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A STANDARD THREE-DIMENSIONAL SEISMIC VELOCITY MODEL FOR SOUTHERN CALIFORNIA

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SUMMARY

The southern california earthquake center (scec) has initiated an effort to develop a single standard 3d velocity model of southern california capable of supporting research needs in of strong ground motion simulations, tectonic studies, tomographic imaging, and earthquake location. We describe the development of version 1 of the model and outline the plans for version 2. The model consists of the major populated basins (los angeles basin, ventura basin, san gabriel valley, san fernando valley, and san bernardino valley) embedded in a crust with velocity smoothly varying with depth, over a constant depth moho, and fits a range of geological and geophysical observations. The model is parameterized as a set of objects and rules that are used to generate any 3d mesh of seismic velocity and density values (at length scales appropriate for different uses). This parameterization is convenient to store, transport, and update as new information and verification results become available.

INTRODUCTION

The dense population and active tectonics of southern California necessitate extensive seismic hazard evaluations that include precise earthquake location determinations, path effect studies and strong ground motion simulations. These studies require a realistic three-dimensional (3D) seismic velocity model with a spatial scale appropriate for each application. The Southern California Earthquake Center (SCEC) has an ongoing effort to develop a single standard 3D velocity model capable of supporting all these needs. Here, we describe the development of Version 1 of the model, and some of the current efforts to produce Version 2.

The model is constructed from geological, geophysical, and geotechnical data. The model is parameterized as a set of objects (constructed from those data) and rules implemented in a computer code that generates any 3D mesh of seismic velocity and density values. This parameterization is convenient to store, transfer, and update as new information and verification results become available. It allows any distribution of velocities; for example, fast-over-slow velocities are easily modeled. Version 1 of the model (Figure 1) consists of the major populated southern California basins (Los Angeles basin, Ventura basin, San Gabriel Valley, San Fernando Valley, Chino basin, and San Bernardino Valley) embedded in a crust with velocity smoothly varying with depth, over a constant depth Moho. We achieve a fine spatial resolution by the use of geologic information to constrain the locations and ages of structural and stratigraphic boundaries.

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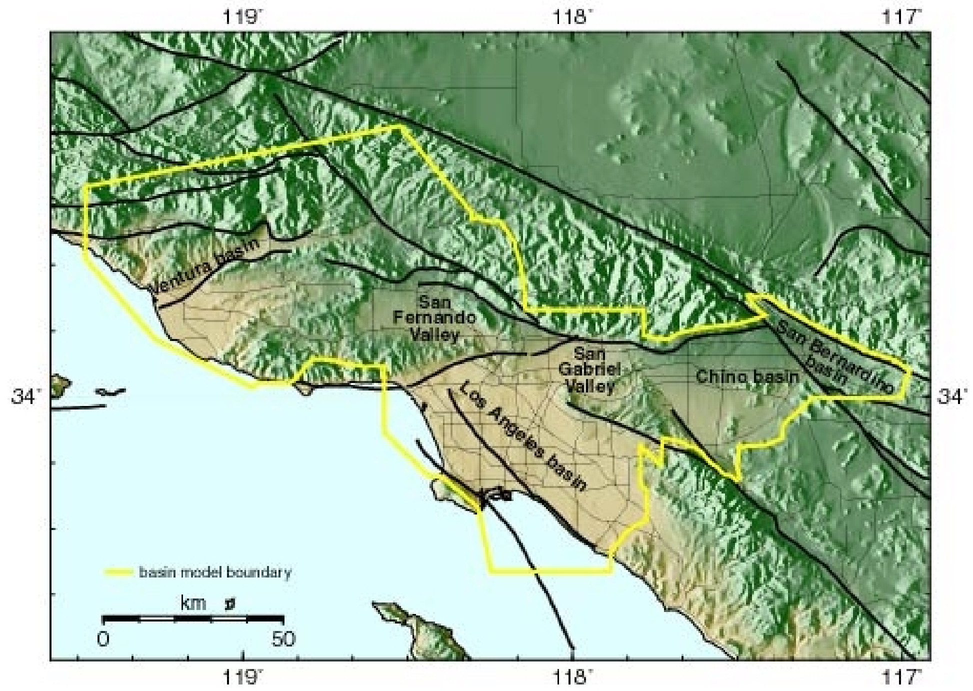

Figure 1. Location map showing seismic velocity model extent and basin names.

