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# 1 **Unified Structural Representation of the southern California** 2 **crust and upper mantle**

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31 **Abstract**

32 We present a new, 3D description of crust and upper mantle velocity structure in  
33 southern California implemented as a Unified Structural Representation (USR). The  
34 USR is comprised of detailed basin velocity descriptions that are based on tens of  
35 thousands of direct velocity ( $V_p$ ,  $V_s$ ) measurements and incorporates the locations and  
36 displacement of major fault zones that influence basin structure. These basin  
37 descriptions were used to developed tomographic models of crust and upper mantle  
38 velocity and density structure, which were subsequently iterated and improved using 3D  
39 waveform adjoint tomography. A geotechnical layer (GTL) based on  $V_s30$   
40 measurements and consistent with the underlying velocity descriptions was also  
41 developed as an optional model component. The resulting model provides a detailed  
42 description of the structure of the southern California crust and upper mantle that reflects  
43 the complex tectonic history of the region. The crust thickens eastward as Moho depth  
44 varies from 10 to 40 km reflecting the transition from oceanic to continental crust. Deep  
45 sedimentary basins and underlying areas of thin crust reflect Neogene extensional  
46 tectonics overprinted by transpressional deformation and rapid sediment deposition  
47 since the late Pliocene. To illustrate the impact of this complex structure on strong  
48 ground motion forecasting, we simulate rupture of a proposed M 7.9 earthquake source  
49 in the Western Transverse Ranges. The results show distinct basin amplification and  
50 focusing of energy that reflects crustal structure described by the USR that is not  
51 captured by simpler velocity descriptions. We anticipate that the USR will be useful for a  
52 broad range of simulation and modeling efforts, including strong ground motion  
53 forecasting, dynamic rupture simulations, and fault system modeling. The USR is  
54 available through the Southern California Earthquake Center (SCEC) website  
55 ([www.scec.org](http://www.scec.org)).

56

57 Key words: velocity structure; fault models; southern California; tomography; seismic  
58 wave propagation; strong ground motions

59

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68

69

## 70 **1. Introduction**

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

82

83 To facilitate these and other studies, we present a Unified Structural Representation  
84 (USR) of southern California (Fig. 1). The USR consists of two major components: a 3D  
85 description of seismic wavespeeds ( $V_p$ ,  $V_s$ ) and density ( $\rho$ ), known as a community  
86 velocity model (CVM); and a 3D description of the major fault systems in the region,  
87 known as a community fault model (CFM). The CVM includes a framework of geologic  
88 horizons that define the various rock units in the region and integrates a wide range of  
89 direct observations that define velocity structure. These include tens of thousands of  
90 velocity measurements in boreholes, as well as constraints from seismic reflection and  
91 refraction studies in sedimentary basins. The basin structures are used to develop travel  
92 time tomographic models of the crust and upper mantle extending to a depth of 33 km,  
93 and a teleseismic shear wave model of the upper mantle to a depth of 150 km. This  
94 combined velocity model was then subjected to a series of 3D adjoint tomographic  
95 inversions that highlight areas of the starting model that were responsible for  
96 mismatches between observed and synthetic waveforms (Tape et al, 2009; 2010).  
97 Sixteen tomographic iterations, requiring 6,800 fully 3D wavefield simulations, yielded  
98 perturbations to the starting model that have been incorporated into the current CVM.  
99 The second component of the USR is the CFM, which provides 3D descriptions of the  
100 major fault systems in southern California that are considered to pose earthquake  
101 hazards. These 3D fault representations are defined by surface geology, earthquake  
102 hypocentral locations, focal mechanisms, well, and seismic reflection data. The USR  
103 provides compatible fault and velocity models, in which the locations and displacements  
104 of major faults are explicitly represented in the velocity descriptions.

105

## 106 **2. Tectonic history and structure**

107 Southern California sits astride a tectonic plate boundary that has been active for at least  
108 200 million years. Beginning in the Jurassic Period, subduction of oceanic crust beneath

109 North America created the Sierra Nevada arc and associated igneous terrains, a  
110 widespread series of forearc deposits including the Great Valley sequence, and the  
111 Franciscan accretionary complex, which is exposed in the Coast Ranges (e.g., Hamilton,  
112 1969; Ernst, 1970; Dickinson, 1981; Cowan and Bruhn, 1992). These north-south  
113 trending elements define the primary tectonic fabric and bedrock geology of the state  
114 (Fig. 2). In southern California, these features have been displaced and overprinted by  
115 two Tertiary tectonic events. In the Neogene, parts of the southern California continental  
116 lithosphere were captured by the Pacific plate and moved obliquely away from North  
117 America (Nicholson et al., 1994). This motion led to the clockwise rotation of the  
118 Transverse Ranges (Luyendyk et al., 1985; Kamerling and Luyendyk, 1985; Hornafius et  
119 al., 1986), the opening of the Inner California Continental Borderland, and development  
120 of a series of deep sedimentary basins along the southern California coast (Crouch and  
121 Suppe, 1993). In the Pliocene, seafloor spreading in the Gulf of California and  
122 development of the modern San Andreas transform system (Hill and Dibblee, 1953;  
123 Atwater, 1970; Allen, 1981; Curray and Moore, 1984) led to a transpressional tectonic  
124 regime (Zoback et al., 1987) that further displaced and locally reactivated the earlier rift  
125 and subduction zone structures. This tectonic regime drives present-day deformation of  
126 the southern California lithosphere (Minster and Jordan, 1978; Bird and Rosenstock,  
127 1984; Humphreys and Hager, 1990; Meade and Hager, 2005), and is characterized by  
128 right-lateral strike-slip motion on the San Andreas, San Jacinto, Eastern California Shear  
129 Zone, and other major northwest trending fault systems (Fig. 2). The Salton Trough has  
130 developed as a result of oblique rifting of Baja California away from Sonora Mexico and  
131 subsequent transfer of slip from the Imperial to the southern San Andreas fault, forming  
132 a pull-apart basin (Rockwell and Sylvester, 1979). Farther north, a major restraining  
133 bend in the San Andreas fault drives active deformation within the Transverse Ranges  
134 (Fig. 2), which is characterized by thrust and oblique reverse faulting (Reed and

135 Hollister, 1936; Namson and Davis, 1988; Yeats, 1988; Yeats et al., 1988; Shaw and  
136 Suppe, 1994). In the eastern part of the state, the crust is also being actively deformed  
137 by Basin and Range extensional tectonics (Wernicke et al., 1988; Burchfiel et al., 1987),  
138 which accommodates a component of Pacific and North American relative plate velocity  
139 (Minster and Jordan, 1978; DeMets et al., 1987). The Garlock fault, an active left-lateral  
140 strike slip system (Smith 1962; 1975; Smith and Ketner, 1970; Astiz and Allen, 1983;  
141 McGill and Sieh, 1993), defines the southern boundary of this Basin and Range  
142 extensional province and separates it from the Mojave region (Minster and Jordan,  
143 1987). The Mojave region is characterized by dextral slip on faults that comprise the  
144 Eastern California Shear Zone (Dokka and Travis, 1990; Savage et al., 1990).

145

146 This complex tectonic history is manifest in the geologic and geophysical structure of the  
147 southern California crust and upper mantle. The depth of the crust, defined by the  
148 Mohorovičić discontinuity, changes abruptly from about 10 km in the Pacific Plate to  
149 about 20 km in the continental shelf (Fig. 3). The crust generally continues to thicken  
150 eastward, with the Moho reaching a maximum depth of about 40 km (Yan and Clayton,  
151 2007; Tape et al., 2012). In central California, this eastward thickening reflects the  
152 transition from oceanic crust, through the Franciscan assemblage, the forearc sequence  
153 of the Great Valley, to the thick crustal roots of the Sierra Nevada arc. This pattern is  
154 made complex in southern California by the rotation and translation of the Western  
155 Transverse Ranges that unroofed the Inner California Borderland during the Neogene.  
156 Crustal thickness has also been affected by the Pliocene and Quaternary deepening of  
157 the coastal basins and formation of the Salton Trough along the southern San Andreas  
158 fault system. As a result, the crust is thickest (35 – 40 km) beneath the Transverse and  
159 Peninsular Ranges and thinnest ( $\approx 20$  km) beneath the coastal basins.

