Supplementary Material for

Unified Structural Representation of the southern California crust and upper mantle

John H. Shaw, Andreas Plesch, Carl Tape, M. Peter Suess, Thomas H. Jordan, Geoffrey Ely, Egill Hauksson, Jeroen Tromp, Toshiro Tanimoto, Robert Graves, Kim Olsen, Craig Nicholson, Phil Maechling, Carlos Rivero, Peter Lovely, Charles M. Brankman, Jason Munster

Earth and Planetary Science Letters

January 13, 2015

S1 GTL parameterization

The GTL implemented in the USR was based on *Ely et al.* (2010) and uses the geology-based Vs30 maps of *Wills and Clahan* (2006) to specify velocity values at the Earths surface in the voxet. V_P, and in turn density, are inferred from surface V_S using the scaling laws of *Brocher* (2005). These values were parameterized to a depth of $z_T = 350$ meters with the following formulations:

$$V_S(z) = f(z)V_{ST} + g(z)V_{S30} \tag{S1}$$

$$V_P(z) = f(z)V_{PT} + g(z)P(V_{S30}), \tag{S2}$$

where z' is depth, V_{ST} and V_{PT} are are S- and P-wave velocities extracted from the crustal velocity model at depth z_T, $P()$ is the *Brocher* (2005) P-wave velocity scaling law, and

$$z = z'/z_T \tag{S3}$$

$$f(z) = z + b(z - z^2) \tag{S4}$$

$$g(z) = a - az + c(z^2 + 2z - 3z) \tag{S5}$$

The coefficient a controls the ratio of surface velocity to original 30 meter average, b controls overall curvature, and c controls near-surface curvature of the velocity profile. The coefficients $a = 1/2$, $b = 2/3$, and $c = 3/2$ were chosen to fit the generic rock profile of *Boore and Joyner* (1997) while also producing smooth and well-behaved profiles when combined with the underlying basin and crustal velocity models (*Ely et al.*, 2010) (Figure 7).

S2 Model validation, comparison, and uncertainty

The velocity model (CVM) component of the USR described here is assembled from several different data sets and models, and thus it is challenging to formally assess model resolution and uncertainties. One clear step for the sedimentary basins is to assess the variability in well data that is not represented in the final model. As we discussed, these data measure interval transit times over borehole distances of less than 1 m, whereas the velocity model uses smoothed (25 m sampled) versions of these data. To make this assessment, we compared observations directly with the velocity values represented at 108 well bore locations in the Los Angeles basin. Our analysis shows a standard deviation of 6.5% around a mean of 1.0 for the ratio between compressional wave slowness in logs and the model in a population of ca. 1.1 million samples. This corresponds to a standard deviation in V_P of $\pm$99 m/s at 2000 m/s.

For general descriptions of resolution of the crust and mantle velocity representations, readers are referred to *Hauksson* (2000), *Tape et al.* (2009, 2010), and *Prindle and Tanimoto* (2006). Given that the USR described here is assembled from several different data sets and models, not from any single inversion, there is no formal assessment of resolution. There are, however, several possibilities for evaluating complex seismic velocity models such as the CVM. We review them here in order to highlight some possible future directions, as well as to demonstrate some of the challenges that arise from constructing a model from many different data sets across different scales. Any seismic velocity model could be interrogated with a wide range of different data sets, such as gravity data, teleseismic data (e.g., receiver functions), ambient-noise cross correlations, regional earthquake data, wide-angle seismic refraction data, and seismic reflection data. The basic approach is to compare the synthetic wavefield predicted by the model with the observed wavefield, by formally evaluating some measure of misfit. For such comparisons, a key choice is the frequency content of the seismic data; filtering at higher frequencies will decrease the quality of predictive capability of the velocity model. Much of the data used in the CVM are from well logs that provide direct measurements of V_P within the sedimentary basins. However, most regions of southern California could be evaluated by comparing wavefield predictions from CVM with the observed wavefield for regional earthquakes that were not used in constructing the crustal model (*Tape et al.*, 2009).

