Body Wave Tomography for Regional Scale Assessment of Geothermal Indicators in the Western Great Basin

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Keywords

Seismic imaging, regional seismic velocity structure

ABSTRACT

Body and surface wave tomography are two of the primary methods for estimation of regional scale seismic velocity variations. Seismic velocity is affected by temperature and rock composition in complex ways, but when combined with geologic and structural maps, relative temperature can in some cases be estimated. We present preliminary tomographic models for compressional and shear-wave velocity using local and regional earthquakes recorded by Earthscope Transportable Array stations, network stations operated by the Nevada Seismological Laboratory, and other stations of opportunity in the western Great Basin. Preliminary results show correlations with notable geologic structures in eastern California and western Nevada.

Seismic Velocity Studies in the Western Great Basin

The Earthscope Transportable Array (TA) is the mobile seismic network component of a major earth sciences initiative funded by the National Science Foundation. The array will develop seismic data for the entire United States using a slowly moving network of about 400 stations installed on a grid of about 70 by 70 km. This grid is rather coarse compared with common exploration-scale networks, but it is unprecedented in terms of its resolution and uniformity of coverage. All stations include a broadband seismometer and high-dynamic-range datalogger, and return continuous data at 40 samples/second. All data are permanently archived and publically available. Details about Earthscope and the Transportable Array are available at www.earthscope.org. The TA has come and gone from the Great Basin of the western US, but the applications and geologic insights to be gained from it are still in their beginning stages.

Prior to the deployment of the Transportable Array, resolution of crustal thickness and upper mantle velocities was generally limited to a scale of 50-100 km [e.g., *Hearn et al*., 1991; *Hearn and Rosca*, 1994; *Priestly et al*., 1980; *Ozalaybey et al*., 1997]. For most of Nevada surface wave and receiver function results indicate an average crustal thickness of ~30 km, with a range from ~25 km under the Battle Mountain Heat Flow High [*Stauber and Boore*, 1978; *Priestly et al*., 1980] to ~38 km under east central NV [*Ozalaybey et al*., 1997; *Gilbert and Sheehan*, 2004]. Shallow mantle compressional velocities fall in the range of ~7.8±0.2 km/s, with some relationships to faults and regions of high shear strain [*Biasi and Humphreys*, 1992; *Humphreys and Dueker,* 1994; *Biasi*, 2005]. Surface wave studies have made important progress through the use of ambient noise cross-correlation (*Yang et al., 2008; Lin et*

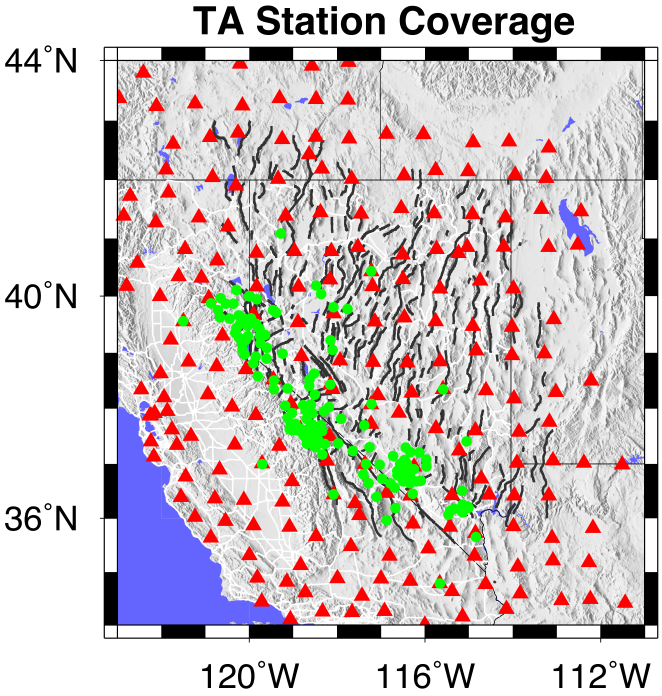

Figure 1. Station coverage. Red triangles are the USArray Transportable Array stations. The permanent seismic network (green circles) cannot match the TA for coverage or data quality, but they do contribute the body-wave ray coverage in western and southern Nevada.