160

161 The stratigraphy and composition of the crust in southern California also reflects this  
162 region's tectonic history. Mesozoic to early Tertiary deposits are generally part of the  
163 forearc system, yet they have been dissected and displaced by Neogene and younger  
164 deformations. Neogene deposits are widespread in southern California, with the thickest  
165 accumulations occurring in rift and subsequently transpressional basins that formed in  
166 response to microplate capture, rotation of the Transverse Ranges, and opening of the  
167 Inner California Borderland (Nicholson et al., 1994; Crouch and Suppe, 1993). Thick  
168 Pliocene and younger deposits are localized in coastal basins such as Ventura and Los  
169 Angeles (Fig. 2) that continued to subside as a result of sedimentary and tectonic  
170 loading (Yerkes et al., 1987; Wright, 1991; Namson and Davis, 1988; Shaw and Suppe,  
171 1994).

172

173 The seismic wavespeed structure in southern California reflects this complex geologic  
174 history. In order to represent this structure accurately, we need to generate consistent  
175 representations of faults and basins, and to incorporate a variety of different types of  
176 data and models in a self-consistent manner. We term this a Unified Structural  
177 Representation, and describe in the following section how it was constructed.

178

### 179 **3. Development of a Unified Structural Representation**

180 The USR incorporates a variety of different velocity constraints, ranging in resolution  
181 from 10-cm-scale borehole observations in shallow sedimentary sections to 3D  
182 tomographic models that describe the upper mantle at scales of tens of kilometers.  
183 These components must be assembled in a way that ensures their internal consistency.  
184 Thus, we developed a workflow for building the USR that begins with the development of  
185 structural representations of the basins and parameterization of their internal velocity  
186 structures, including gradients associated with major faults. These basin models are



187 then used as input for the development of tomographic models of the crust and upper  
188 mantle. Integrated basin and tomographic models were subsequently evaluated and  
189 improved using 3D, adjoint waveform tomographic methods. Finally, a geotechnical layer  
190 based on Vs30 measurements was developed as an optional overprint to facilitate the  
191 model's use in strong ground motion studies and engineering applications. The following  
192 sections describe the development of each of these model components.

193

### 194 **3.1 Basin structures**

195 Deep sedimentary basins in southern California form significant velocity structures in the  
196 crust. These basins are generally filled with thick (> 10 km) sequences of relatively low  
197 velocity and density sediments that have been shown to amplify seismic waves and  
198 localize hazardous ground shaking during large earthquakes (e.g., Bonamassa and  
199 Vidale, 1991; Frankel and Vidale, 1992; Bouchon and Barker, 1996; Olsen, 2000;  
200 Graves et al., 1998; Bielak et al., 1999; Aagaard et al., 2001; Komatitisch et al., 2004;  
201 Minster et al., 2004; Graves et al., 2011). Thus, the first step in our development of the  
202 USR was to generate accurate descriptions of the 3D geometry and velocity structures  
203 of the major basins.

204

205 The initial step in representing basin structures was to identify stratigraphic horizons or  
206 surfaces that define the extent of basins or represent abrupt changes in velocities or  
207 velocity gradients. An analysis of our borehole data shows that several lithologic markers  
208 represent significant, laterally continuous velocity and density boundaries in the basins.  
209 The most important of these is the transition from sedimentary to basement rocks, which  
210 defines a major velocity discontinuity throughout most of southern California (Fig. 4).  
211 This sediment-basement boundary defines the depth and extent of the basins, and  
212 represents juxtaposition of different rock types and ages in various parts of the crust. In

213 the western Los Angeles basin, the California Borderland, and the Santa Barbara basin  
214 the sediments are generally underlain by Catalina schist and other metamorphic rocks  
215 that are part of the Franciscan subduction zone complex. In the eastern Los Angeles  
216 and San Bernardino basins the basement is generally formed by igneous rocks (Wright,  
217 1991; Crouch and Suppe, 1993). In the Ventura, Santa Maria, and Salton Trough basins,  
218 the basement surface represents a transition from Neogene and younger sedimentary  
219 rocks to early Tertiary and Mesozoic metasedimentary sequences (Fuis and Kohler,  
220 1984; Yerkes et al., 1987; Brankman, 2009; Namson and Davis, 1990; Lovely et al.,  
221 2006). In the Ventura and Santa Maria basins this boundary generally represents a  
222 distinct unconformity, whereas in the Salton Trough the top of basement likely  
223 represents a geothermal boundary that reflects the high present-day crustal heat flow in  
224 the region.

225

226 The depth and shape of the basement surface are highly variable across southern  
227 California, ranging from surface outcrops along the basin edges to depths of more than  
228 10 km in Ventura and Los Angeles (Fig. 1B). Surface outcrops of the basement surface  
229 were digitized from the California State geologic map (Jennings et al., 1977) with more  
230 local detail added based on the Dibble Map Series (e.g., Dibble, 2005). The subsurface  
231 location of the basement surface is defined directly by two primary types of data (Fig. 4).  
232 The first are well penetrations, generally acquired by the petroleum or geotechnical  
233 industries, which use cuttings and/or electric logs to define this lithologic boundary.  
234 Dozens of wells in the western Los Angeles, Ventura, and Santa Maria basins, and in  
235 the Inner California Borderland directly penetrate this horizon and are used as direct  
236 constraints on basin depth and shape (see Wright, 1991). The second type of constraint  
237 on the basement surface is provided by seismic reflection data. The petroleum industry  
238 has acquired tens of thousands of line kilometers of 2D seismic reflection profiles and

239 several 3D surveys in the southern California coastal basins and offshore. As the  
240 sediment-basement interface generally represents an abrupt velocity contrast, it is often  
241 imaged by a prominent reflector in these data (e.g., Legg and Nicholson, 1993; Shaw  
242 and Suppe, 1994; Bohannon and Geist, 1998; Rivero et al., 2011). The quality of the  
243 data, as well as the depth and magnitude of the impedance contrast across the surface,  
244 controls the character of this reflection and our ability to map it precisely. The basement  
245 reflector is best defined in surveys from the western Los Angeles basin, the California  
246 Borderland, and Santa Barbara basin. Moreover, the reflector is tied directly to well  
247 penetrations throughout these regions. Together, these surface geologic, well, and  
248 seismic reflection constraints define the basement surface throughout much of southern  
249 California. In areas where the basement is not directly defined, geologic cross sections  
250 (e.g., Namson and Davis, 1988; 1990; Shaw and Suppe, 1994, 1996; Huftile and Yeats,  
251 1995; Tsutsumi et al., 2001) and potential field studies (e.g., McCulloh, 1960) provide  
252 further estimates that help us generate a continuous basement surface (Fig. 1).

253

254 The shapes and velocity structures of the sedimentary basins in southern California are  
255 influenced significantly by the locations and displacement of major fault systems. The  
256 southern California crust contains more than 150 active faults that are deemed capable  
257 of generating moderate to large magnitude earthquakes (Plesch et al., 2007), as well as  
258 many other structures that were active in earlier tectonic periods (Fig. 1C). Neogene-age  
259 normal and strike-slip faults that accommodated rotation of the Western Transverse  
260 Ranges and opening of the Inner California Borderland localized the development of the  
261 major coastal basins (Luyendyk et al., 1985; Hornafius et al., 1986; Crouch and Suppe,  
262 1993; Nicholson et al., 1994). As such, these faults often bound basins and are related  
263 to many internal basin structures that influence basin shapes. Moreover, Pliocene and  
264 younger faulting has displaced the basement surface in many locations, producing

265 abrupt lateral contrasts in velocity between rocks and sediments. Thrust and reverse  
266 faults have, in some cases, displaced the basement over stratigraphic units leading to  
267 velocity inversions (i.e., downward decreases in velocity). These velocity inversions have  
268 been shown to be important in wave focusing and amplification (e.g., Graves et al.,  
269 1998), and thus it is important to represent them in models that are used for strong  
270 ground motion simulations.

271

272 To represent these faults in our basin structures, we developed in parallel a  
273 comprehensive 3D fault model (SCEC Community Fault Model [CFM]; see Plesch et al.,  
274 2007). This model represents faults as triangulated surface representations (tsurfs) that  
275 are defined by wells, seismic reflection profiles, geologic cross sections, earthquake  
276 hypocentral locations (e.g., Shearer et al., 2005; Lin et al., 2007), and focal mechanism  
277 solutions (Yang et al., 2012) (Fig. 1C). We use a subset of these fault representations,  
278 along with other faults that are no longer active and thus not included in the CFM, to help  
279 define our representations of the Los Angeles, Ventura, Santa Barbara, and Santa Maria  
280 basins. We included faults that had significant total displacements in two ways. Those  
281 that bounded the basins were used to model the shape of the basement horizon. Others  
282 were used to offset the basement surface (see Fig. 5).

