MODELING CRUSTAL VELOCITY HETEROGENEITY IN NORTH CENTRAL WYOMING: RESULTS FROM THE BIGHORN ARCH SEISMIC EXPERIMENT (BASE) ACTIVE SOURCE COMPONENT

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ABSTRACT

The Bighorn Arch Seismic Experiment (BASE) is a multi-scale, hybrid active/passive seismic experiment designed to determine crust and mantle structure below the Bighorn Mountains in north central Wyoming. This region experiences a spectrum of manmade and natural events, from regional earthquakes and teleseisms to mine blasts and single-fired shots. The BASE deployments provide unprecedented spatial sampling of the seismic wavefield that can be used to more fully characterize three-dimensional (3D) wave propagation effects in a complex regional setting. Here we present preliminary crustal-scale compressional wave velocity models for the Bighorn mountain region extracted from analysis of seismic data collected during the active source portion of the experiment.

The active source component of BASE was conducted July–August 2010 and consisted of ~1800 Texan seismographs deployed at 100–500 m spacing along two profiles: one crossing the arch from east to west and one along strike the arch from north to south. Data from 20 single-fired shots, ranging 500–2000 lb, were recorded by the Texans. The BASE passive-component short-period array (5–10 km spacing) and broadband array (~35 km spacing) also recorded these shots. Additionally, four shots were recorded on a grid of passive-mode Texans that were deployed at 1 km spacing to densify the short-period array. This data coverage will enable future 3D modeling of the velocity structure in the region.

Results of the active-source seismic experiment thus far include two-dimensional (2D) tomographic P-wave velocity models of the crust and upper mantle below the Bighorn Arch. The north-south profile lies west of the arch and crosses its southern curve. Crustal velocities on this profile are laterally continuous in the upper crust, and mantle velocities (>7.8 km/s) are observed at ~50 km depth below surface elevation. The velocity model along the east-west profile, sub-parallel to the direction of contraction across the mountains, shows basin structure on either side of the arch within the upper ~5–10 km, which correlates with that derived from previous geologic work and industry seismic imaging. Low-velocity zones emerge within the upper 20 km of the crust that may coincide with known or predicted large-scale fault zones and will be targets for future modeling and reconstruction efforts. The vertical velocity gradient increases on both profiles at ~25 km depth, which we interpret as a mid-crustal transition associated with compositional changes within the crust. Above this mid-crustal transition, the model shows evidence for thickening of the upper crust across the arch. We find mantle velocities (>7.8 km/s) at ~45–50 km depth below surface elevation beneath the arch, consistent with a Moho boundary modeled using PmP and Pn phase arrivals at source-receiver offsets of 210–250 km, resulting in a measure of crustal thickness across the arch.

OBJECTIVES

The primary objective for this work is ultimately to quantify the degree of regionalization and instrumentation necessary for successful discrimination in a tectonically complex region. This result will provide a basis for assessing regional discrimination performance in areas with comparatively sparse datasets. During a May–December 2010 field season, we collected a large and diverse seismic dataset in north-central Wyoming. The work we present here is our initial analysis of two active-source, wide-angle reflection and refraction profiles across the Bighorn Mountains and the Bighorn and Powder River Basins (Figure 1).

The work for this contract is integrated with BASE, a project sponsored by the National Science Foundation EarthScope program. The focus of BASE is imaging the deep structure of basement-cored arches in order to understand the mechanisms of the formation of the Rocky Mountains. Other BASE science goals are focused on the nature of faults at depth in the crust and deep crustal rheology. In addition to producing velocity models of the crust and upper mantle, the seismic imaging experiment will determine whether faults at depth remain discrete or if they diffuse into a broader zone of ductile deformation.