MODEL CONSTRUCTION

Reference Surfaces and Rule Definition

There exists a great deal of information about the age and depth of the sediments in the basins of southern California from oil and water exploration activities and other geologic studies (Figure 2). From this information we define reference surfaces (objects) of known depth and age in the detailed portion of the model representing the sedimentary basins. We examine structural cross sections and maps to define widespread, well-defined reference surfaces representing stratigraphic horizons, sediment-basement contacts, and faults (many of the surfaces are in multiple pieces). The maps and cross sections are digitized, and the reference surfaces are carefully interpolated and resampled on regular grids with a spacing of 100 to 300 meters. Uplift of each reference surface is estimated, or is sometimes explicitly mapped [*e.g.*, Wright, 1991].

Faust [1951] examined well surveys from North America and determined an empirical relation between sediment age, depth, and P-wave seismic velocity:

$$v = k\,(da)^{1/6} \tag{1}$$

where v is P-wave velocity, d is the maximum depth of burial of the sediments, a is the sediment age, and k is a constant. The one-sixth power reflects the tendency of sediments to compact as they are buried and to indurate as they age [Dobrin, 1976]. Age at any point in a basin can be interpolated from the reference surfaces. The constant k is calibrated for each basin by comparison to oil well sonic logs and seismic refraction surveys. At each point of interest within a basin (defined by a latitude, longitude, and depth) for which the velocity is desired: (1) The age of the point is interpolated by comparing the point depth to the depths and ages of the reference surfaces at the same latitude and longitude. (2) The maximum depth of burial is found by correcting the current depth by the any known amount of uplift. (3) The P-wave velocity is determined from the Faust equation. (4) Other physical parameters are derived: density is found from the P wave velocity using the relation of Nafe and Drake [1960]; density is used to find Poisson's ratio with the relation of Ludwig et al. [1970]; S-wave velocity is calculated from the P-wave velocity and Poisson's ratio. Outside and below the basins, velocities are assigned according to a smoothed version of the regional seismic model of Hadley and Kanamori [1977].