283

284 Once the sedimentary basin volumes are defined by topography, bathymetry, and the  
285 basement surface, we parameterize the internal basin velocity structure. Direct  
286 measurements of seismic velocities are provided by several different types of  
287 observations. Velocities are recorded by sonic logs, which are wireline tools passed  
288 along a borehole that measure interval transit times between pairs of sound sources and  
289 receivers. These transit times are readily converted into interval velocities (Fig. 4). Most  
290 sonic logs measure only  $V_p$ ; however, dipole sonics acquired by the energy industry and

291 suspension logs in the geotechnical industry can evaluate both  $V_p$  and  $V_s$ . Active source  
292 experiments, including seismic refraction and reflection surveys, also provide estimates  
293 of seismic velocity. These data have been acquired in many of the southern California  
294 basins, and are most abundant in coastal and offshore basins that have been explored  
295 by the petroleum industry. In addition, industry reflection data typically provide stacking  
296 velocities, which can be converted to interval velocities. While these derived velocities  
297 are far less precise than those from sonic logs, they offer the advantage of broad  
298 coverage across basins and generally constrain velocities at depths that are greater than  
299 most well penetrations.

300

301 Based on these observations, previous velocity models in southern California have used  
302 several different approaches to parameterize sediment velocities. Magistrale et al.  
303 (2000) used a rule-based approach that defined  $V_p$  as a function of sediment age and  
304 depth using the method of Faust (1951). These relations were defined based on sonic  
305 logs, and the model was parameterized by mapping these functions to a sediment  
306 volume that included several geologic horizons of known age and depth. In a similar  
307 fashion, Brankman (2009) developed a simple non-linear function of velocity increases  
308 with depth in the Ventura basin. Lovely et al. (2006) developed a velocity  
309 parameterization for the Salton Trough that was based on sediment and total basin  
310 depths. Basin depth was shown to reflect sediment velocities in several wells because it  
311 correlated with changing sediment facies. All of these approaches, in general, are best  
312 suited to basins where velocity data are sparse and geologic units have simple, uniform  
313 velocity gradients with depth. In contrast, Suess and Shaw (2003) and Rivero et al.  
314 (2004) used geostatistical interpolations from direct velocity measurements to  
315 parameterize sediment velocities in the Los Angeles basin and Inner California  
316 Borderland, respectively. Tens of thousands of direct velocity measurements from

317 boreholes and stacking velocities, as well as variance analyses were used to define  
318 vertical and horizontal velocity correlation functions. Based on these functions, kriging  
319 techniques were then applied to parameterize sediment velocities. These resulting  
320 geostatistical parameterizations generally reflect the average velocity values manifest in  
321 the rule-based models, but exhibit a greater degree of complexity in internal basin  
322 structures (Suess and Shaw, 2003).

323

324 Basin structures in the USR were assembled in a manner that was compatible with  
325 these different types of sediment velocity parameterizations, as no single, effective  
326 approach could be implemented for all of the basin structures in southern California.  
327 Geostatistical parameterizations were used in the Los Angeles (after Suess and Shaw,  
328 2003) and Santa Maria (after Munster, 2007, and Shaw and Plesch, 2012) basins, and in  
329 the Inner California Borderland (after Rivero, 2004). Simple depth-dependent velocity  
330 descriptions were used in the Ventura (after Brankman 2009) and Salton Trough (after  
331 Lovely et al., 2006) basins. The San Bernardino basin was parameterized by a depth-  
332 dependent rule based on local well log data and seismologic studies (Stephenson et al.,  
333 2002; Anderson et al., 2004; and Graves, 2008). To blend these different local velocity  
334 parameterizations into a single USR, we used the basement surface to define the extent  
335 of different velocity parameterizations and simple smoothing techniques to ensure  
336 gradual changes between regions within the sedimentary volumes. Most of these  
337 junctures occurred at transitions from onshore to offshore basins.

338

### 339 **3.2 The crust and upper mantle**

340 The initial 3D crustal velocity model of southern California used in constructing the USR  
341 was determined by tomographic inversion based on local earthquake data (Hauksson,  
342 2000). We used the inversion code SIMULPS (Thurber, 1993) and travel time P and S-

343 P picks from the Southern California Seismic Network to determine gridded Vp and  
344 Vp/Vs models with linear interpolation between adjacent nodes. The starting model was  
345 similar to the standard southern California 1D layered model (Hutton et al. 2010) with a  
346 near-surface low velocity layer. First, we inverted for a 40 km horizontal and  $\approx 4$ km  
347 vertical spacing coarse grid-node model, followed by an interpolation to a refined grid  
348 (15 km horizontal and the same vertical spacing), and repeated the inversion.

349

350 To update the model by Hauksson (2000), we replaced the velocity values at nodes  
351 located within the basins with velocity values from the basin models described  
352 previously. We repeated the inversion using this new starting model with basin velocity  
353 values held fixed, and the same travel-time data set from Hauksson (2000). The final  
354 model exhibits lower average velocities in the near-surface, consistent with the basin  
355 representations, and slightly higher average velocities at depth.

356

357 Mantle structure was then modeled using teleseismic surface wave data, recorded by  
358 the California Integrated Seismic Network (CISN). A two-station waveform matching  
359 technique was developed for these network data (Prindle and Tanimoto, 2006) and was  
360 applied to 114 large earthquakes ( $M > 6.0$ ) to derive phase velocity variations. Rayleigh-  
361 wave phase velocity data for frequencies between 0.025 and 0.050 Hz (40 to 20s) and  
362 Love-wave phase velocity data between 0.030 and 0.045 Hz (33.3 to 22.2s) were  
363 retrieved by this method and used as inputs for subsequent mantle structure inversion.

364

365 For the inversion of upper mantle structure, the crustal structure, obtained from the  
366 previous basin descriptions and tomographic models, was held fixed. Also, because the  
367 lateral resolving wavelength of surface waves is longer than what can be achieved from  
368 body-wave data, this crustal velocity structure was averaged over a block size 0.2

369 degree (lat) x 0.25 degree (lon) before surface-wave inversion. The result is a mantle  
370 structure that is relatively smoother (averaged over 20-30 km) in comparison to the  
371 crust. This surface wave inversion approach was used to directly infer S-wave structure  
372 in the model. P-wave variations in this model were derived from surface wave data only,  
373 through a relation  $d(\ln V_p)/d(\ln V_s) = 0.8$ , and thus may be considered less accurate  
374 than the S-wave structure.

375

376 In summary, this approach, of using basin velocity descriptions as a starting point for 3D  
377 tomographic inversions, helps to ensure consistency between the basin, crustal, and  
378 upper mantle velocity descriptions. This model, in turn, served as the starting point for  
379 3D waveform tomographic inversion to further refine the crustal velocity descriptions.

380

### 381 **3.3 3D Adjoint waveform tomography**

382 Computational and theoretical developments over the past 15 years (Komatitsch et al.,  
383 2002) have led to an era where complex seismological models, such as the CVM, can  
384 be iteratively improved through formal tomographic inversion methods (e.g., Chen et al.,  
385 2007; Tape et al., 2009; Fichtner et al., 2009; Lee et al., 2014a,b). Seismic wave  
386 propagation codes can be used to partition a particular model into hundreds to  
387 thousands of parts, allowing for an extremely large (in terms of grid points) problem to be  
388 solved by parallel computing clusters. These seismic wavefield simulations produce  
389 synthetic seismograms, which are highly accurate solutions to the wave equation for the  
390 input structural and earthquake models.

391

392 The tomographic inverse problem starts with the specification of a misfit function  
393 measuring the difference between a set of recorded seismograms and a set of synthetic  
394 seismograms computed from wavefield simulations. The accuracy of the wavefield



395 simulations is also exploited by the tomographic inversion. The same solver can be used  
396 to compute the gradient of the misfit function, per earthquake, with respect to each  
397 model parameter, such as the shear velocity at each grid point (Tarantola 1984; Tromp  
398 et al. 2005). The individual gradients (or “event kernels”) can be used within standard  
399 gradient-based iterative optimization algorithms (e.g., Tape et al. 2007).

400

401 The CVM with basin, crust, and upper mantle velocity descriptions was used within the  
402 large-scale iterative tomographic inversion of Tape et al. (2009, 2010). The inversion  
403 included 143 regional earthquakes (Mw 3.8–5.2), each of which was recorded by up to  
404 160 stations on three-component seismograms filtered between 2 s and 30 s. The  
405 moment tensor and depth of each earthquake source was estimated using the initial  
406 model and also the final model using the method of Liu et al. (2004).

