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Unified Structural Representation of the southern California crust and upper mantle

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ABSTRACT

We present a new, 3D description of crust and upper mantle velocity structure in southern California implemented as a Unified Structural Representation (USR). The USR is comprised of detailed basin velocity descriptions that are based on tens of thousands of direct velocity (Vp, Vs) measurements and incorporates the locations and displacement of major fault zones that influence basin structure. These basin descriptions were used to developed tomographic models of crust and upper mantle velocity and density structure, which were subsequently iterated and improved using 3D waveform adjoint tomography. A geotechnical layer (GTL) based on Vs30 measurements and consistent with the underlying velocity descriptions was also developed as an optional model component. The resulting model provides a detailed description of the structure of the southern California crust and upper mantle that reflects the complex tectonic history of the region. The crust thickens eastward as Moho depth varies from 10 to 40 km reflecting the transition from oceanic to continental crust. Deep sedimentary basins and underlying areas of thin crust reflect Neogene extensional tectonics overprinted by transpressional deformation and rapid sediment deposition since the late Pliocene. To illustrate the impact of this complex structure on strong ground motion forecasting, we simulate rupture of a proposed M 7.9 earthquake source in the Western Transverse Ranges. The results show distinct basin amplification and focusing of energy that reflects crustal structure described by the USR that is not captured by simpler velocity descriptions. We anticipate that the USR will be useful for a broad range of simulation and modeling efforts, including strong ground motion forecasting, dynamic rupture simulations, and fault system modeling. The USR is available through the Southern California Earthquake Center (SCEC) website (http://www.scec.org).

1. Introduction

Recent advances in numerical methods and parallel computing technology have enabled large-scale 3D simulations of seismic

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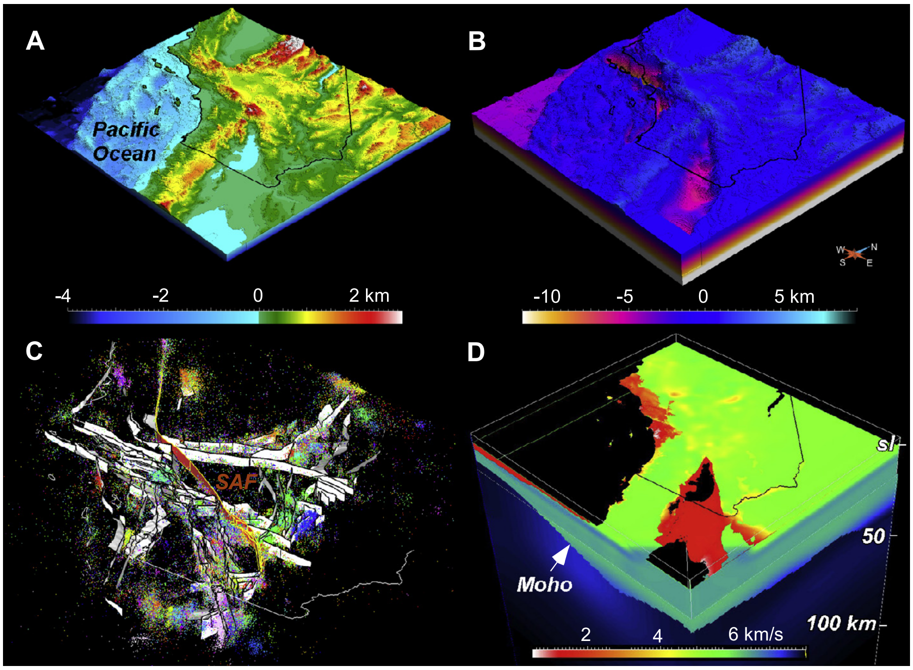

Fig. 1. Perspective view of components of the Unified Structural Representation (USR). A) Topography and bathymetry; B) top basement surface; C) Community Fault Model (CFM) (Plesch et al., 2007); and D) USR showing Vp. SAF is the San Andreas fault. Topographic and bathymetric surfaces are derived from USGS 3″ digital elevation model data and a National Oceanic and Atmospheric Administration 30″ grid (TerrainBase).