RESEARCH ACCOMPLISHED

Data

The active source component of BASE consisted of two profiles. BASE01 extended ~300 km west to east (Figure 1), crossing the Bighorn Basin, the Bighorn Arch, and the Powder River Basin. This profile included ~1300 Reftek RT125 (Texan) seismographs with vertical component 4.5 Hz geophones deployed at 500 m spacing within the basins. For a 100-km-long section in the mountains, receiver interval spacing along the profile was decreased to 100 m in order to improve imaging of near-vertical incidence arrivals. BASE02 traveled north to south (Figure 1), sub-parallel to the arch, for ~250 km on the western flank of the Bighorn Mountains. This profile included ~500 Texans deployed at 500 m spacing. Data from 20 single-fired shots, ranging in size from 500 to 2000 lb, were recorded by the Texans across both profiles, contributing to 3D coverage across the region. For this paper, we restrict our analysis to a 2D inversion scheme, using data from 14 inline shots along BASE01 (Figures 2–4) and 6 inline shots along BASE02 (Figure 5). The dominant energy in the shots ranged from 8 to 20 Hz.

Methods

Our compressional wave velocity models for the BASE profiles (Figures 6 and 7) were constructed through a series of linearized tomographic inversions of travel-time data derived from the seismic shot gathers (Figures 2–5) following the general method of van Avendonk et al. (2004). Phase arrival times are picked from plots of shot gathers (e.g., Figure 2). The starting model for each profile contains a smooth vertical velocity gradient in the crust and is laterally homogeneous. For BASE01, the starting model also includes a boundary layer at ~45 km depth that represents the Moho. Velocities increase stepwise by 0.5 km/s at this boundary layer.

For each modeling iteration, we trace rays in the current velocity model using the shortest path method (SPM) (Moser, 1991) and ray-bending (Moser et al., 1992; van Avendonk et al., 2001) to develop a set of calculated raypaths and travel times. Subsequently, we invert for an update to the current velocity model using the difference between picked and calculated travel times. In each inversion, we tune the strength of smoothness and damping constraints. The updated velocity model becomes the starting model for the next iteration of ray-tracing and inversion until a normalized data misfit, χ^2, of ~1 is achieved (van Avendonk et al., 2004).

The velocity model shown for BASE01 (Figure 6) incorporates 10,796 first-arrival travel times and 467 PmP and Pn travel-time picks. The root-mean-square error is 167 ms, with a chi-squared of 1.5. The model shown along BASE02 (Figure 7) includes 1946 first-arrival travel times. This model has a root-mean-square error of 119 ms and a chi-squared of 1.0.

Preliminary Results

The BASE01 velocity model (Figure 6) defines low-velocity (3.5–4 km/s) basin structure on either side of the Bighorn Arch in the upper ~5–10 km. Basin geometries in the model correlate well with that derived from previous geologic work and industry seismic imaging (Blackstone, 1993). Low-velocity zones that emerge within the upper 20 km of the crust may coincide with known or predicted large-scale fault zones and will be targets for future modeling and reconstruction efforts. The vertical velocity gradient displays a marked increase at ~25 km depth, which we interpret to represent a mid-crustal transition associated with compositional changes within the crust.

Above this mid-crustal transition, the model shows evidence for thickening of the upper crust beneath the arch. We find mantle velocities (>7.8 km/s) at ~45–50 km depth below surface elevation beneath the arch, consistent with a Moho boundary modeled using PmP and Pn phase arrivals at source-receiver offsets of 210–250 km, resulting in a measure of crustal thickness across the arch.

Crustal velocities on BASE02 (Figure 7) are laterally continuous in the upper crust. The vertical velocity gradient increases markedly at ~25 km depth, as seen on the east-west profile. Mantle velocities (>7.8 km/s) are observed at ~50 km depth below surface elevation.

CONCLUSIONS AND RECOMMENDATIONS

We present preliminary results based on a subset of data. As such, it is too early to draw detailed conclusions regarding the degree of regionalization and instrumentation necessary for successful determination in a tectonically complex region. Of note, however, is the considerable amount of velocity heterogeneity in the upper crust, beneath the basins, observed across the BASE01 profile.

We are continuing analysis of the data and ultimately plan to integrate 2D and 3D compressional and shear-wave velocity models of the crust and upper mantle derived from both active and passive seismic methods.

ACKNOWLEDGEMENTS

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Seismic instruments were provided through the USArray Flexible Array, a pool of instruments available through the National Science Foundation EarthScope program that is housed at the PASSCAL Instrument Center of IRIS at the New Mexico Institute for Mining and Technology. Data will be archived and available through the IRIS Data Management Center.