407

408 The final model, after 16 iterations, included large perturbations (up to 40%) from the  
409 initial 3D model. The changes were concentrated in the uppermost 20 km of the crustal  
410 model and were attributed to both compositional features (e.g. the southernmost San  
411 Joaquin basin) and to thermal features (e.g., Quaternary and Holocene volcanism in the  
412 eastern Mojave). An independent set of 91 earthquakes, not used in the inversion, was  
413 used to validate the improvements between the initial and final models. The misfit  
414 reduction from the independent set of earthquakes was essentially the same as the  
415 misfit reduction for the earthquakes used in the inversion (Tape et al. 2009). These  
416 perturbations to the starting model were included in the USR for the crust. The basin  
417 representations were left unchanged, given their high resolution and the expanded  
418 representations that occurred separately during the course of the inversion, but they  
419 could be modified in future inversions.

420

### 421 **3.4 Geotechnical layer (GTL)**

422 Shallow subsurface velocity structures, particularly shear wave speeds ( $V_s$ ), have a  
423 significant influence on strong ground motions. Thus, some applications for the USR  
424 require parameterization of this near surface structure. To address this need, the USR  
425 framework includes a representation of shallow subsurface  $V_p$ ,  $V_s$ , and density structure  
426 in the form of a Geotechnical Layer (GTL) that can be overlain on the underlying basin  
427 and crustal velocity descriptions (Ely et al., 2010).

428 The GTL is based on the widely accepted use of  $V_{s30}$ , or average shear wave speed  
429 down to 30 meters depth, as a method of parameterizing velocities at the model's  
430 ground surface.  $V_{s30}$  is measured by logging in geotechnical boreholes and can be  
431 inferred from surface geology or topographic gradients (Wald and Allen, 2007). In our  
432 GTL, we used the geology-based  $V_{s30}$  maps of Wills and Clahan (2006).  $V_p$ , and in turn  
433 density, are inferred from surface  $V_s$  using the scaling laws of Brocher (2005). We  
434 evaluated a number of depth-dependent velocity formulations with the goal of effectively  
435 representing a wide range of soil and rock velocity profile types and providing a smooth  
436 transition to the underlying crustal velocity model. We sampled velocities in the  
437 underlying model at a depth of 350 meters, which corresponds roughly with the upper  
438 limit of independent velocity measurements from well data in the underlying models and  
439 typically avoided artifacts associated with the topographic surface. The selected model  
440 includes cubic and square-root depth dependence for  $V_p$  and  $V_s$  based on Boore and  
441 Joyner's (1997) generic rock profile and the velocities in the underlying model after Ely et  
442 al. (2010). The specific formulations used in these parameterizations are described in  
443 the Supplemental Information for this article. The GTL layer is provided as an optional  
444 overlay on the underlying USR, so that it can be implemented when necessary to  
445 support ground motion, seismic hazard assessment, and other applications.

446

#### 447 **4. Assembly of the USR**

448 The upper solid surface of the USR is marked by topographic or bathymetric elevations.  
449 For bathymetry we use ETOPO-1 (Amante and Eakins 2009) and, where available,  
450 measurements derived from seafloor reflectors of seismic surveys. For topography we  
451 used GTOPO30 (USGS, 1996). ETOPO-1 and GTOPO30 have resolutions of about 1.8  
452 km and 0.9 km, respectively.

453

454 The various components of the USR, including the topography, basin representations,  
455 basement and Moho surfaces, tomographic crust and upper mantle velocity models, and  
456 the GTL were assembled by parameterizing a set of voxets, or regular grids of voxels,  
457 with velocity values and by appropriately resampling surfaces. These nested voxets  
458 include a high-resolution grid (250 by 250 m horizontally, 100 m in depth) centered  
459 around the Los Angeles basin, where we had the greatest density of data. This voxel was  
460 embedded in a medium resolution grid (1 by 1 km resolution) for the remainder of  
461 southern California. Areas beyond the extent of the voxets are extrapolated by a 1D  
462 velocity model (Dreger and Helmberger, 1990; Wald et al., 1995; Hutton et al., 2010).  
463 Below 15 km, the model resolution is 1 km vertically and 10 km horizontally.

464

465 Most of the data used to define the velocity structure within the sedimentary basins  
466 sample  $V_p$ ,  $V_s$  and rock density ( $\rho$ ) are defined for sediments in the model using the  
467 empirical relationship of Brocher (2005), which are based on well logs that independently  
468 constrained  $V_p$ ,  $V_s$ , and density. The tomographic crust and upper mantle models define  
469 both  $V_p$  and  $V_s$ , and the GTL specifies  $V_p$  and  $V_s$  values as described in the  
470 Supplemental Information. Thus,  $V_s$  values for these model components were used  
471 directly to parameterize the USR.

472

473 The USR is accessed through the SCEC website, where users download the voxets and  
474 use a query tool to parameterize arbitrary points (x, y, and z) with  $V_p$ ,  $V_s$ ,  $\rho$ . The code  
475 delivers these values, along with the properties we described, for the closest grid point in  
476 the model, along with the precise location of that grid point. The basement surface and  
477 Moho are provided as separate structural elements (tsurfs) along with the voxets. In  
478 addition, every grid point within the voxets contains properties that describe the region of  
479 the model that they represent (sediment, crust, upper mantle). Properties also specify  
480 the vertical distance to the basement and Moho horizons, which is useful information for  
481 developing computational meshes or grids. The USR is provided through the SCEC  
482 website as a series of CFM and CVM model components. CFM version 5.0 and CVM-H  
483 15.1.0 are used for this manuscript. For a discussion of model resolution and  
484 uncertainty, the reader is referred to the Supplemental Information accompanying this  
485 article.

486

## 487 **5. Description**

488 The primary velocity structures in the upper crust of southern California are the deep  
489 sedimentary basins. Average velocity functions for sediments within these basins all  
490 show general trends of increasing velocity with depth (Fig. 6A). Notably, the average  
491 velocity profiles for the Los Angeles, Ventura, and Santa Barbara basins are similar,  
492 reflecting that these basins contain comparable Neogene to recent stratigraphic  
493 sequences. The Inner California Borderland exhibits a similar velocity gradient to these  
494 basins, with the exception of a shallow ( $\approx 500$  m) velocity inversion that is associated  
495 with a Tertiary volcanic section inter-bedded with sediments (Crouch and Suppe, 1990;  
496 Bohannon and Geist, 1998; Rivero, 2004). The Santa Maria and San Bernardino basins  
497 also show broadly similar velocity gradients, yet typically exhibit faster velocities at

498 shallow depths. This results from thinner Pliocene and younger sedimentary strata in  
499 these basins. In contrast, the Salton Trough basin shows very slow near surface  
500 velocities, but also the steepest velocity gradient of any basin from about 200 to 3000m  
501 depths. This rapid increase in velocities likely reflects the high geothermal gradient in the  
502 area, which lithifies and metamorphoses the sediments thereby increasing their  
503 wavespeeds and densities

504

505 Lateral variations in velocities modeled within the basins reflect both the amount of the  
506 data that were used to parameterize them as well as sedimentological and tectonic  
507 controls. The Los Angeles, Ventura, and Santa Maria basins have the greatest sediment  
508 thicknesses (up to  $\approx 10$ , 12, and 5 km, respectively), and the highest density of direct  
509 velocity data coverage from well and seismic reflection data (Suess and Shaw, 2004;  
510 Munster, 2007; Brankman, 2009). These basins generally exhibit the largest lateral  
511 contrasts in velocities (from 1.5 to 4.5 km/s) at shallow depths ( $< 2$  km), due to situations  
512 where faults laterally juxtapose faster, older sedimentary rocks with slower, younger  
513 sediments. Below 2 km, sediment velocities generally exhibit smaller, but nonetheless  
514 significant lateral variations. In the Los Angeles basin, for example, modeled sediment  
515 velocities vary laterally by about 1 km/s from 2 to 7 km, representing a variance of about  
516 20 to 30% from the average velocity values (Fig. 6B). This pattern reflects compaction  
517 and diagenesis of the different types of clastic sedimentary sections that comprise the  
518 basin (Suess and Shaw, 2004). Moreover, these strata have also been folded and  
519 uplifted by faulting, producing lateral juxtapositions of different lithologic units. The most  
520 significant lateral variations in velocity occur across major faults, including both thrust  
521 and strike-slip systems. In the Los Angeles basin, the Newport-Inglewood, Palos Verdes,  
522 Puente Hills, and Whittier faults all produce abrupt, local velocity contrasts within the  
523 sedimentary strata. Moreover, these as well as other structures, including the Santa

524 Monica fault, locally juxtapose crystalline basement adjacent to, or above, the  
525 sedimentary strata (Fig. 5). These fault boundaries can produce local increases in  
526 velocity ( $V_p$ ) of more than 350% moving from unconsolidated sediments to basement  
527 rocks. The Ventura basin also exhibits such abrupt velocity gradients, mainly along the  
528 San Cayetano, Ventura, Pitas Point, and Oak Ridge faults. Similar lateral velocity  
529 variations in the Santa Maria basin result from a series of east-west trending folds that  
530 are underlain by blind-thrust faults (Munster, 2007; Shaw and Plesch, 2012).

