blast and the M 2.8 Paso Robles, CA earthquake. The optimized model yielded a crustal root beneath the Sierra Nevada Mountains with an approximate depth of 55 km, assuming a Moho velocity of 7.6 km/s beneath the Sierra Nevada, and centered at least 100 km west of the topographic crest (Pullammanappallil and Louie, 1994). To the northeast of the root, the inversion confirms a typical 30-32 km-thick crust in northern Nevada, thickening to the north toward the Nevada-Idaho state border. The model agrees with the 1986 PASSCAL refraction and the COCORP 40N reflection experiment that both revealed 30 km thick crust in northern Nevada (Klemperer et al., 1986; PASSCAL Working Group, 1988; Benz et al., 1990).

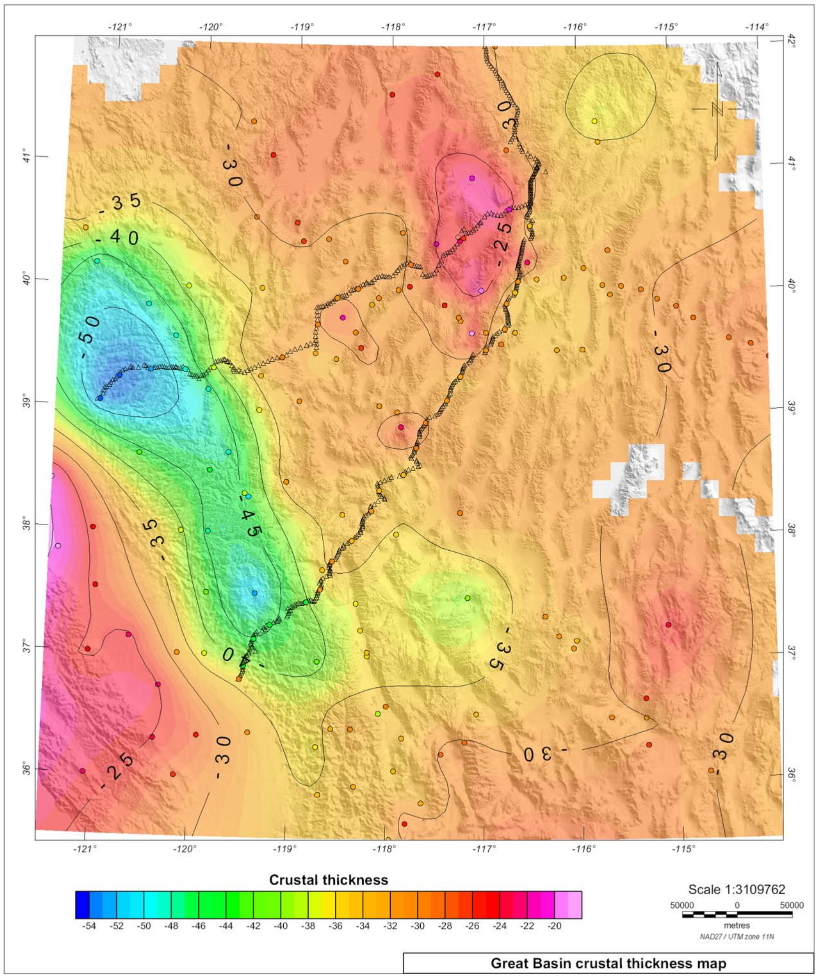

Figure 3. Crustal thickness map for the Great Basin and surrounding region. Colors are contoured at every 1 km change in thickness and the black lines are contoured at every 5 km. Colored circles indicate the location of data and the small black triangles denote the location of the NWL and INC experiments (also see Figure 1).

In order to confirm and expand on the experiment's basic model, a second tomography inversion was completed (Figure 2). The second model utilized re-picked first arrivals from the Paso Robles, CA earthquake and the Barrick GoldStrike 232 blast, as well as an additional Barrick GoldStrike blast on Julian day 233. The second inversion confirms our original picks (without a 2.5 second delay that was originally added to the Paso Robles, CA event), and adds clarification to features in the initial version (Pullammanappallil and Louie, 1994). From Model 2, we observe a crustal root of only 44 km +/- 2 km with steep sides, centered 40 km west of the topographic crest at the latitude of approximately 37 N. Within northern Nevada, we observe 30-32 +/- 2 km-thick crust that is in agreement with Model 1, as well as the 1986 PASSCAL and the COCORP 40 N transect (Klemperer et al., 1989; Benz et al., 1990; PASSCAL Working Group, 1988). This gives confidence to the picks and the model inversion. There is little transition between the steep-sided root on its eastern side and the Basin and Range. At the latitude of Long Valley, we observe a steeply dipping 14-20 km step in the Moho. Assuming a root Pn velocity of 7.6 km/s and a Pn velocity in Nevada of 7.8 km/s, this forces the Moho interpretation of Model 2 to cut across the velocity boundaries defined by the inversion. Where the change from 7.6 to 7.8 km/s actually takes place cannot be determined from this study alone. We assume that the Pn, uppermost-mantle, velocity changes at the eastern boundary of the root where compositional and/or temperature changes are likely to occur. On the north side of Barrick GoldStrike, where we have no Pn first arrival picks, we have extrapolated the Moho to a depth of 31 km based on the recent refraction experiment of Lerch et al. (2007). The refraction experiment by Lerch et al. (2007) extends west of INC and across northern Washoe and Pershing Counties, Nevada, revealing approximately 31 km-thick crust that is not any thicker (as previously thought). On the western side of the Sierra Nevada, within the Great Valley, we have again extrapolated the Moho, this time to a depth of 28-30 km based on refraction experiments within the Great Valley and coast ranges (Fliedner et al., 2000; Mooney and Weaver, 1989).