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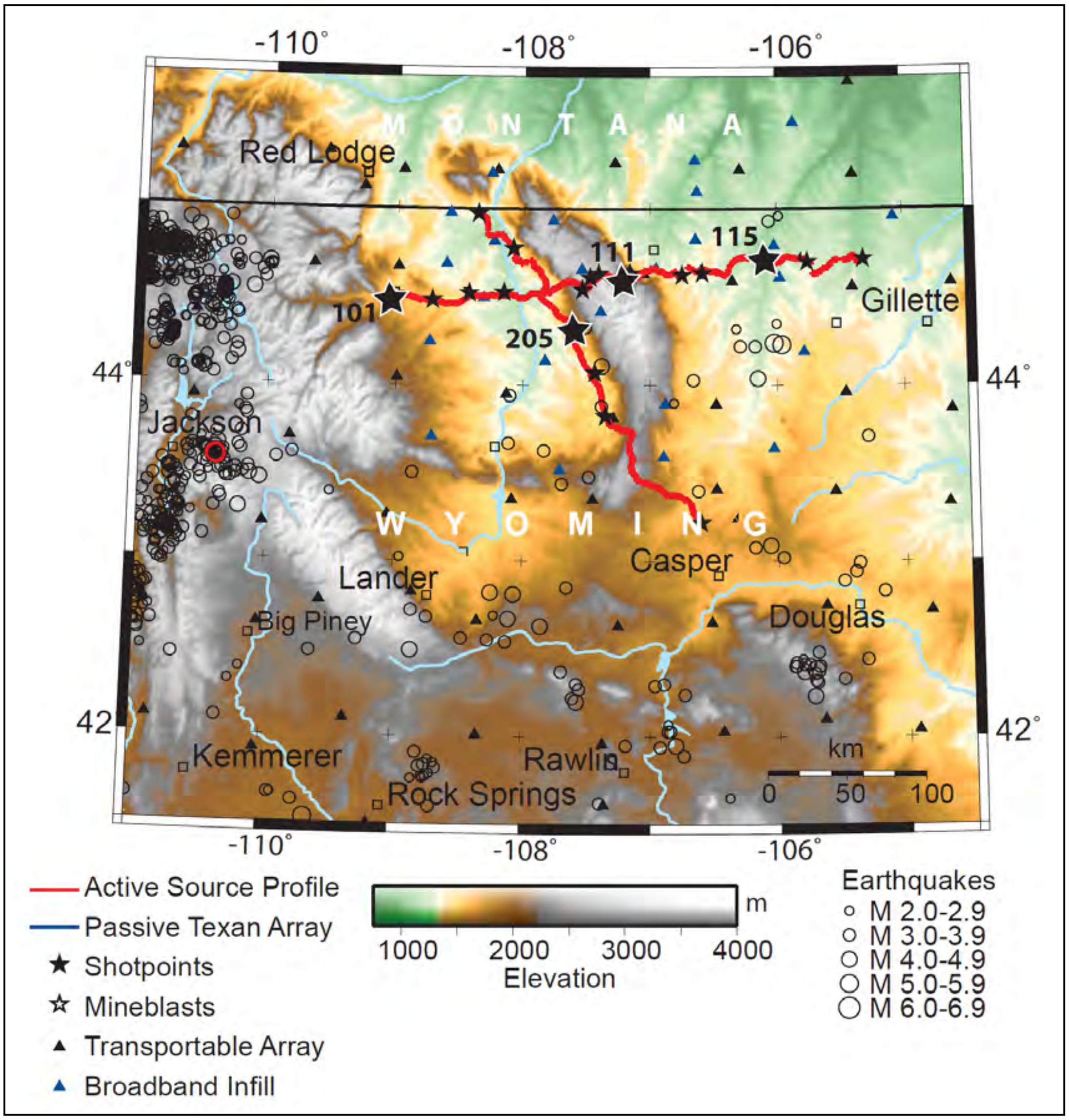

Figure 1. Topographic map of north-central Wyoming showing the experiment geometry for the active source profiles and regional seismicity (Jackson Hole earthquakes recorded by our array are shown as red circles). Single-fire shots (black stars) of 250 to 2000 lb of emulsion blasting agent were fired into 1850 Texans (red crosses) deployed along two profiles at intervals of 100 m to 1000 m.