531

532 These basin descriptions, when combined with the tomographic models and overlain by  
533 the GTL, provide a comprehensive description of the crust and upper mantle structure in  
534 southern California (Figs. 7 and 8). Beginning at the shallowest depths (0 to 300m), the  
535 changes from near-surface to deeper sediment velocities are significant ( $\approx$  800 to 2400  
536 m/s). However, the transition is smooth given that the GTL used underlying velocity  
537 values in its parameterization (Fig. 7) [see electronic supplement]. The near surface  
538 velocities in the GTL vary across the model as a function of rock types, with the slowest  
539 velocities in the sedimentary basins, intermediate velocities in ranges comprised of  
540 sedimentary rock, and the fastest velocities in regions that expose crystalline rocks (Fig.  
541 7). The sedimentary basins are characterized by increasing velocity with depth, yet  
542 include internal velocity variations due to changes in lithology and the presence of faults.  
543 At the bottom of the sedimentary basins, velocities generally change abruptly across the  
544 top basement horizon (Figs. 8 and 9). These contrasts are greatest ( $\approx$  from 2000 to  
545 5,500 m/s) in shallow parts of the basins, where sediments are poorly lithified. In the  
546 deepest part of basins, velocity changes across the sediment-basement interface are  
547 substantially less ( $\approx$  from 4,500 to 5,500 m/s). This results from the compaction of  
548 sedimentary units at depth, yielding faster velocities that approach those of the  
549 underlying basement rocks.

550

551 The underlying crust and mantle structure exhibit general trends that reflect the major  
552 tectonic elements in southern California (Fig. 8). In the upper 15 kilometers of the crust,  
553 low velocity roots are present beneath most of the sedimentary basins. This pattern may  
554 result, in part, from a smearing of the low velocity basins to depth in the tomographic  
555 models. However, it may also reflect crustal thinning related to the Neogene rifting and  
556 formation of the basins. A similar low-velocity region underlies the San Gabriel  
557 Mountains and Coast Ranges, which contain deformed early Tertiary sedimentary and  
558 metasedimentary sections that were not explicitly represented in the model. In contrast,  
559 the Peninsular Ranges are underlain by a fast velocity region (Fig. 9A). This likely  
560 reflects the deep crystalline roots of these Ranges, which correspond with one of the  
561 thickest areas of continental crust in southern California (Fig. 3).

562

563 The USR is compared with the velocity model of Lee et al. (2014b,a) at shallow depths  
564 in Figure 8. Lee et al. (2014b,a) applied full-3D tomography using a combination of the  
565 scattering-integral method and the adjoint-wavefield method to iteratively improve a 3-D  
566 starting model of the southern California based on Magistrale et al., (2000). These  
567 authors provided a formal comparison of their model to a version of the crustal velocity  
568 description incorporated in the USR to which the readers are referred. In Figure 8 we  
569 highlight the difference in model representations at shallow crustal levels where basin  
570 and fault structures have the greatest influence on velocity structure. Both models show  
571 low velocity sediments within the Los Angeles and other basins. However, the USR  
572 exhibits larger basins that extend offshore and include more complex internal velocity  
573 structures. These internal velocity structures result from the larger well and seismic  
574 reflection datasets that were used as constraints in the USR, and the incorporation of  
575 faults that directly influence basin geometries.

576

577 **6. Applications to earthquake simulations**

578

579 A fundamental use for the USR is to provide the most accurate information available  
580 (faults and velocity structure) for earthquake simulations. These simulations, in turn, can  
581 be used to obtain better estimates of earthquake source models (e.g., Liu et al., 2004).  
582 The CVM has been tested with earthquake simulations (Komatitsh et al., 2004; Lovely et  
583 al. 2007; Tape et al. 2009; Graves and Aagaard, 2011) and with ambient noise cross  
584 correlations (Ma et al. 2008). A second purpose of the earthquake simulations is to  
585 iteratively improve the CVM.

586

587 We demonstrate the importance of 3D structure on realistic earthquake simulations in  
588 Figures 9 and 10. We consider a Mw 7.9 scenario thrust earthquake that is  
589 approximately aligned with the Ventura-Pitas Point fault system (Hubbard et al., 2014).  
590 The earthquake rupture model (Figure 9a) is the 2008 Wenchuan, China, earthquake,  
591 which is one of the largest continental thrust faults recorded in the past decade (Shao et  
592 al., 2010). The kinematic source model is derived from seismic and geodetic  
593 observations using the method of Ji et al. (2002).

594

595 The earthquake simulation is performed using SPECFEM3D software (Komatitsch et al.,  
596 2004; Peter et al., 2011), which uses a spectral element method for representing wave  
597 propagation on unstructured hexahedral finite element meshes. The wavefield is  
598 computed throughout the volume, and synthetic seismograms are saved at designated  
599 points. From each synthetic seismogram, the peak velocity is saved and plotted in  
600 Figure 9. Comparison of Figures 9b and 9c, which show the computer peak velocities  
601 from the regional 1-D model and the USR, respectively, demonstrate the well-known



602 effect of the amplification of seismic waves from basin structures (e.g., Komatitsch et al.,  
603 2004, Graves, 2008).

604

605 The wavefield simulations contain far more information than is represented in the peak  
606 ground velocity maps. Snapshots of the simulations (Figure 10) show the influence of  
607 the 3D basin structures (and topography) on the seismic wavefield. The simulation in the  
608 1D model reveals a strong source pulse directed to the southeast. This pulse is much  
609 weaker in the 3D model, where much of the energy is trapped within the basin  
610 structures. These results illustrate the importance of using realistic models of velocity  
611 and fault structure such as the USR in forecasting the amplitude and duration of  
612 hazardous ground shaking that will result from large earthquakes.

613

## 614 **7. Conclusion**

615 We present a methodology for developing precise and internally consistent descriptions  
616 of Earth structure that span the range of wavespeed from low velocity sediments in the  
617 shallow subsurface to upper mantle structure. This involves the careful integration of  
618 many datasets, including borehole observations, seismic reflection and refraction  
619 surveys, and earthquake body and surface wave data. The workflow that we have  
620 developed for constructing the USR, involving development of basin descriptions, crust  
621 and upper mantle tomography, and 3D adjoint waveform tomography, ensures the  
622 internal consistency of the model components and promotes the accuracy of the  
623 integrative model. We illustrate this implementation through the development of a USR  
624 for southern California, which describes heterogeneous wavespeed structure in the crust  
625 that formed over a long and complex tectonic history. Finally, we illustrate the value of  
626 compatible fault and velocity representations in the USR through a simulation of a  
627 hypothetical M 7.9 earthquake on thrust faults in the Western Transverse Ranges. This

628 simulation highlights the influence of fault and basin structure in controlling the  
629 distribution and duration of hazardous ground shaking that may result from future  
630 earthquakes.

631 **Figure captions**

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

637

638 2) Map of southern California showing major basins, mountain ranges, and faults noted  
639 in the text. LA is Los Angeles basin; V is Ventura basin, IB is Inner Borderland; SM is  
640 Santa Maria basin; SB is Santa Barbara basin; B is the San Bernardino basin. SAF is  
641 the San Andreas fault; ECSZ is the Eastern California Shear Zone; G is the Garlock  
642 fault; SJF is the San Jacinto fault. Section traces are for profiles plotted in Figure 7.

643 Arrows signify endpoints of sections X and Y that are located outside the map.

644

645 3) Moho depth surface in the CVM, from Tape et al. (2012). The colored circles indicate  
646 the locations of measured points used in estimating the surface; most are from receiver  
647 function studies (e.g., Gilbert et al., 2012) or from wide-angle refraction studies.

648

649 4) Sample of data used to define the basement horizon and velocity structure within  
650 sedimentary basins. (left) Migrated seismic reflection profile in depth from the Inner  
651 California Borderland showing prominent top basement horizon. Log of Vp derived from  
652 sonic logs in a well located northeast of the seismic section, and shown with the same  
653 vertical scale. For Vp, both the raw data (black) and a running 25 m average (red) are  
654 shown. Note the prominent velocity increase that occurs at the bottom of the log where  
655 the well penetrates basement.

