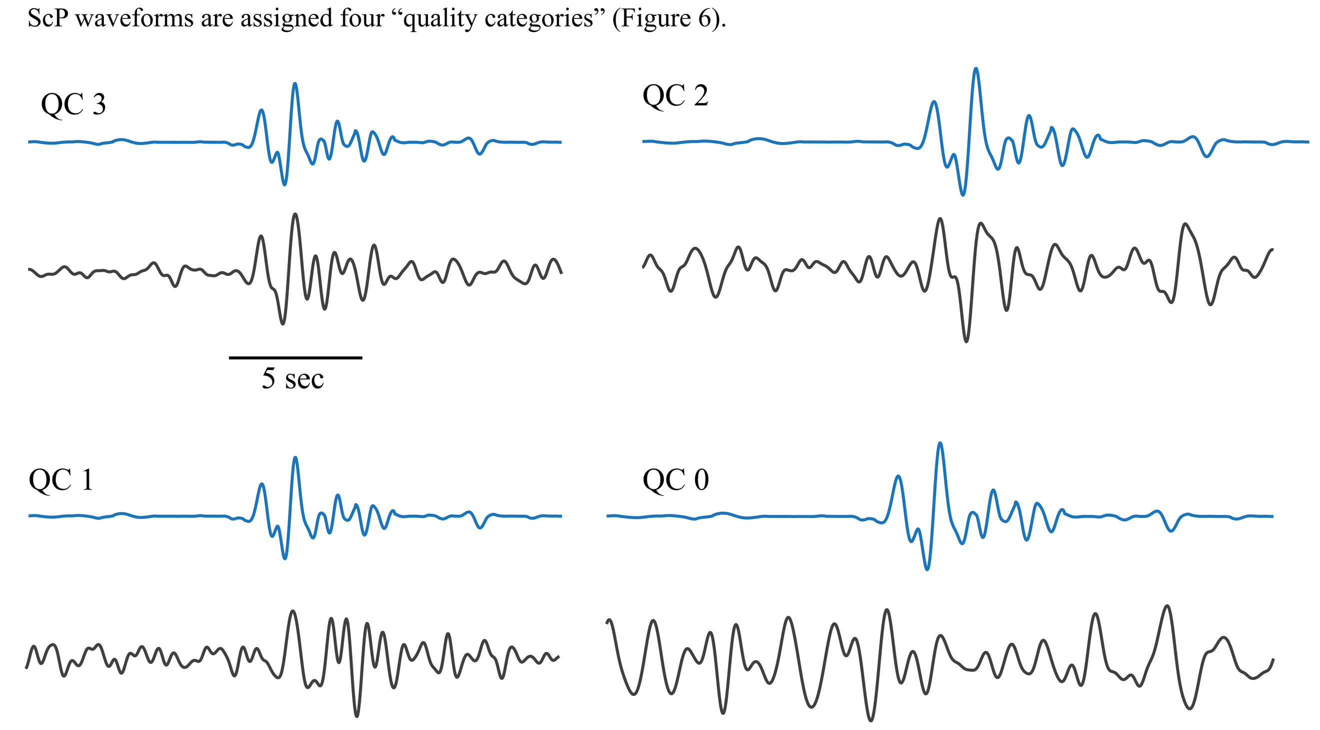


Figure 6. Comparison of Nevada ScP to ScP waveforms of the Transportable Array

QC 3: The ScP waveform closely matches the characteristics of the reference ScP waveform.

QC 2: The ScP waveform displays similar characteristics to the reference waveform but wave shapes are not as neatly defined.

QC 1: Clear and substantial energy at the expected ScP arrival time is seen, but does not match the features of the reference waveform. This category would also include simple ScP reflections, but simple ScP were rarely seen.

QC 0: No ScP signal or energy is seen on the seismogram near the expected ScP arrival time.