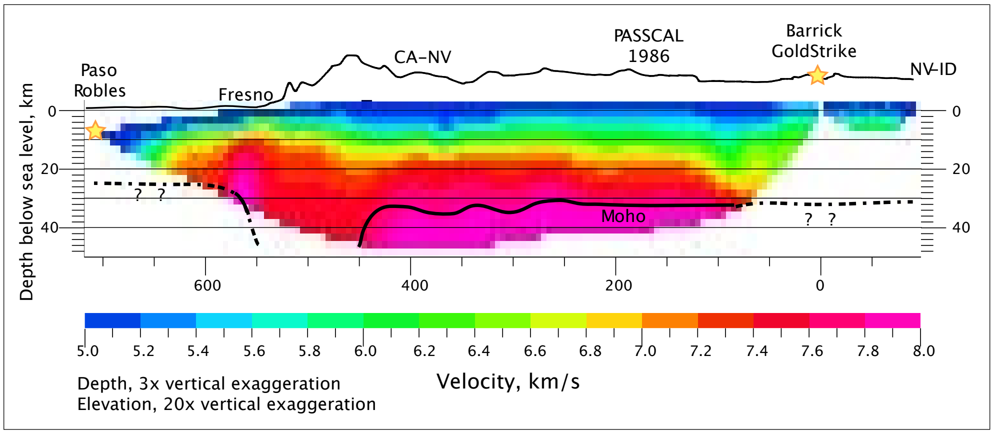

Figure 2. Updated model for the INC seismic refraction transect (see Figure 1 for INC transect location).

3. Updated Crustal Thickness Map

We have compiled a contoured crustal thickness map (Figure 3) based on the NWL (Louie et al., 2004) and the updated INC seismic refraction results presented in this paper (Figure 2), as well as previous geophysical studies within the Great Basin. This paper presents an updated version of the crustal thickness map for the Great Basin. We extracted information concerning crustal thickness from the crust-mantle (Moho) refraction velocities and arrival times, cross-over distances, and from models presented in the literature. A kriging algorithm was used to interpolate a crustal thickness map. The colors on the map are contoured every 1 km, and the black outlines are for every 5 km, showing a more general trend. In addition, a preliminary version of this map was used in assessing areas for future refraction experiments, such as our NNUT experiment completed in August 2005 (Figure 1). On a first-order basis, the contoured crustal thickness data correlate well with heat flow observations for the Great Basin (Coolbaugh et al., 2005; Heimgartner et al., 2006).

The updated or preferred model eliminates most of the discrepancies between adjacent points, but leaves results in places where no other data exist. Combining these data sets allows better visualization of key features, permits discrepancies to be better addressed, and evaluates how well the proposed models fit the actual data. There are several key features to note: one, the crustal root is centered west of the Sierra's topographic crest; two, the root deepens north of Fresno, California; three, there is an abrupt step of approximately 18 km at the Sierra-Basin and Range transition; four, normal, 30-km thick Basin and Range crust occurs adjacent to the root on its east side; and five, the thin area of crust near Battle Mountain, Nevada may be larger than 100 km in area based on the compilation of the NWL and previous work in the area.

Conclusions

The Northern Walker Lane, Idaho-Nevada-California and Northern-Nevada-Utah transects are contributing to our efforts to understand regional geophysical properties and their relationships to the occurrence of geothermal resources. Our refraction experiments will help provide a more accurate crustal model for the northern Great Basin where little previous seismic refraction control exists. A detailed resolution of crustal thickness makes it possible to quantitatively evaluate the role that crustal-scale processes play in controlling the location of geothermal systems, and that evaluation is in progress.

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References

1986 PASSCAL Basin and Range Lithospheric Seismic Experiment Working Group, 1988. "The 1986 PASSCAL Basin and Range lithospheric seismic experiment." Eos, v. 69, no. 20.