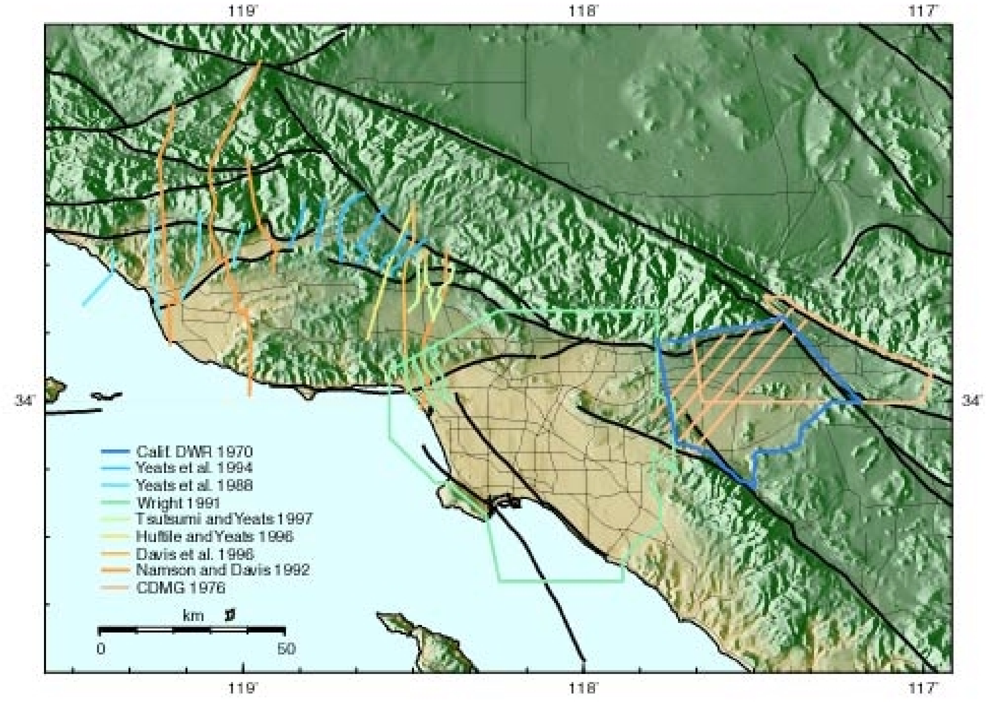

Figure 2. Sources of basin reference surface information.

Los Angeles basin and San Gabriel Valley

Wright [1991], in an extensive summary, presents structure-contour maps of two widespread sediment stratigraphic horizons: the base of the Repetto Formation, about 4.5 Ma; and the base of the Mohnian Stage, about 14 Ma. Age control of the stratigraphic horizons is from microfossils [e.g., Blake 1991]. Wright [1991] also presents a contour map of the amount of uplift during the Pasadenan deformation (3.5 Ma to present); this is used to correct current sediment depths to depth of maximum burial. McCulloh [1960] and Yerkes *et al.* [1965] show a structure-contour map of the top of crystalline basement rocks. The age we use of this horizon is not the rock age, but rather an early Miocene age (20 Ma) that just predates the development of major basement relief and so dates the base of the sediment fill. The age and distribution of material at the ground surface is indicated on California Division of Mines and Geology (CDMG) geologic maps [Jennings 1962, Rogers 1965; 1967, Jennings and Strand 1969].

The Santa Monica area within the Los Angeles basin is of particular interest to strong motion modelers because of the unexpectedly high damage to the area from the Northridge earthquake. Wright [1991] shows four detailed cross sections that we use to refine the Mohnian, Repetto, and basement surfaces in that area.

We calibrate the model by adjusting the constant k in the Faust relation (equation 1) to match seven oil well sonic logs (Figure 3) in the Los Angeles basin and the San Gabriel Valley [Brocher *et al.* 1998]. In the Los Angeles basin, $k = 197$; in the San Gabriel Valley, $k = 218$. The sonic logs indicate a velocity inversion within the sediments of the San Gabriel Valley, occurring at a constant fraction of the depth to the Mohnian reference surface, allowing a straightforward inclusion of the inversion into the model.

This version of the Los Angeles basin and the San Gabriel Valley differs from a previous version [Magistrale *et al.* 1996] in the different values of k, the San Gabriel Valley velocity inversion, and the Santa Monica area details.