al., *2008*). Results from comparable studies in California (*Shapiro et al*., *2005*) suggest that some caution in interpretation is advised, perhaps because surface waves are susceptible to systematic unmodeled influences on surface wave paths. Detailed studies within the state [e.g., *Knuepfer et al*., 1987; *Benz et al*., 1990; *Hauser et al*., 1987] report generally flat or gently dipping Moho and in some places highly reflective lower crust is interpreted as the brittle-ductile transition. Crustal velocities reveal low-velocity basins (<5 km/s) and bounding mountain ranges (5-6 km/s) down to ~10 km depth. Velocities increase to the upper 6 km/s range with depth, and approach ~7.9 km/s at the Moho. An important and largely unresolved issue for geothermal assessment of deeper crustal velocities is just how extension and faulting at the surface is related to shear and reflectance at depth.

The body wave inversions about which we report here are part of a larger study that will combine both body and surface waves into a single integrated model. Surface waves are dispersive, meaning that their velocity and their depth of penetration depend on frequency. We combine body and surface waves because with the coarse spacing of the Transportable Array, body waves tend to travel at mid-crust to shallow mantle depths. Surface waves provide a natural means for filling in at shallow depths. An additional advantage is available in the western Great Basin, because we can supplement TA stations with permanent stations of the Nevada Seismological Laboratory and other operators (Figure 1).

Tomographic Inversion for Structure in the Western Great Basin

We invert for structure using first arrivals computed with a modified Vidale-Hole finite-difference algorithm. An equally spaced grid is employed, but sources and receivers are not required to be on grid nodes. Inversion uses the Conjugate Gradient Least Squares method, with adjustable regularization and model damping. Earthquakes and stations are required to be in the inversion domain. Because of the scale of the model domain, corrections were developed and applied for the curvature of the earth. This correction prevents artificially high velocities from being introduced by longer station-event distances. The inversion simultaneously relocates the seismic events to reduce the degree to which depth and location errors map into velocity structure. Resolution of present inversions is being explored at this time, but can be roughly estimated on the basis of ray coverage (Biasi et al., 2008). Present models use approximately 5500 P-waves and 1360 S-waves. Because both the source and station density is higher in the western half of the modeled area, resolution is better there.

Body-Wave Inversion Results

Results for inversions developed to date are summarized below. Depths are referenced to sea level. Preliminary results show interesting and potentially useful correlations with geologic structures in eastern California and western Nevada.

0 and 5 km Model Layers

The Sierran block, and a "Proto-Sierran" block (PSN) northwest of the Carson Sink (CS) show high compressional wave velocities (Figure 2A). The later structure may be an "island" of less extended rock between the Carson Sink and the Black Rock extensional (BRE) zone. Geologically this "island" is dominantly Mesozoic plutonic rock related to early development of the Sierra Nevada. The Carson Sink appears with clear low P velocity. In the Vp/Vs maps (Figure 2c) there is a low near 39N, 118.5W cor-