Model comparisons can be made either by comparing seismic velocities between two models or by comparing misfit measures for two models, whereby an independent set of observations is used to evaluate the misfit for each model. The recent study of *Lee et al.* (2014a,b) provides comparisons between a previous version of the model described here and a new iteration of their model. Their comparison was made for regional earthquakes for periods of 5!s and longer and provides a quantitative evaluation of the longer length scale features, especially for V_S, in the CVM.

A comprehensive estimation of uncertainties associated with large and complex models such as CVM is not currently tenable due to computational limitations. Uncertainties could be obtained by separately perturbing each grid point within the CVM and then evaluate the change in misfit due to the perturbation. This would require having as large a set of reference data as possible, spanning from the well log scale to the crustal and mantle scales. Certain gridpoints could be perturbed a lot without impacting the misfit; these grid points would have large uncertainties. Other gridpoints, such as those constrained by well logs, could not be perturbed much; these would have small uncertainties. Some information on uncertainties could be obtained with fewer simulations by perturbing the entire model with Gaussian random fields to evaluate how the strength and length scale of the perturbations affect the misfit assessment. The resolution of a model is a characterization of the length scales of features that can be reliably determined within a formal tomographic inversion. The classical model used in seismology for resolution tests are checkerboard patterns (in 2D and 3D). These tests have been performed for 3D reference models (*Chen et al.*, 2007; *Lee et al.*, 2014a,b); however, for gradient-based methods the computational cost of the resolution test is comparable to the inversion itself (*Fichtner et al.*, 2009).

References

Boore, D. M., and W. B. Joyner (1997), Site amplifications for generic rock sites, *Bull. Seis. Soc. Am.*, *87*(2), 327–341.

Brocher, T. M. (2005), Empirical relations between elastic wavespeeds and density in the Earth's crust, *Bull. Seis. Soc. Am.*, *95*(6), 2081–2092.

Chen, P., L. Zhao, and T. H. Jordan (2007), Full 3D tomography for the crustal structure of the Los Angeles region, *Bull. Seis. Soc. Am.*, *97*(4), 1094–1120.

Ely, G., T. H. Jordan, P. Small, and P. J. Maechling (2010), A V_{S30}-derived near-surface seismic velocity model, Abstract S51A-1907 presented at 2010 Fall Meeting, AGU, San Francisco, Calif., 13-17 Dec.

Fichtner, A., B. L. N. Kennett, H. Igel, and H.-P. Bunge (2009), Full seismic waveform tomography for upper-mantle structure in the Australasian region using adjoint methods, *Geophys. J. Int.*, *179*, 1703–1725.

Hauksson, E. (2000), Crustal structure and seismicity distribution adjacent to the Pacific and North America plate boundary in southern California, *J. Geophys. Res.*, *105*(B6), 13,875–13,903.

Lee, E.-J., P. Chen, T. H. Jordan, P. B. Maechling, M. A. M. Denolle, and G. C. Beroza (2014a), Full-3-D tomography for crustal structure in Southern California based on the scattering-integral and the adjoint-wavefield methods , *J. Geophys. Res. Solid Earth*, *119*, 6421–6451, doi:10.1002/2014JB011346.

Lee, E.-J., P. Chen, and T. H. Jordan (2014b), Testing waveform predictions of 3D velocity models against two recent Los Angeles earthquakes, *Seis. Res. Lett.*, *85*(6), 1275–1284.

Prindle, K., and T. Tanimoto (2006), Teleseismic surface wave study for S-wave velocity structure under an array: Southern California, *Geophys. J. Int.*, *166*, 601–621.

Tape, C., Q. Liu, A. Maggi, and J. Tromp (2009), Adjoint tomography of the southern California crust, *Science*, *325*, 988–992.

Tape, C., Q. Liu, A. Maggi, and J. Tromp (2010), Seismic tomography of the southern California crust based on spectral-element and adjoint methods, *Geophys. J. Int.*, *180*, 433–462.

Wills, C. J., and K. B. Clahan (2006), Developing a map of geologically defined stie-condition categories for California, *Bull. Seis. Soc. Am.*, *96*(4A), 1483–1501.