656

657 5) Perspective view looking north of the top basement surface in depth with faults from  
658 the Community Fault Model (CFM) (Plesch et al., 2007). Note that steeply dipping strike-  
659 and oblique-slip faults, such as the Newport-Inglewood and Whittier systems, form steep  
660 boundaries to the basin. Moderately dipping thrust faults, such as the Santa Monica and  
661 Puente Hills thrust, locally duplicate the sediment-basement horizon. The Anaheim fault  
662 is considered to be an inactive structure, and thus is not represented in the CFM.  
663 However, the fault is included in the USR because it influences the basin shape. PHT is  
664 the Puente Hills thrust fault. Filled teeth represent surface emergent faults; open teeth  
665 represent blind faults.

666

667 6) Plots of velocity ( $V_p$ ) in sedimentary basins represented in the USR. (left) Average  
668 velocity functions for each basin. (right) Average velocity function for the Los Angeles  
669 basin superimposed on the distribution of velocity values for the basin included in the  
670 model.

671

672 7A) Perspective view of the northern part of the USR, showing an enlarged transect  
673 across the Los Angeles basin. An enlarged view of the shallow velocity structure in the  
674 basin shows the Geotechnical Layer (GTL), as described in the text. B) Cross sections  
675 showing  $V_p$  across the USR. Section traces are shown in Figure 2. LA is Los Angeles  
676 basin; SB is Santa Barbara basin; IB is Inner Borderland; ST is Salton Trough basin.

677

678 8) Depth slices at – 1000 m elevation comparing  $V_p$  from the USR (left) and CVM-S 4.26  
679 (Lee et al., 2014a,b) (right). LA is Los Angeles basin; IB is Inner Borderland; SB is Santa  
680 Barbara basin; SF is San Fernando basin; SM is Santa Maria basin; ST is Salton Trough  
681 basin; V is Ventura basin.

682

683 9) The influence of 3D structure on the seismic wavefield, Part I. (a) Mw 7.9 finite-source  
684 model (Ji et al., 2002) for the Wenchuan, China, earthquake (Shao et al., 2010). The  
685 model is discretized with 61,970 subsources; the color denotes the moment associated  
686 with each subsurface. (b) Peak ground velocity at a selected number of points within the  
687 simulation using a 1D layered structural model (Dreger and Helmberger, 1990; Wald et  
688 al., 1995). (c) Peak ground velocity using USR (CVM-H 15.1.0). Ground velocities are  
689 much larger in the regions containing deep sedimentary basins, which trap and amplify  
690 seismic waves.

691

692 10) The influence of 3D structure on the seismic wavefield, Part II. The left column  
693 shows snapshots of a seismic wavefield simulation performed for the earthquake source  
694 model in Figure 9a and using a 1D structural model. The right column shows the same  
695 simulation, but instead using the 3D USR structural model (CVM-H 15.1.0). The colors of  
696 the wavefield represent the vertical component of velocity. The background gray is the  
697 uppermost surface of the finite-element mesh in the simulation; hence, the topography is  
698 only visible in the right column. Note the strong, long-lasting shaking within the basin  
699 structures of USR.

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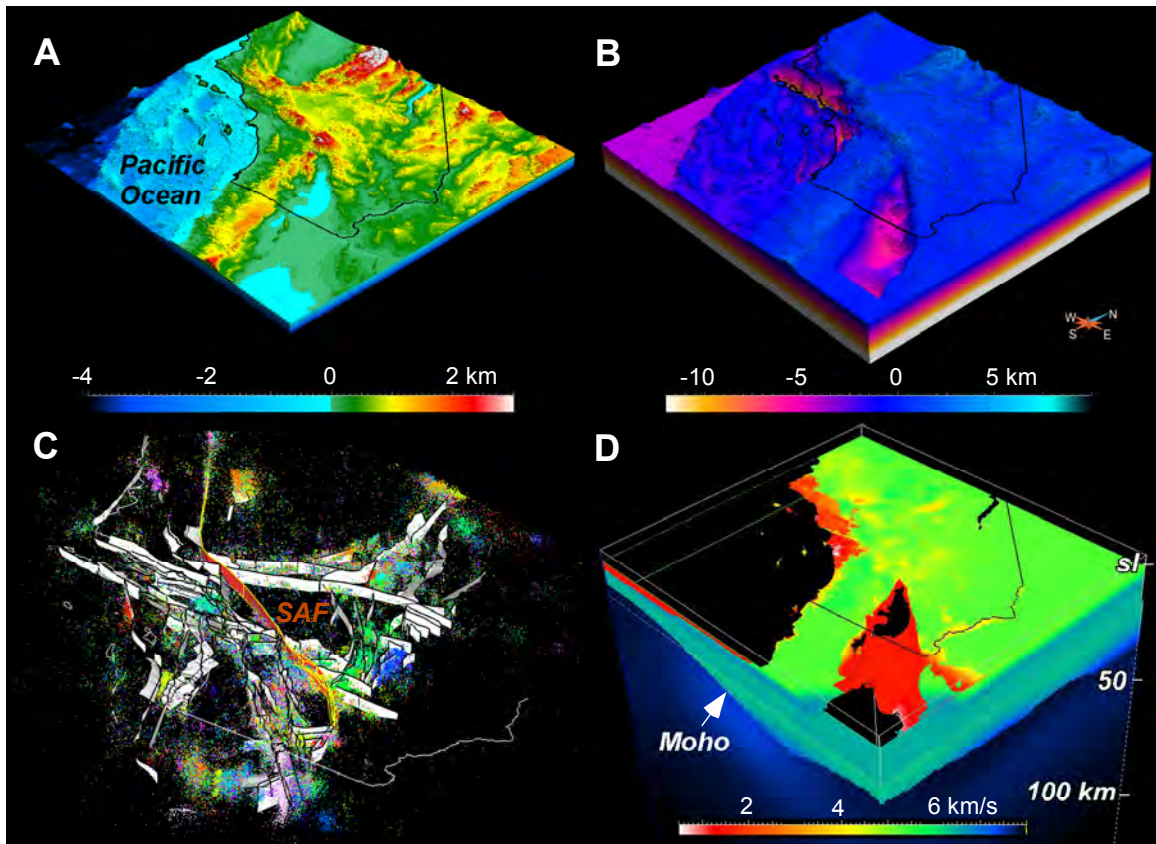