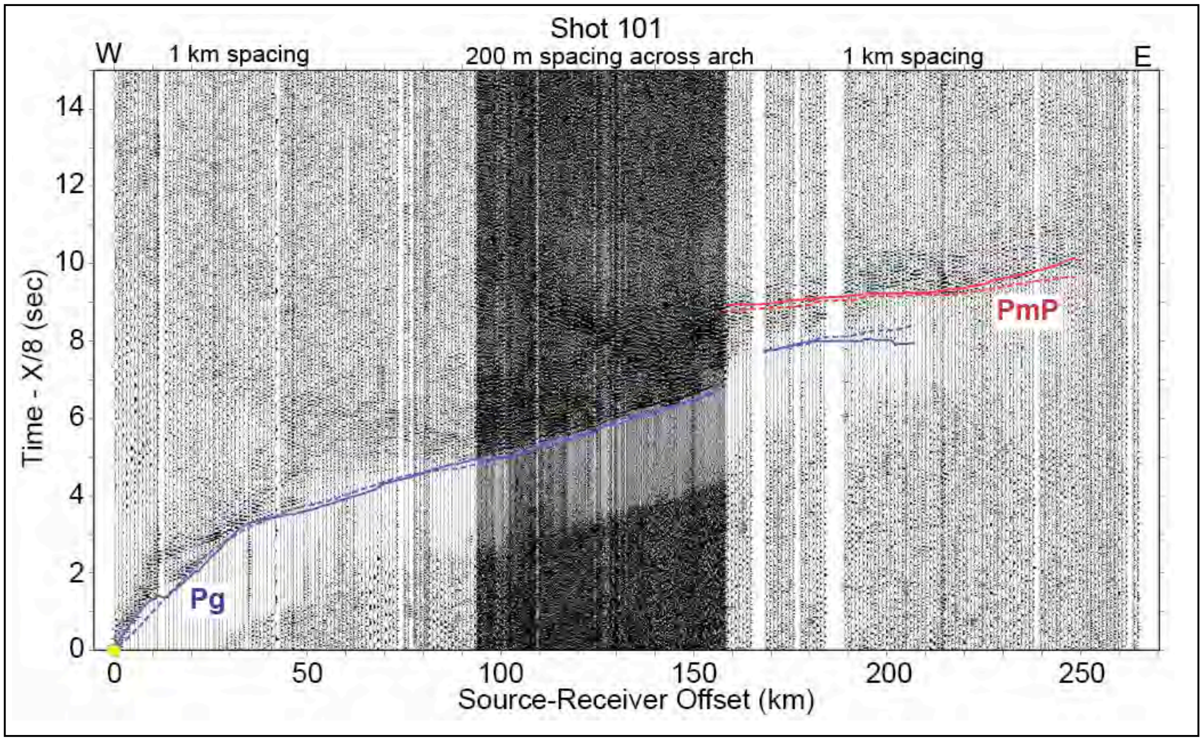

Figure 2. Shot record section shot point 101, the westernmost shot on the east-west profile. Solid lines mark arrivals for crustal refractions (blue) and mantle reflections (red). Dashed lines are calculated travel times through the model shown in Figure 6.