wavefields in realistic earth models (e.g., Olsen et al., 1995; Komatitsch and Tromp, 1999; Komatitsch et al., 2004; Bielak et al., 2010). These simulations are able to capture the effects of basin amplification, resonance, wave focusing, and dynamic rupture propagation. Thus, they offer a physics-based alternative to attenuation relationships (e.g., Abrahamson and Silva, 1997, 2008; Field, 2000; Boore and Atkinson, 2008) for forecasting the distribution of hazardous ground shaking during large earthquakes (e.g., Zhao et al., 2000; Tromp et al., 2005; Tarantola, 1984; Chen et al., 2007). These methods also provide an objective, quantitative means of using seismic observations to improve 3D earth models. The revised models, in turn, help make strong ground motion forecasts more accurate.

To facilitate these and other studies, we present a Unified Structural Representation (USR) of southern California (Fig. 1). The USR consists of two major components: a 3D description of seismic wavespeeds (Vp, Vs) and density (ρ), known as a community velocity model (CVM); and a 3D description of the major fault systems in the region, known as a community fault model (CFM). The CVM includes a framework of geologic horizons that define the various rock units in the region and integrates a wide range of direct observations that define velocity structure. These include tens of thousands of velocity measurements in boreholes, as well as constraints from seismic reflection and refraction studies in sedimentary basins. The basin structures are used to develop travel time tomographic models of the crust and upper mantle extending to a depth of 33 km, and a teleseismic shear wave model of the upper mantle to a depth of 150 km. This combined velocity model was then subjected to a series of 3D adjoint tomographic inversions that highlight areas of the starting model that were responsible for mismatches between observed and synthetic waveforms (Tape et al., 2009, 2010). Sixteen tomographic iterations, requiring 6800 fully 3D wavefield simulations, yielded perturbations to the starting model that have been incorporated into the current CVM. The second component of the USR is the CFM, which provides 3D descriptions of the major fault systems in southern California that are considered to pose earthquake hazards. These 3D fault representations are defined by surface geology, earthquake hypocentral locations, focal mechanisms, well, and seismic reflection data. The USR provides compatible fault and velocity models, in which the locations and displacements of major faults are explicitly represented in the velocity descriptions.

2. Tectonic history and structure

Southern California sits astride a tectonic plate boundary that has been active for at least 200 million years. Beginning in the Jurassic Period, subduction of oceanic crust beneath North America created the Sierra Nevada arc and associated igneous terrains, a widespread series of forearc deposits including the Great Valley sequence, and the Franciscan accretionary complex, which is exposed in the Coast Ranges (e.g., Hamilton, 1969; Ernst, 1970; Dickinson, 1981; Cowan and Bruhn, 1992). These north–south trending elements define the primary tectonic fabric and bedrock geology of the state (Fig. 2). In southern California, these features have been displaced and overprinted by two Tertiary tectonic events. In the Neogene, parts of the southern California continental lithosphere were captured by the Pacific plate and moved obliquely away from North America (Nicholson et al., 1994). This motion led to the clockwise rotation of the Transverse Ranges (Luyendyk et al., 1985; Kamerling and Luyendyk, 1985; Hornafius et al., 1986), the opening of the Inner California Continental Borderland, and development of a series of deep sedimentary basins along the southern California coast (Crouch and Suppe, 1993). In the Pliocene, seafloor spreading in the Gulf of California and development of the modern San Andreas transform system (Hill and Dibblee, 1953; Atwater, 1970; Allen, 1957, 1981; Curray and Moore, 1984) led to a transpressional tectonic regime (Zoback et al., 1987) that further displaced and locally reactivated the earlier rift and subduction zone structures. This tectonic regime drives present-day deformation of the southern California lithosphere (Minster and Jordan, 1978; Bird and Rosenstock, 1984; Humphreys and Hager, 1990; Meade and Hager, 2005), and is characterized by right-lateral strike-slip motion on the San Andreas, San Jacinto, Eastern Califor-