Benz, H.M., R.B. Smith, and W.D. Mooney, 1990. "Crustal structure of the northwestern Basin and Range province from the 1986 program for array seismic studies of the continental lithosphere seismic experiment." Journal of Geophysical Research, v. 95, B13

Braile, L.W., W.J. Hinze, R.B. von Frese, and G.R. Keller, 1989. "Seismic properties of the crust and uppermost mantle of the conterminous United States and adjacent Canada, in Pakiser, L.C., and W.D. Mooney: Geophysical Framework of the Continental United States." Geological Society of America Memoir, v. 172, p. 655-680.

Catchings, R.D., and W.D. Mooney, 1991. "Basin and Range crustal and upper mantle structure, northwest to central Nevada." Journal of Geophysical Research, v. 96, p. 6247-6267.

Coolbaugh, M., R. Zehner, C. Kreemer, D. Blackwell, G. Oppliger, D. Sawatzky, G. Blewitt, A. Pancha, M. Richards, C. Helm-Clark, L. Shevenell, G. Raines, G. Johnson, T. Minor, and T.Boyd, 2005. "Geothermal potential map of the Great Basin, western United States." Nevada Bureau of Mines and Geology Map 151.

Diment, W.H., S.W. Stewart, and J.C. Roller, 1961. "Crustal structure from the Nevada Test Site to Kingman, Arizona, from seismic and gravity observations." Journal of Geophysical Research, v. 66, p. 201-21.

Eaton, J.P., 1963. "Crustal structure from San Francisco, California, to Eureka, Nevada, from seismic refraction measurements." Journal of Geophysical Research, v. 68, p. 5789-5806.

Fliedner, M.M., S. Ruppert, and Southern Sierra Nevada Continental Dynamics Working Group, 1996. "Three-dimensional crustal structure of the southern Sierra Nevada from seismic from profiles and gravity modeling." Geology, v. 24, no. 4, p. 367-370.

Fliedner, M.M., S.L. Klemperer, and N.I. Christensen, 2000. "Three-dimensional seismic model of the Sierra Nevada arc, California, and its implications for crustal and upper mantle composition." Journal of Geophysical Research, v. 105, no. B5, p. 10.

Gibbs, J.F., and J.C. Roller, 1966. "Crustal structure determined by seismic-refraction measurements between the Nevada Test Site and Ludlow, California." U.S. Geol. Survey Prof. Paper 550-D, p. D125-D131.

Hauge, T.A., R.W. Allmendinger, C. Caruso, E.C. Hauser, S.L. Klemperer, S. Opdyke, C.J. Potter, W. Sanford, L.D. Brown, S. Kaufman, and J. Oliver, 1987. "Crustal structure of western Nevada from COCORP deep seismic-reflection data." Geological Society of America Bulletin, v. 98, p. 320-329.

Hauser, E., C. Potter, T. A. Hauge, S. Burgess, S. Burtch, J. Mutschler, R. W. Allmendinger, L. Brown, Sidney Kaufman, and Jack E. Oliver, 1987. "Crustal structure of eastern Nevada from COCORP deep seismic reflection data." Geological Society of America Bulletin, vol. 99, p. 833 - 844.

Heimgartner, M., J.N. Louie, J.B. Scott, W. Thelen, C.T. Lopez, and M. Coolbaugh, 2006. "The crustal thickness of the Great Basin: using seismic refraction to assess regional geothermal potential." Geothermal Resources Council, Transactions, v. 30, p. 83-86.

Heimgartner, M., J.B. Scott, W. Thelen, C.T. Lopez, and J.N. Louie, 2005. "Variable crustal thickness in the western Great Basin: a compilation of old and new refraction data." Geothermal Resources Council, Transactions, v. 29, p. 239-242.

Holbrook, W.S., 1990, "The crustal structure of the northwestern Basin and Range Province, Nevada, from wide-angle seismic data." Journal of Geophysical Research, v. 95, no. B13:21.

Johnson, L.R., 1965. "Crustal structure between Lake Mead, Nevada, and Mono Lake, California." Journal of Geophysical Research, v. 70, no. 12.

Jones, C.H., and R.A. Phinney, 1998. "Constraints on the seismic structure of the lithosphere from teleseismic converted arrivals observed at small arrays in the southern Sierra Nevada and vicinity, California." Journal of Geophysical Research, v. 103, p. 10,065-10,090.

Klemperer, S.L., T.A. Hauge, E.C. Hauser, J.E. Oliver, and C.J. Potter, 1986. "The Moho in the northern Basin and Range province, Nevada, along the COCORP 40N seismic-reflection transect." Geological Society of America Bulletin, v. 97.

Lerch, D.W., S.L. Klemperer, J.M.G. Glen, D.A. Ponce, E.L. Miller, and J.P. Colgan, 2007. "Crustal structure of the northwestern Basin and Range Province and its transition to unextended volcanic plateaus" Personal communication.