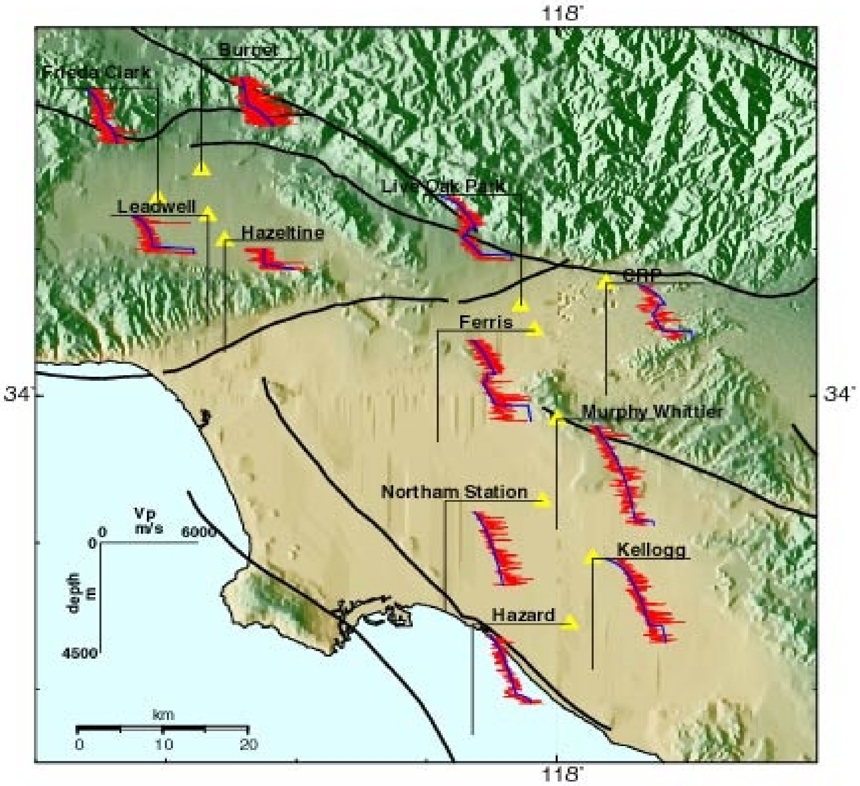

Figure 3. The fit of the model velocities (blue lines) to oil well sonic logs (red lines). Yellow triangles indicate oil well locations.

San Fernando Valley and Ventura basin

The San Fernando Valley and the Ventura basin share similar stratigraphy and so are considered together. Yeats *et al.* [1988], Namson and Davis [1992], Yeats *et al.* [1994], Huftile and Yeats [1996], Davis *et al.* [1996], and Tsutsumi and Yeats [1999] present structural cross sections of the San Fernando Valley and the Ventura basin from which we define 12 reference surfaces in 57 pieces. The lateral extent of the reference surfaces at the Earth's surface is from a CDMG geologic map [Jennings and Strand 1969].

The reference surfaces in the Ventura basin have ages of 0.5, 1.0, 1.5, 2.3, 5.0, 24, 37, 47, 67, 75, and 100 Ma; lacking independent calibration, we set k=180 for all those surfaces. In the San Fernando Valley, the 1.0, 1.5, 24, and 47 Ma surfaces are not present, and a 2.0 Ma age is used for the surface assigned the 0.5 Ma age in the Ventura basin. Four oil well sonic logs (Figure 3) are available in the San Fernando Valley [Brocher *et al.* 1998]; from these we determine a different k for each reference surface (k=189, 189, 160, 180, 123, 180, 180 for the 2.0, 2.3, 5.0, 37, 67, 75, and 100 Ma surfaces, respectively). We correct current sediment depth to maximum depth of burial by calculating the average depth of each reference surface and, because the strata are deformed largely by relatively recent (< 1 Ma, *e.g.,* Huftile and Yeats 1995) activity, assume any depth above the average depth was formerly at least as deep as the average. If the current depth is below the average depth, the current depth is used as the maximum depth of burial.

This version of the San Fernando Valley is completely different from, and supplants, a previous version [Magistrale *et al.* 1996].

San Bernardino and Chino basins

The Chino and San Bernardino basins are shallow (generally < 1 km deep) basins filled mostly with terrestrial sediments. We use structural cross sections and maps of the depth to the base of water bearing strata from Department of Water Resources [1970] and Fife *et al.* [1976] to define three reference surfaces: a 14.5 Ma Mohnian and a 6.0 Ma Miocene (both limited to the westernmost portion of the Chino basin), and the base of the water bearing strata. The age and distribution of material at the ground surface is from CDMG geologic maps [Rogers 1965; 1967].