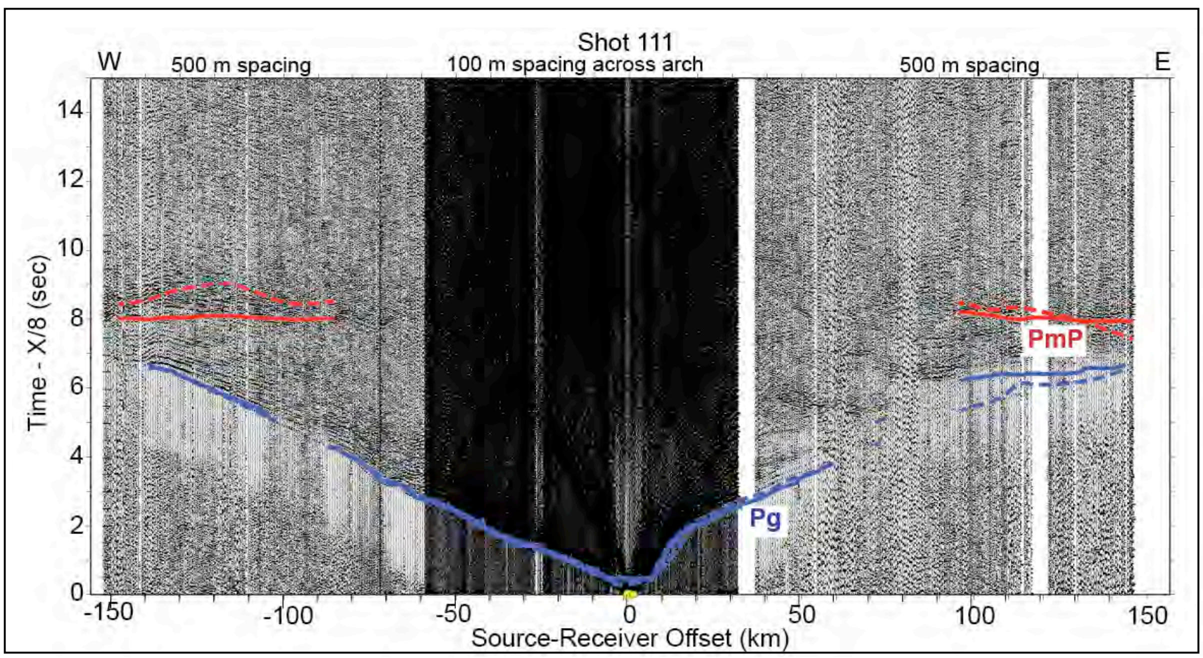

Figure 3. Shot record section shot point 111, in the Bighorn Arch along BASE01. Solid lines mark arrivals for crustal refractions (blue) and mantle reflections (red). Dashed lines are calculated travel times through the model shown in Figure 6.