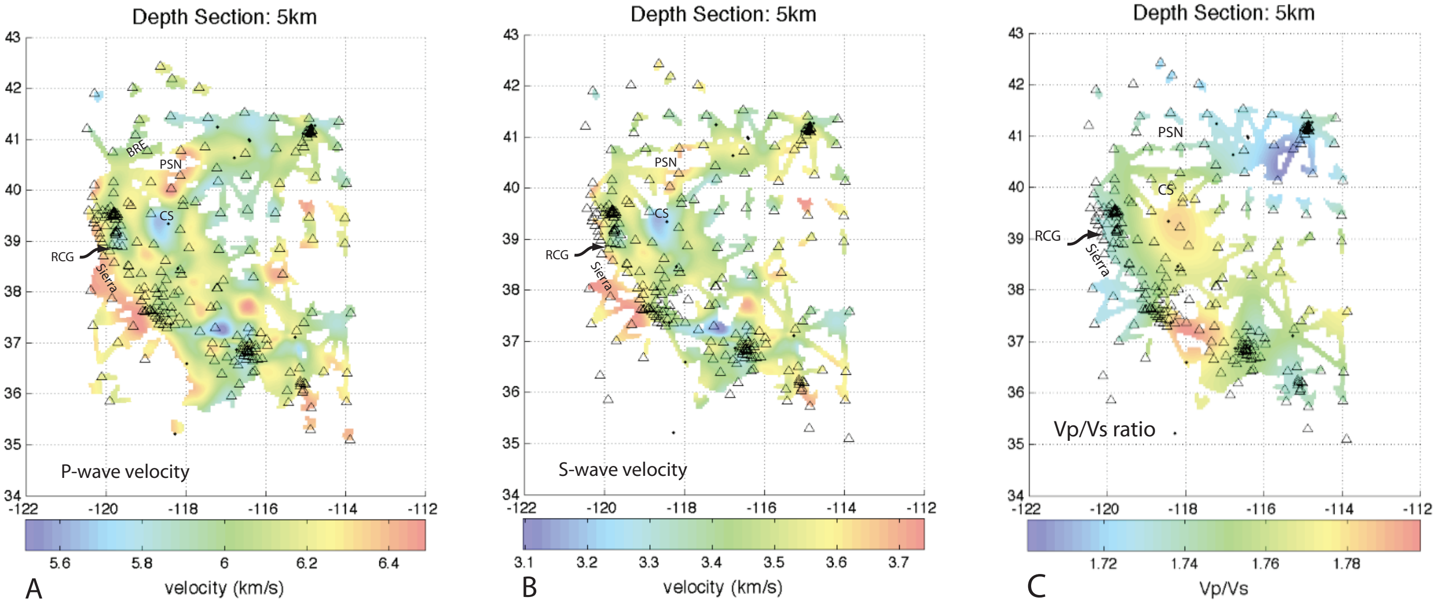

Figure 2. (A) Preliminary P-wave tomographic model results for the five kilometer model depth. Triangles indicate stations contributing to data coverage. Dots indicate earthquake locations that occur in this layer. The "zero" kilometer layer above this is highly correlated with this layer but covers less area because the ray density is lower. Abbreviations for place reference are explained in the text. Model regions with too few crossing rays to control the inversion are uncolored. In central and eastern Nevada low ray density causes cones with some velocity control around stations. (B) Shear-wave velocity for the five km depth. V_s is affected more by temperature and fracture density than is V_p. (C) V_p/V_s ratio in the five km depth. Resolution is comparable or somewhat lower than that for Vs.

