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Integration of controlled and passive sources used to generate a tomographic image of the Santa Monica basin.

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Damage during the 1994 Northridge earthquake was anomalously concentrated in Santa Monica, California. Aftershock studies suggest that the basin substructure caused localized amplification of seismic waves by focusing the energy. However, the geometry and velocities of the geological structure are uncertain, relying on extrapolation from widely separated boreholes. We present results of a tomographic study, which includes inverting over 30,000 travel times from a seismic array experiment on a 194-station array and a 10-km long Vibroseis, survey. We find that the damage zone is located above a subbasin several kilometers deep where low-velocity sediments of the northeastern Los Angeles basin are separated from higher velocity rocks of the Santa Monica Mountains by the steeply dipping Santa Monica-Portrero Canyon fault zone. Three-dimensional ray tracing through this structure shows that focusing of rays from the Northridge earthquake epicenter occurs in the region where damage was greatest and where aftershock amplitudes are magnified.

The primary data are earthquake and explosion P-wave arrival times measured on our portable seismic array and Vibroseis arrival times measured on the Vibroseis profile. The seismic array experiment took place from 14 to 26 October 1999, with shots recorded from 20 to 24 October 1999 and earthquakes recorded over the whole period. The Vibroseis experiment took place from 19 to 24 June 2000. The seismic array experiment involved continuous recording of shots and earthquakes on 75 seismic stations with (Reftek) high-capacity recorders and recording of the shots at an additional 119 low-capacity recorders (Texans, SGR's, and EDA's). The experiment was designed to use diving waves generated by earthquakes and explosions that would refract through the structures beneath Santa Monica. The Vibroseis experiment traversed along a 10-km line with groups of geophones placed every 30-m and vibes every 60 m. The whole line (345 stations) was active for each vibe.

The tomographic inversion uses a computer algorithm (SIMUL2000), originally developed by Thurber (1983) and was modified to include flexible gridding by Thurber and Eberhardt-Phillips (1999). The inversion of the data determines a perturbation from an initial model that improves the fit of the model to observed travel times. A three-dimensional grid of points represents the initial velocity model, with velocities linearly interpolated between the points. Our model extended in the north-south direction from the San Fernando Valley to Marina Del Rey and in the east-west direction from West Los Angeles to several kilometers offshore. The lateral grid spacing was chosen to be denser (0.3 km spacing) near the Santa Monica fault, incrementally increasing to 5.0 km spacing on the periphery. Our model extended in depth from 0.0 to 40.0 km. The eight upper layers are separated by 0.5 km and the grid layers increased in spacing to 8 km in the depth range 4 –40 km. The initial velocities were taken from the current SCEC velocity model (Magistrale et al., 1992).

After inversion of the 30,339 travel time data using the Local Earthquake Tomography algorithm (SIMUL2000), the standard deviation of the residuals decreased from 0.291s for the starting model to 0.105 s for the final model. The standard deviations of the velocities were on average 9%. In general, individuals nodes were poorly resolved ($R<0.1$); thus clusters of adjacent nodes are resolved at about 0.5 km resolution, except near the surface in the vicinity of the Vibroseis line, where the resolution is about 0.1 km.

A three-dimensional ray-tracing program (P. Davis, pers. comm.) was used to determine if the velocity model could reproduce the effect of focusing and to locate where focused rays intersect at the surface. Rays were traced from the Northridge earthquake hypocenter into northwest Santa Monica. The ray-tracing program used the three-dimensional equations by Cerveny et al. (1977). The ray path from the source to receiver was calculated in fresnel path increments determined from the spatial gradients of the velocity field. The process of ray path extension was repeated until either the ray traversed out of the model volume before reaching the surface, or the ray reached the surface. In either case, the ray-termination point was plotted. The three-dimensional ray tracing through this structure shows that focusing –clustering of ray termination points- occurs in the region where damage was greatest and where aftershock amplitudes are magnified.