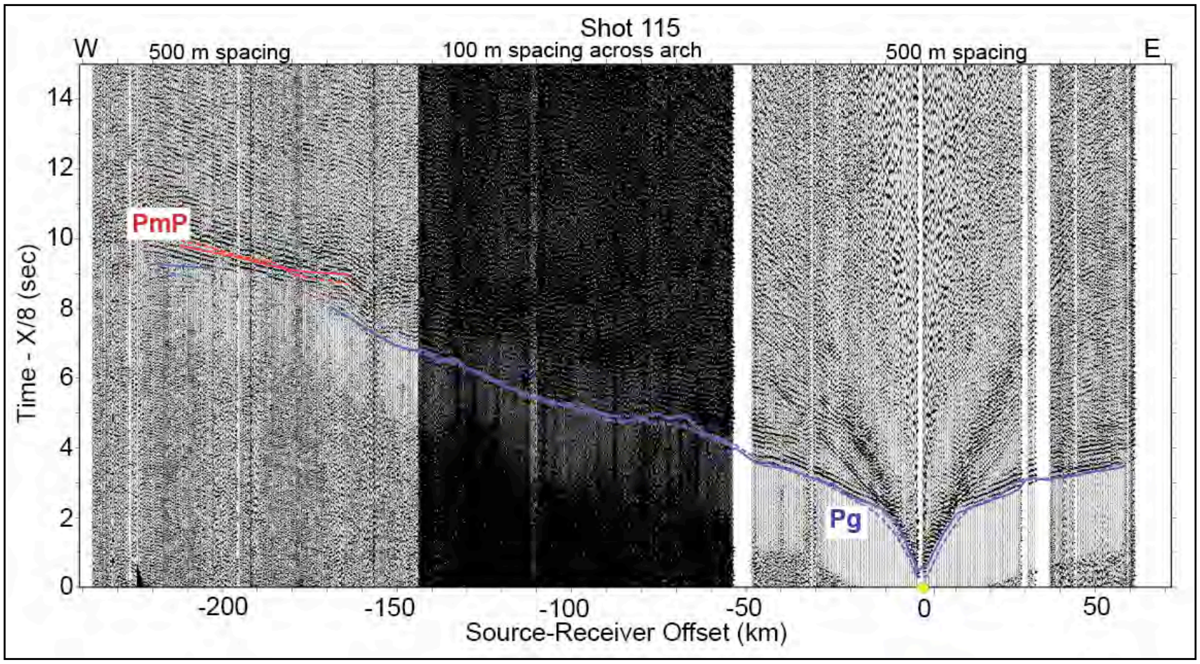

Figure 4. Shot record section shot point 115, in the Powder River Basin on BASE01. Solid lines are arrivals for crustal refractions (blue) and mantle reflections (red). Dashed lines are calculated travel times through the model shown in Figure 6.

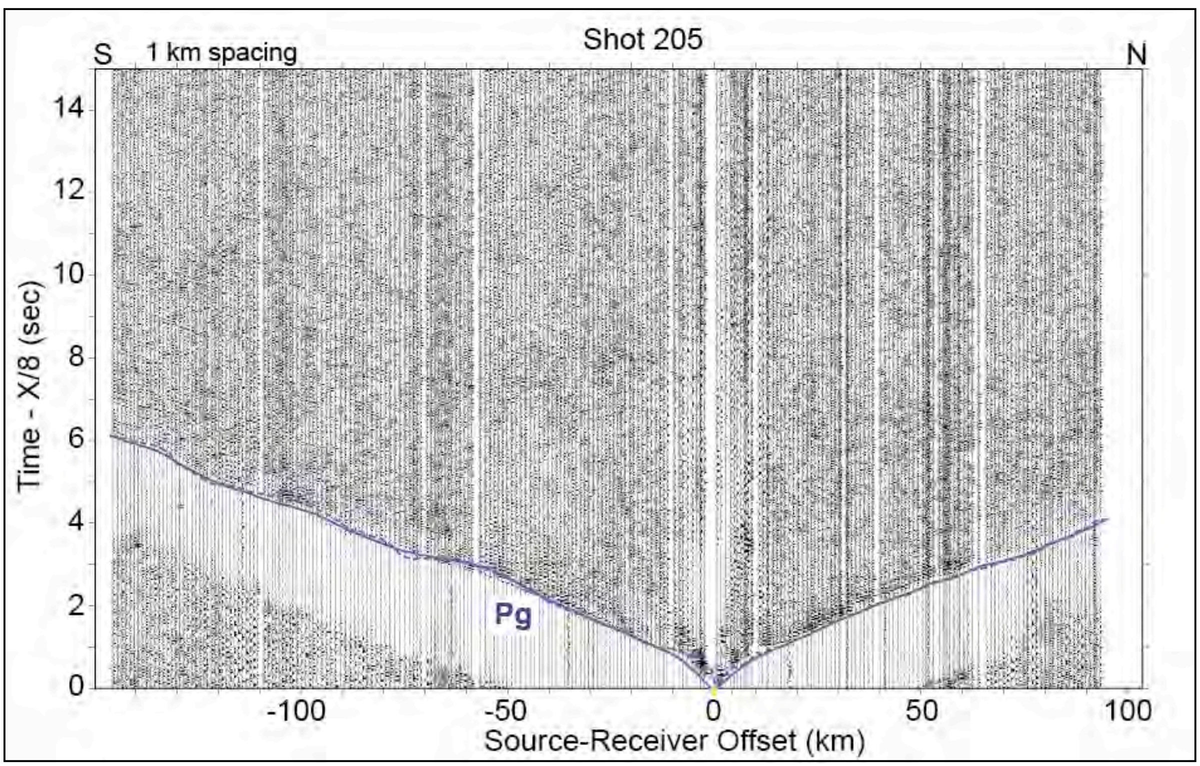

Figure 5. Shot record section shot point 205, on BASE02. Solid lines are arrivals for crustal refractions (blue). Dashed lines are calculated travel times through the model shown in Figure 7.