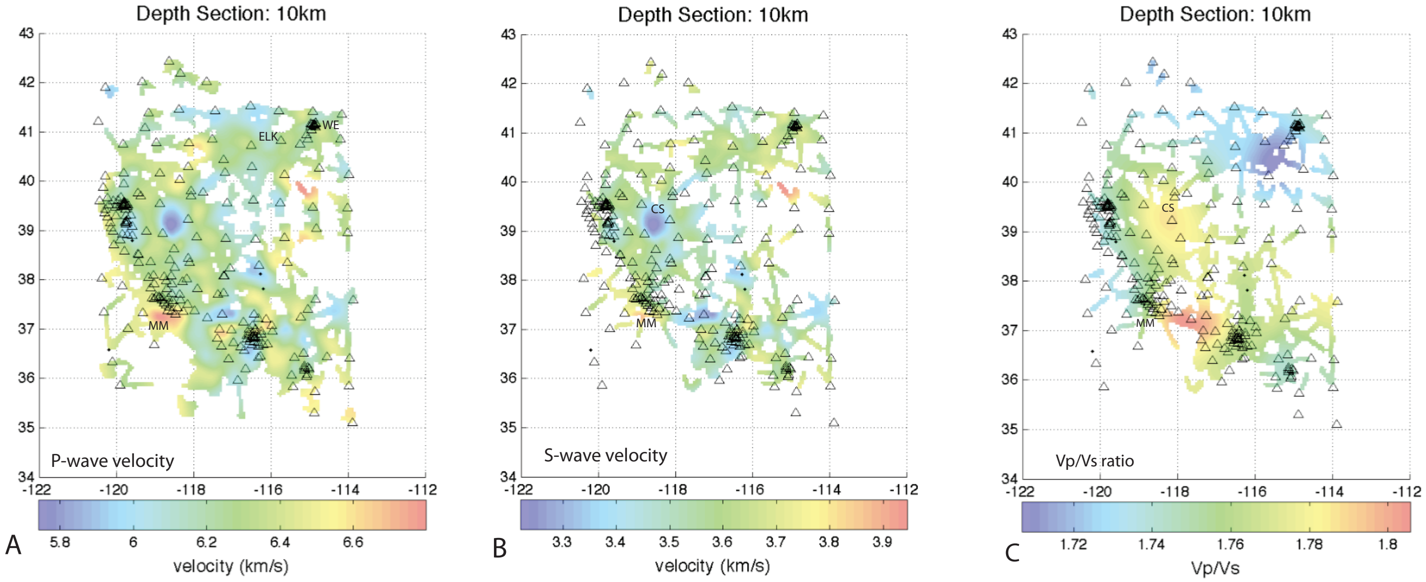

Figure 3. Tomographic model for the 10 km depth (~12 km below the ground surface). Body waves traveling 30 to perhaps 100 km travel in this and the 15 km depth layers. The 15 km layer is similar in general features, and not shown. (A) Vp model result. (B) Vs model velocities. C) Vp/Vs model inversion result. MM is Mammoth Mountain; CS is the Carson Sink. See text for discussion of anomalies.

responding to a major shear zone identified in geodetic measurements of the central Walker Lane. Pervasive shear and elevated temperature can cause the Vp/Vs ratio to increase because both affect the shear modulus, and thus Vs, to a greater degree than Vp. Either or both causes may be effective in the Central Nevada Seismic Belt. In the 5 km depth slice the Reno-Carson-Gardnerville basin structure is suggested in a 0.1 to 0.2 km/sec ΔVp lineation east of the Sierra.

10 and 15 km Model Layers

At 10-15 km depth patterns are similar to those at 5 km, but are generally less pronounced. The Carson Sink (CS) is still a bulls-eye of low velocities. At this depth, generally lower velocities are also observed in east-central Nevada (117.5-115 W). Perhaps unexpectedly, a high-velocity block SW of Mammoth Mountain (MM) is indicated beneath the Sierran batholith. The velocity contrast with the caldera side is clear, but the caldera is not a pronounced low-velocity structure. This structure is on the edge of the resolved area, and would be improved with better station coverage to the southwest. A high Vp/Vs ratio anomaly is observed centered on 39.2, -118.2W, roughly beneath the south end of Toiyabe and Toquima ranges. A second, more prominent structure near 37.2 N, 117 to 118 W could correspond to a deep relay structure transferring deep extension of the Death Valley-Fish Lake Valley system west beneath the White Mountains and perhaps also north of there. Confirmation of this structure could be of importance as it may indicate how strain between the Sierra and central Nevada is accommodated at depth. High Vp/Vs ratios are also indicated under Wells (WE) and Elko (ELK). The Reno-Carson-Gardnerville area shows a lower than average Vp/Vs ratio, suggesting that the structure responsible for the valley includes extension of some sort at depth.

All correlations here are based on preliminary inversions, but the patterns and their potential for regional interpretation indicate inversions will be of interest for regional geothermal assessments. One potential mitigating factor is that some interesting structures in central Nevada are on a comparable scale with the station spacing, and may require improved ray coverage. We expect that surface wave reconstructions will mitigate this problem.

Conclusions

Crustal tomographic inversion of permanent and Transportable Array data provide new regional seismic images of Nevada and the Great Basin. Body and surface wave tomographic images will set a new standard for resolution. Present images show good correlations with known and suspected shear zones including the Carson Sink and the Reno-Carson City corridor. Velocity measurements provide direct indications of anomaly location and, indirectly, a basis for estimates of parameters such as temperature and composition. Tomographic imaging of the Western Great Basin is thus a useful tool for regional geothermal resource evaluation in the Great Basin.

Acknowledgements

This work was supported by the Great Basin Center for Geothermal Energy, U.S. Department of Energy, DE-FG36-02ID14311. Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under Contract DE-AC04-94AL85000.

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