Fig. 1

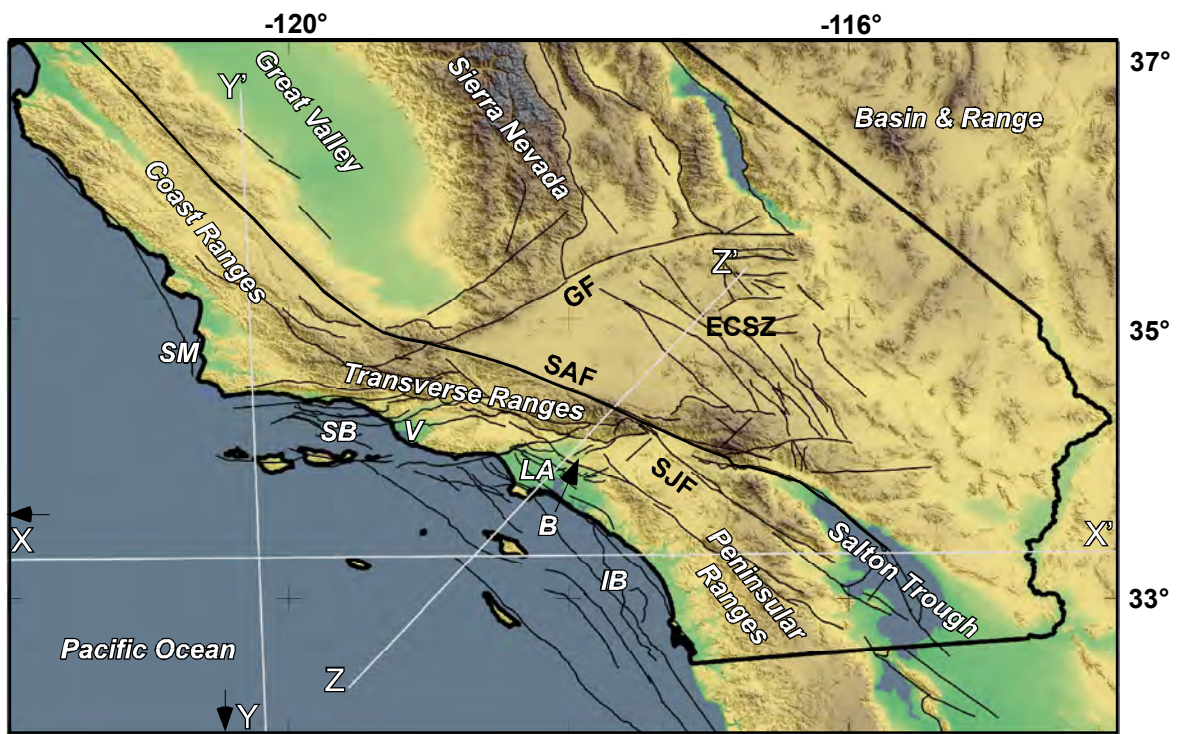


Fig. 2

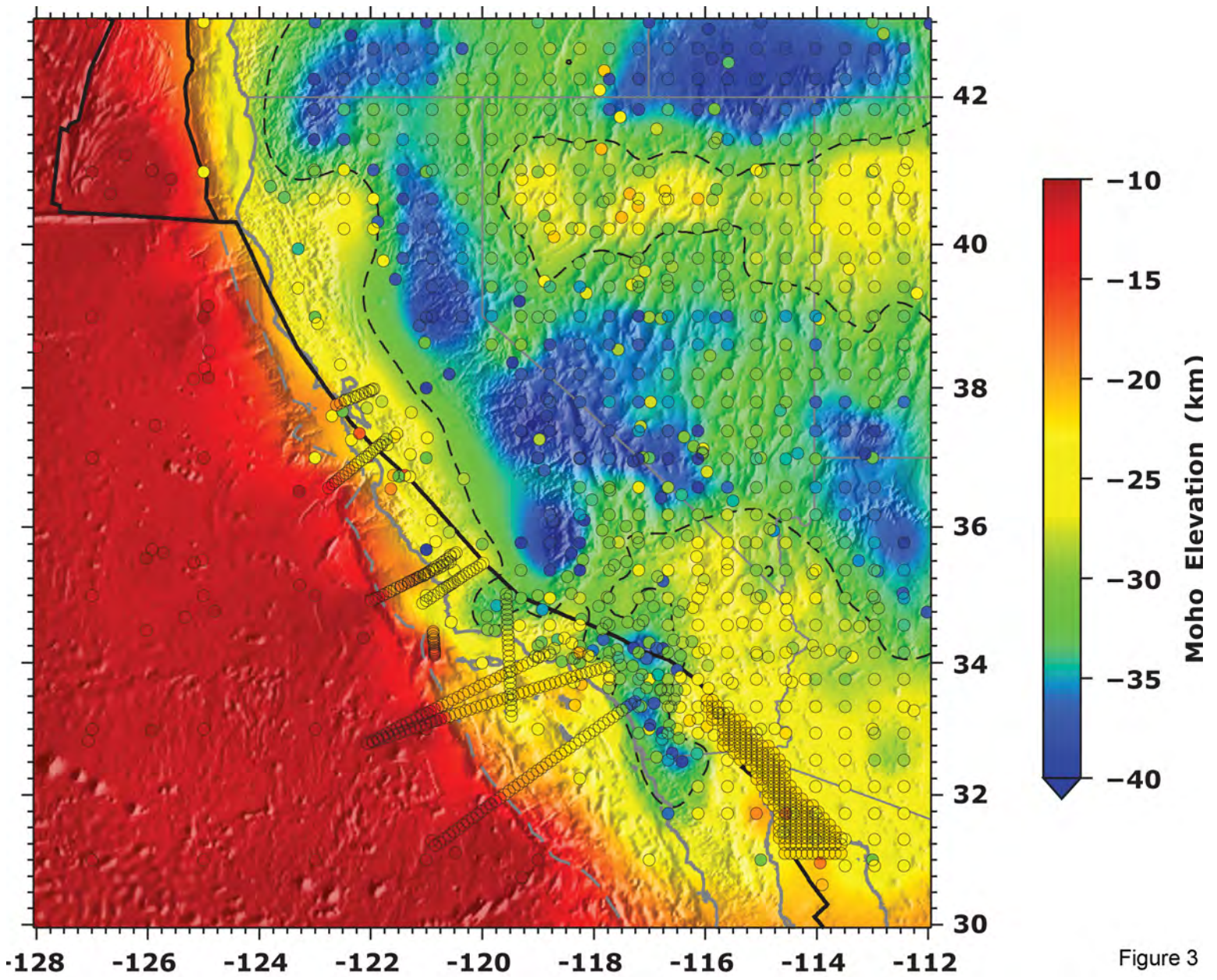


Figure 3



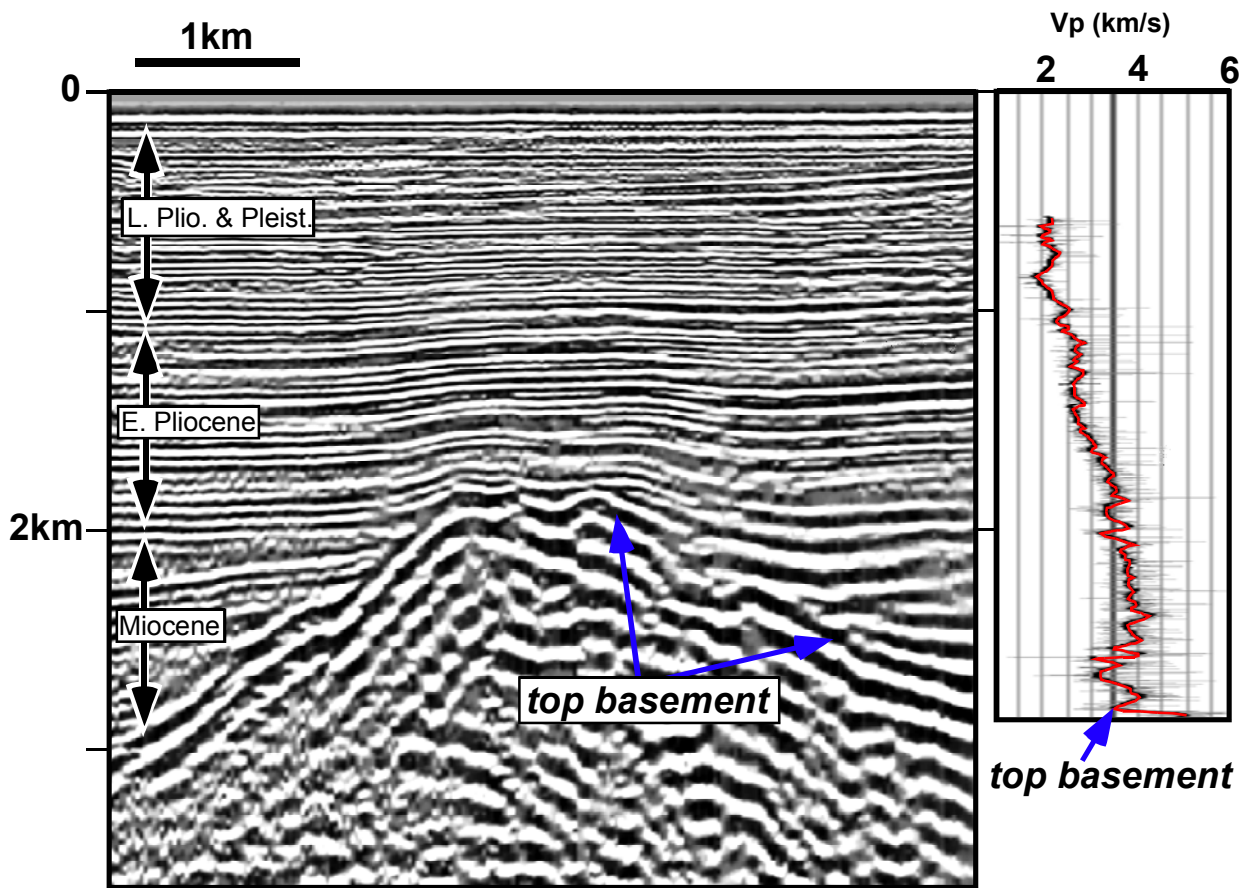


Fig. 4