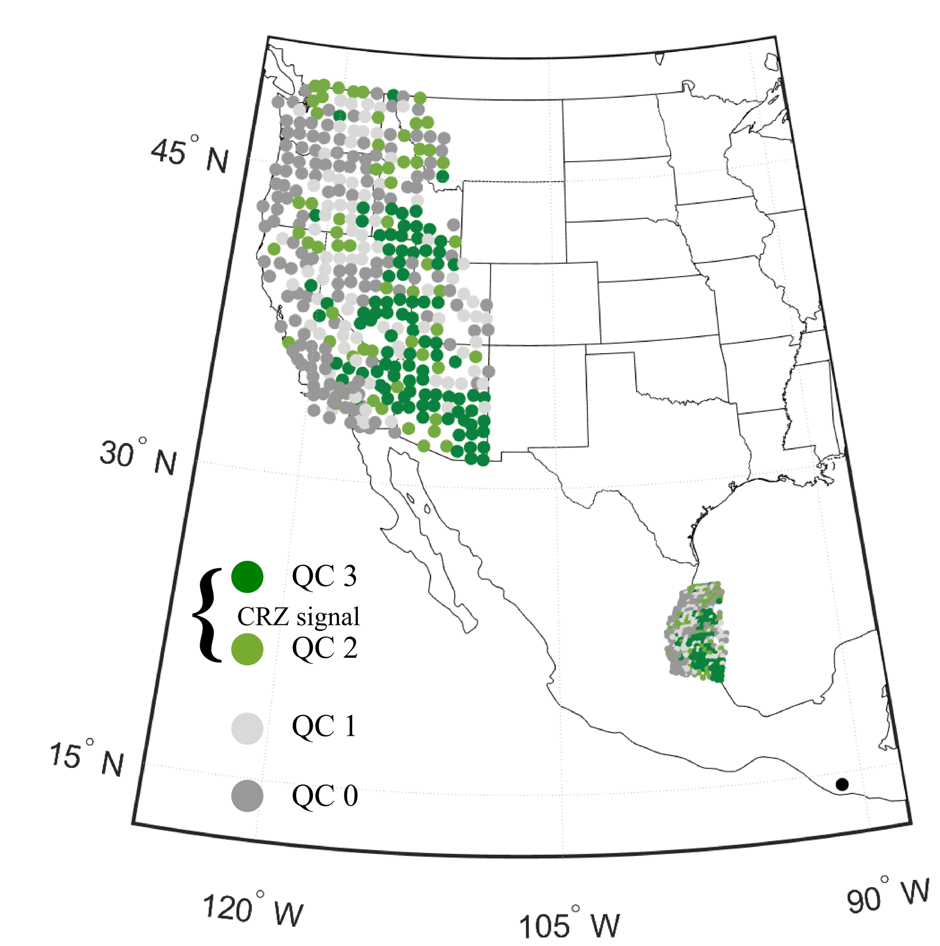


Figure 7. Spatial Extent of CRZ Signal across the Transportable Array.

The earthquake examined at the tightly spaced Nevada Array (Fig. 1) was also recored at 392 individual seismometers of the Transportable Array.

As described in Figure 6, ScP at each site was compared to the stacked Nevada data with dark green being most similar and dark grey least similar.

The CRZ signal is concentrated on the core-mantle boundary beneath the coast of eastern Mexico in three primary regions.

The CRZ signal systematically fades to the west.

Conclusions & Further Work

Strong evidence for spatially extended patches of CRZ beneath eastern Mexico.

A Core Rigidity Zone Signal (CRZ) from ScP waveforms is observed at a tightly spaced array in western Nevada. The highly constrained stacked waveform is modeled with a CRZ structure of:

CRZ thickness: 1.1 km Vs: 1.8 km Density: -10%

Modeling of ScP and Sc*sP is very sensitive to CRZ thickness and Vs velocity tradeoffs.

Reverberated phases in the CRZ can mimic the shape and timing of post-cursory arrivals in the ScP waveform, but not the amplitudes. The density decrease in the CRZ only very modestly affects reverberation amplitudes.

It is hypothesized that topography on the core-mantle boundary may focus the reverberated wavefield, although this can not be constrained by the present data. Even modest topography on the CMB would affect the CRZ model due to the tradeoffs in CRZ thickness and Vs velocity.

The observed waveforms are qualitatively similar to CRZ signals observed in Rost & Revenaugh 2001, but the best fitting model in that study (0.14 km thickness, Vs = 0.7 km/s, and density reduction of 10%) is significantly different than the models required by this data.

Future work should examine:

1. The effect of CMB topography on CRZ waveform amplitudes.

2. Incorporate 2-D/3-D models of CRZ in synthetics.

3. Study other waveforms that are sensitive to CRZ (PcS? ScS?).

References

Rost, S., and Revenaugh, J., 2001, Seismic detection of rigid zones at the top of the core.: Science (New York, N.Y.), v. 294, p. 1911–4, doi:10.1126/science.1065617.

ZRAYAMP: Available at http://www.spice-rtn.org/library/software/Raytheory/softwarerelease.2006-08-15.7329827767.html (last accessed on 2018-12-05)