Hadley and Combs [1974] obtained a seismic refraction profile in San Bernardino basin. We note that the top of their 2.9 km/s P-wave velocity layer corresponds to the base of the water bearing strata, and we interpret the top of that layer to correspond to the top of weathered crystalline basement rock. Below the 2.9 km/s layer is a 5.3 km/s layer that we interpret to represent hard rock, and we define a hard rock reference surface at a constant depth below the weathered basement surface to mark the bottom of the basin. We compare model velocity profiles to the seismic refraction profile and calibrate the model by adjusting the nominal ages of the weathered and hard basement surfaces (while keeping *k* fixed at 180) to match the refraction results. The final ages are 6.0 and 16.5 Ma, respectively.

Frankel [1993] combined the Hadley and Combs [1974] refraction profile and water well logs to develop a model of the San Bernardino basin to use in ground motion simulations. That model used the base of water bearing strata in the well logs and the top of the 5.3 km/s refraction profile layer to define the top of the basement, and thus is dominated by a deep basement trough at the refraction profile site. The current basin model differs greatly by having a relatively flat bottom.

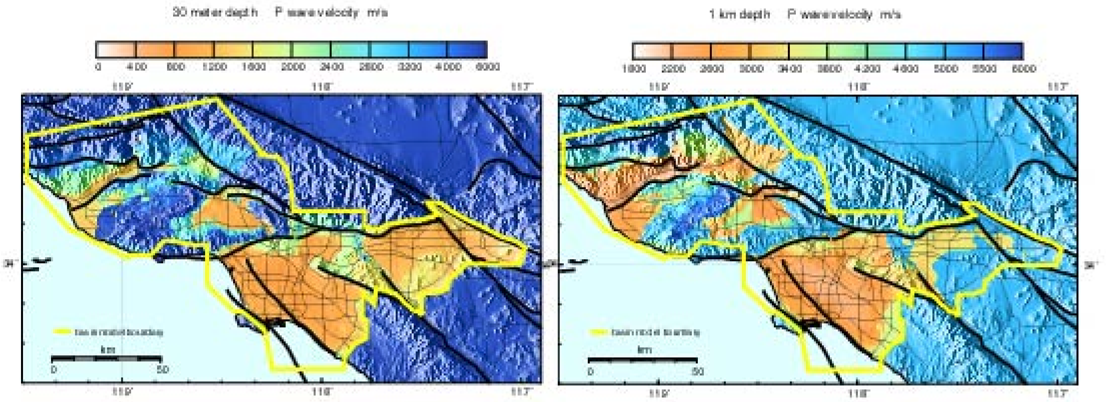

Figure 4. Slices through the Version 1 model showing P-wave velocity at 30 m (left) and 1 km (right) depth. Velocity scales differ in each panel.

Next Version Model

Version 1 of the model (Figures 4 and 5) is being tested by: (1) The ability of the model to produce synthetic waveforms that match observations of the Landers and Northridge earthquakes. (2) The ability of the model to match earthquake travel times. (3) How well the model matches newly released data, such as oil well sonic logs.

Version 2 of the model is planned to include: (1) Direct constraints on near surface velocities from geotechnical borehole logs. Vp, Vs, and density data are available, permitting development of local velocity-density relationships. (2) Additional oil well sonic logs. These can be used to refine the current Faust equation parameters, or may be spaced densely enough to define isovelocity reference surfaces that could be used with a velocity interpolation rule between surfaces. (3) Adding the Salton trough. A model based on seismic refraction results has been developed. (4) Bedrock velocities from local earthquake tomography. Crustal velocities outside the basins can be defined more realistically by integrating the basin model with the results of tomographic inversions. Also, tomography can help to constrain sediment velocities in basins where we lack independent data to calibrate the model. (5) A depth varying Moho. Moho depth variations are being determined with a receiver function technique using broadband data recorded at dozens of sites; the depth determinations will account for local Vp/Vs crustal variations. (6) Upper mantle velocities determined from teleseismic tomographic studies.

Availability

Version 1 and, when ready, Version 2 of the standard three-dimensional seismic velocity model for southern California are available as a FORTRAN or C source code and associated files on the SCEC Data Center website at http://www.scecdc.scec.org.