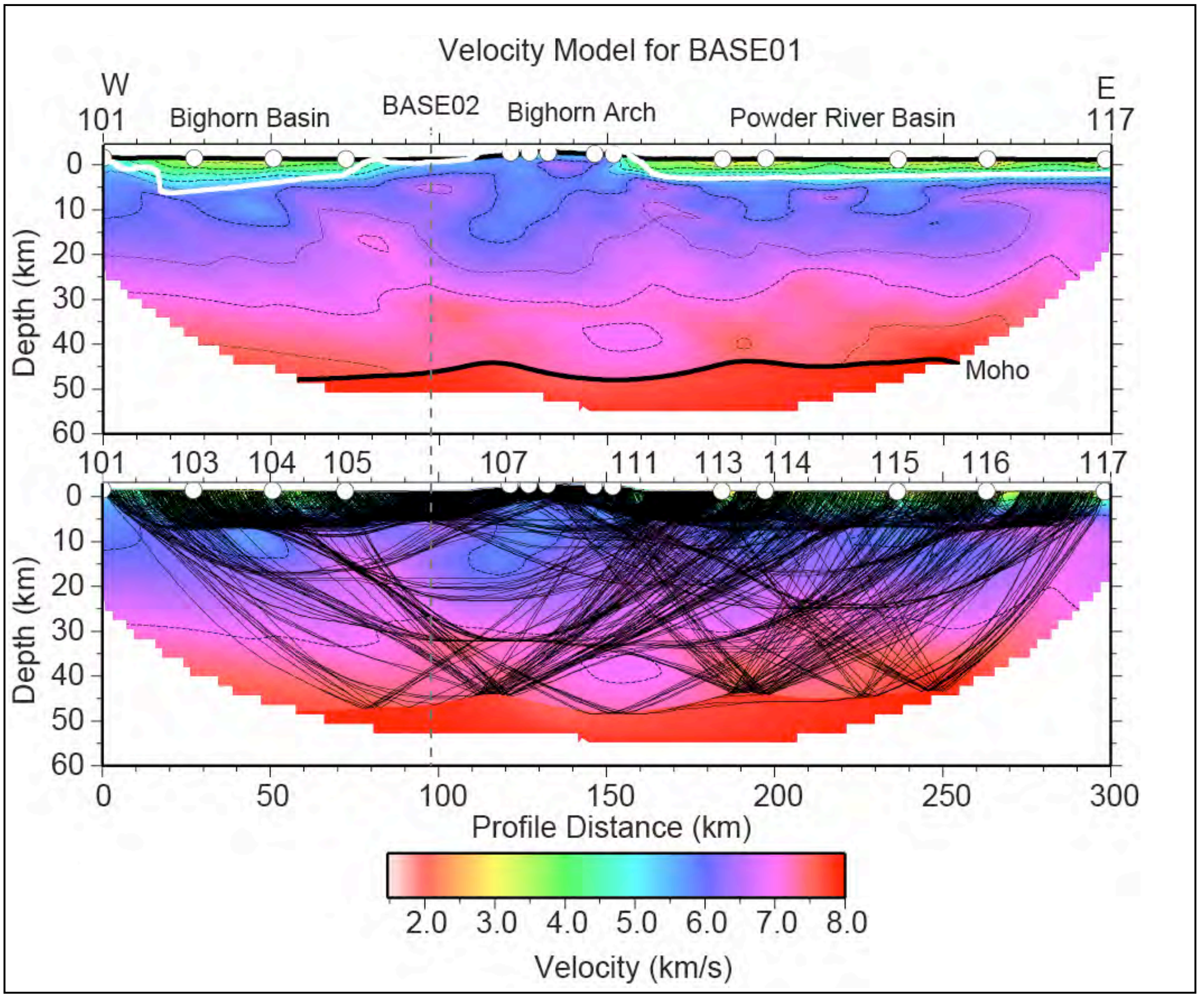

Figure 6. Velocity model along BASE01, the east-west profile (top), shown with calculated raypaths (bottom). Shot point locations are indicated by white circles. The white line within the model represents the top of basement from Stone (1993). Contour interval = 0.5 km/s.