Louie, J.N., W. Thelen, S.B. Smith, J.B. Scott, M. Clark, and S. Pullammanappallil, 2004. "The Northern Walker Lane refraction experiment: Pn arrivals and the northern Sierra Nevada root." Tectonophysics, v. 388, no. 1-4, p. 253-269.

Mangio, S.G., G. Zandt, and C.J. Ammon, 1993. "The receiver structure beneath Mina, Nevada." Bulletin of Seismological Society of America, v. 83, p. 542-560.

Mavko, B.B., and G.A. Thompson, 1983. "Crustal and upper mantle structure of the northern and central Sierra Nevada." Journal of Geophysical Research, v. 88, no. B7

Mooney, W.D., and C.S. Weaver, 1989. Regional crustal structure and tectonics of the Pacific Coastal States; California, Oregon, and Washington, in Pakiser, L.C., and Mooney, W.D., Geophysical framework of the continental United States: Boulder, Colorado, Geological Society of America Memoir 172.

Özalaybey, S., M.K. Savage, A.F. Sheehan, J.N. Louie, and J.N. Brune, 1997. "Shear-wave velocity structure in the northern Basin and Range province from the combined analysis of receiver functions and surface waves." Bulletin of Seismological Society of America, v. 87, p.183 - 199.

Pakiser, L.C. and J.N. Brune, 1980. "Seismic models of the root of the Sierra Nevada". Science, v. 210, no. 4474, p. 1088-1094.

Potter, C.J., C. Liu, J. Huang, L. Zheng, T.A. Hauge, E.C. Hauser, R.W. Allmendinger, J.E. Oliver, S. Kaufman, and L. Brown, 1987. "Crustal structure of north-central Nevada; results from COCORP deep seismic profiling." Geological Society of America Bulletin, v. 98, p. 330-337.

Priestley, K.F., A.S. Ryall, and G.S. Fezie, 1982. "Crust and upper mantle structure in the northwest Basin and Range province." Bulletin of Seismological Society of America, v. 72, no. 3, p. 911-923.

Prodehl, C., 1979. "Crustal structure of the western United States." U.S. Geol. Survey Prof. Paper, p. 1034:74.

Pullammanappallil, S.K., and J.N. Louie, 1994. "A generalized simulated-annealing optimization for inversion of first-arrival times." Bulletin of Seismological Society of America, v. 84, p. 1397.

Roller, J.C., 1964. "Crustal structure in the vicinity of Las Vegas, Nevada, from seismic and gravity observations." U.S. Geol. Survey Prof. Paper 475-D, p. D108-D111.

Roller, J.C., and J.H. Healy, 1963. "Seismic-refraction measurements of crustal structure between Santa Monica Bay and Lake Mead." Journal of Geophysical Research, v. 68, no. 20.

Ruppert, S., M.M. Fliedner, and G. Zandt, 1998. "Thin crust and active upper mantle beneath the Southern Sierra Nevada in the western United States." Tectonophysics, v. 286, p. 237-252.

Ryall, A., and D.J. Stuart, 1963. "Travel times and amplitudes from nuclear explosions, Nevada Test Site to Ordway, Colorado." Journal of Geophysical Research, v. 68, no. 20

Savage, M.K., Li Li, J.P. Eaton, C.H. Jones, and J.N. Brune, 1994. "Earthquake refraction profiles of the root of the Sierra Nevada." Tectonics, v. 13, no. 4, p. 803-817.

Spieth, M.A., D.P. Hill, and R.J. Geller, 1981. "Crustal structure in the northwestern foothills of the Sierra Nevada from seismic refraction experiments." Bulletin of Seismological Society of America, vol. 71, p. 1075 - 1087

Stauber, D.A., and D.M. Boore, 1978. "Crustal thickness in northern Nevada from seismic refraction profiles." Bulletin of Seismological Society of America, vol. 68, no. 4, p. 1049-1058.

Taylor, S.R., 1983. "Three-dimensional crust and upper mantle structure at the Nevada Test Site." Journal of Geophysical Research, v. 88, no. B3.

Wernicke, B., R. Clayton, M. Ducea, C.H. Jones, S. Park, S. Ruppert, J. Saleeby, J.K. Snow, L. Squires, M. Fliedner, G. Jiracek, R. Keller, S. Klemperer, J. Luetgert, P. Malin, K. Miller, W. Mooney, H. Oliver, and R. Phinney, 1996. "Origin of high mountains in the continents: the southern Sierra Nevada." Science, v. 271, p. 190-193.

Zandt, G., H. Gilbert, T.J. Owens, M. Ducea, J. Saleeby, and C.H. Jones, 2004. "Actice foundering of a continental arc beneath the southern Sierra Nevada in California." Nature, v. 431.