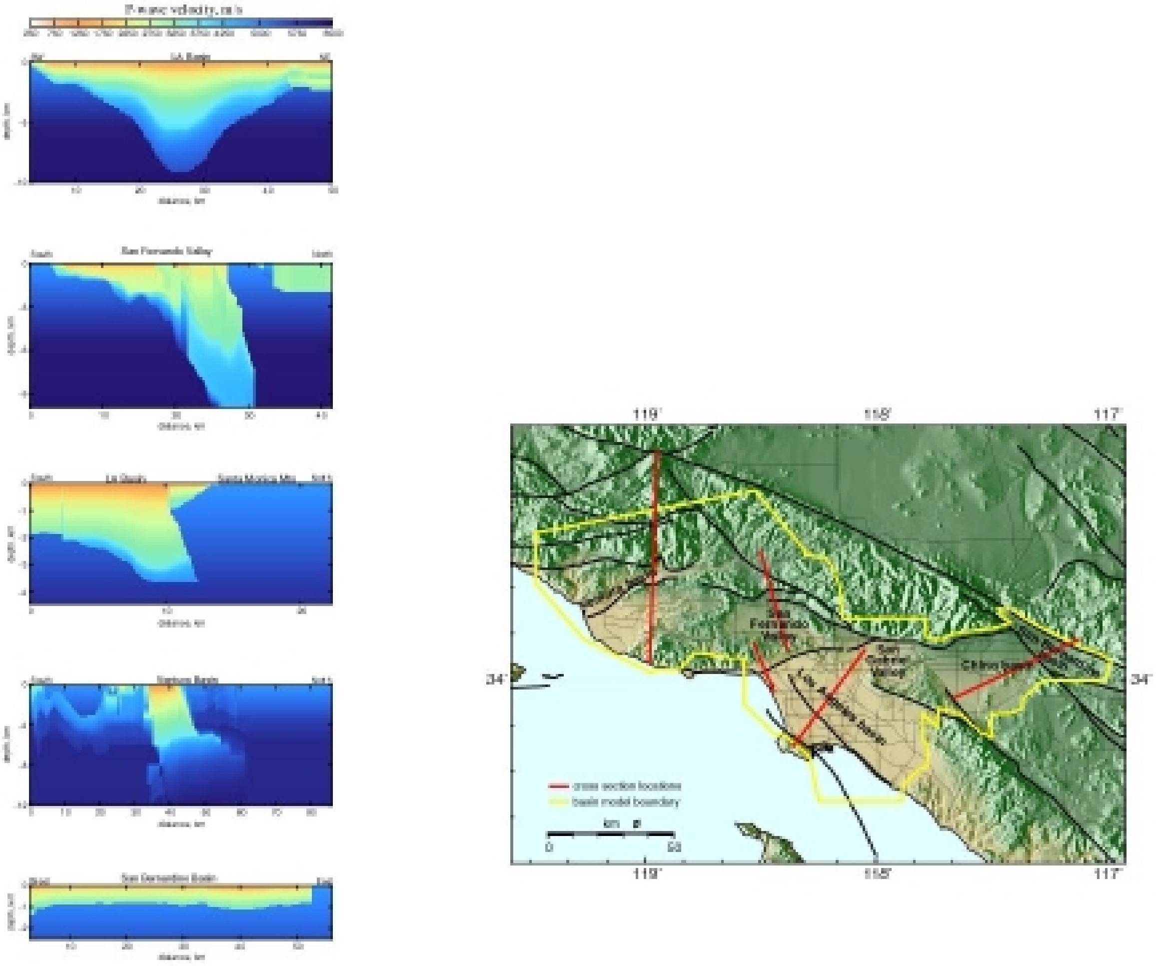

Figure 5. Cross sections (left panels, velocity scale the same for all panels) of the Version 1 model showing P-wave velocity. Cross section locations shown as red lines in right panel.

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