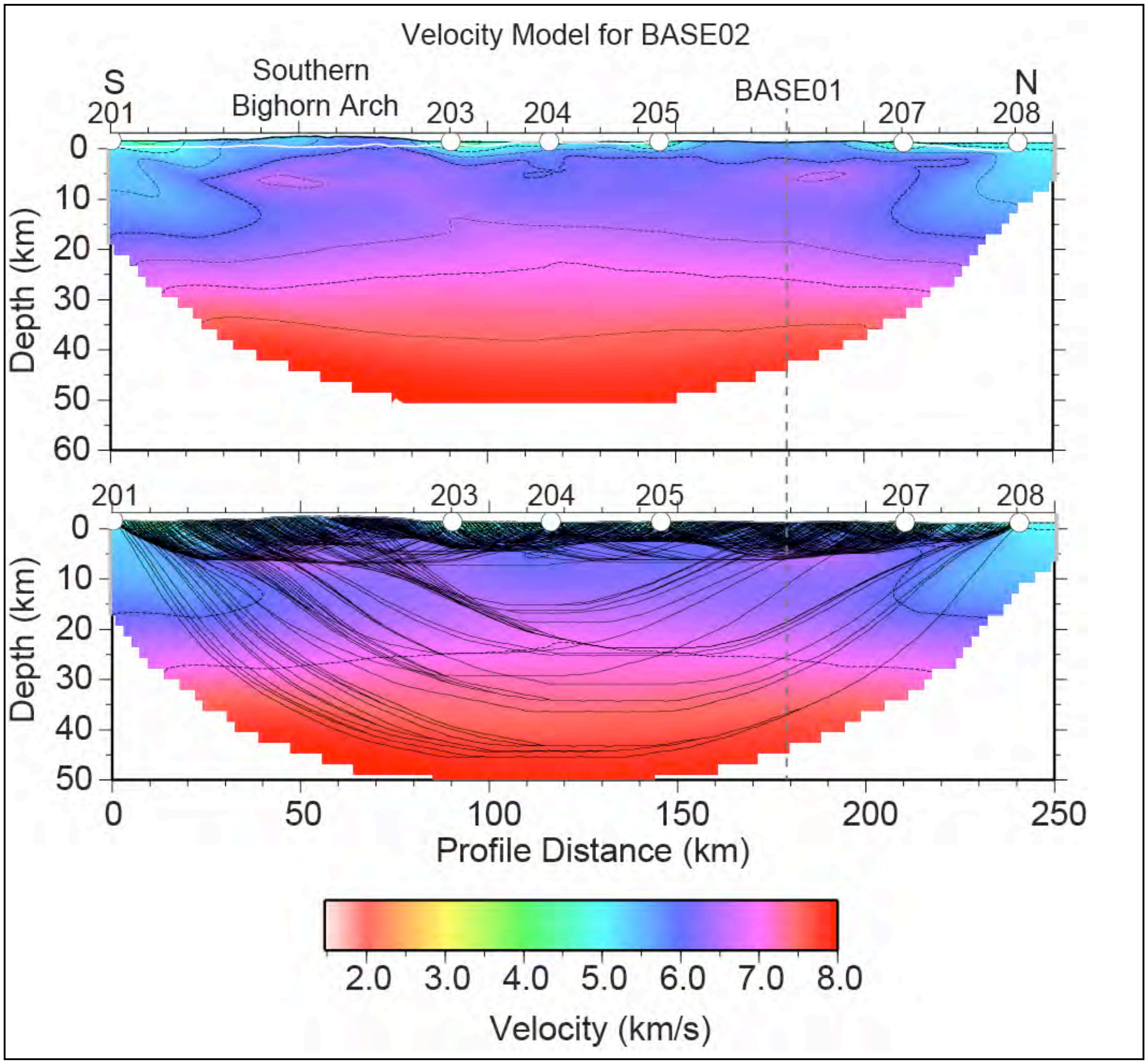

Figure 7. Velocity model along BASE02, the north-south profile (top), shown with calculated raypaths (bottom). Shot point locations are white circles. Contour interval = 1.0 km/s.