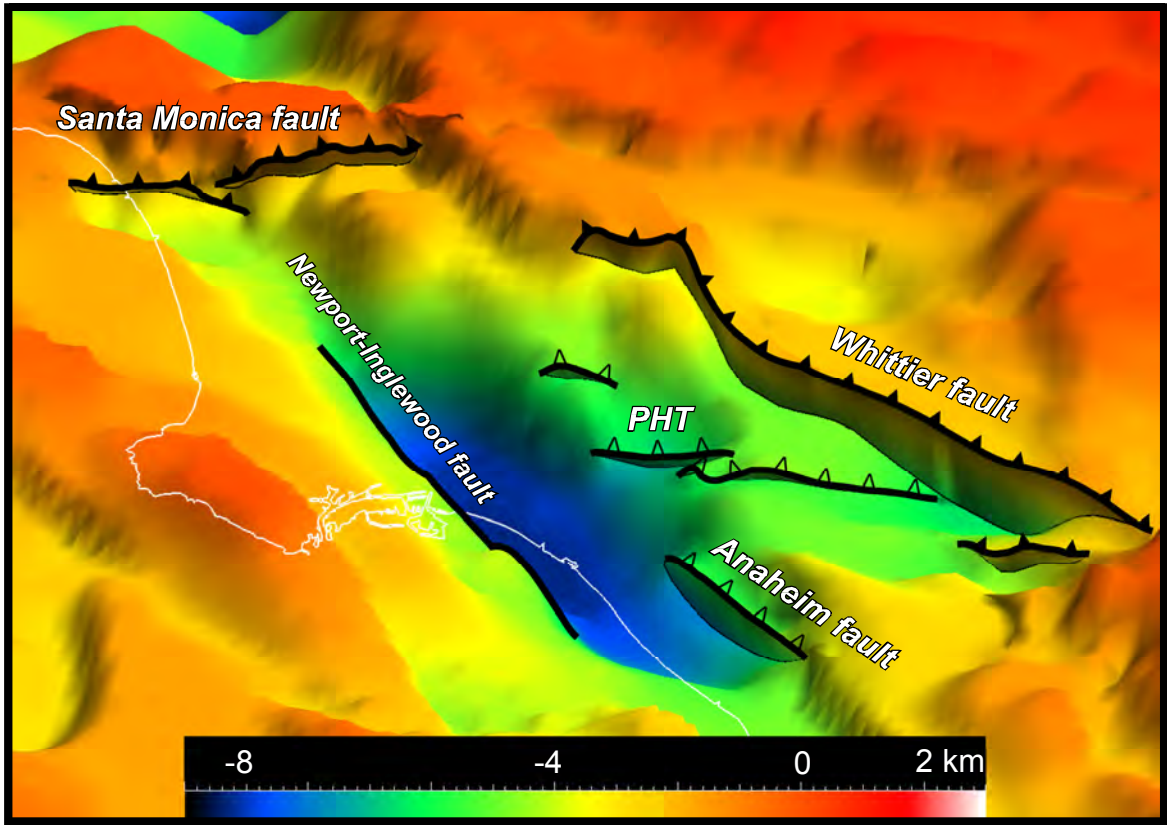


Fig. 5

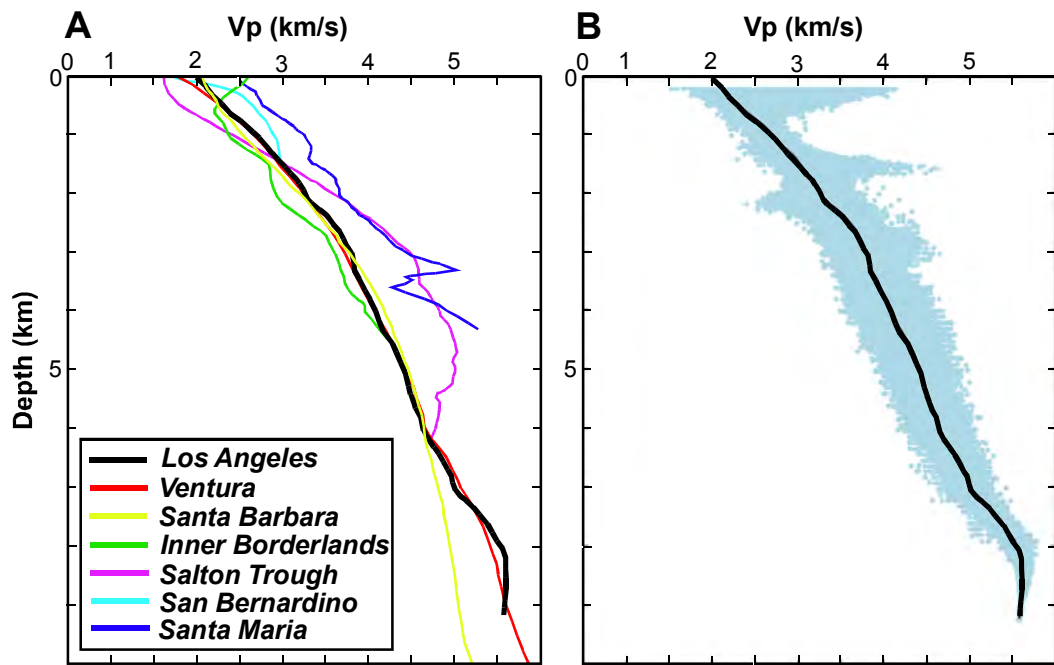


Fig. 6

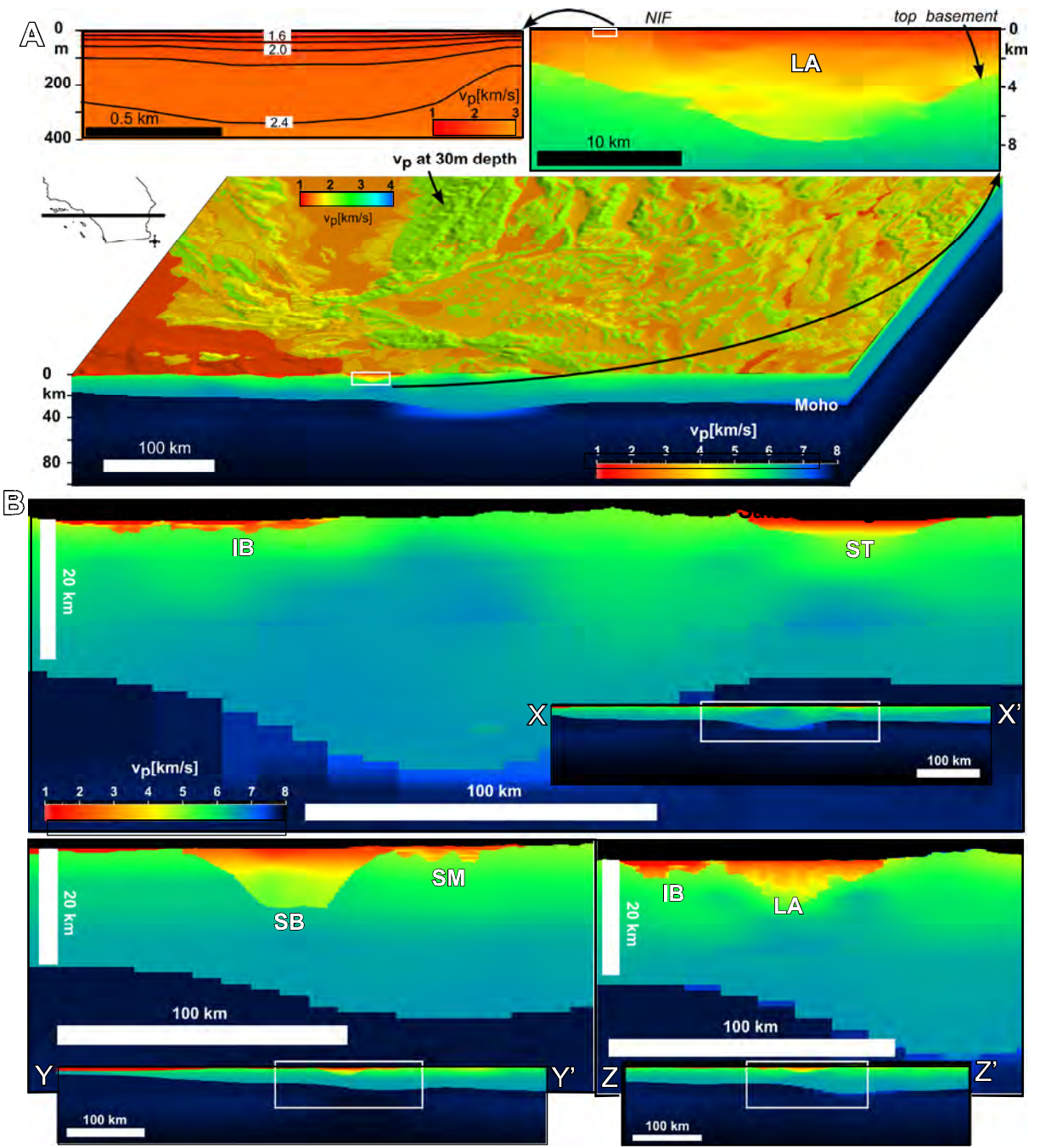


Fig. 7

USR

CVM-S4.26

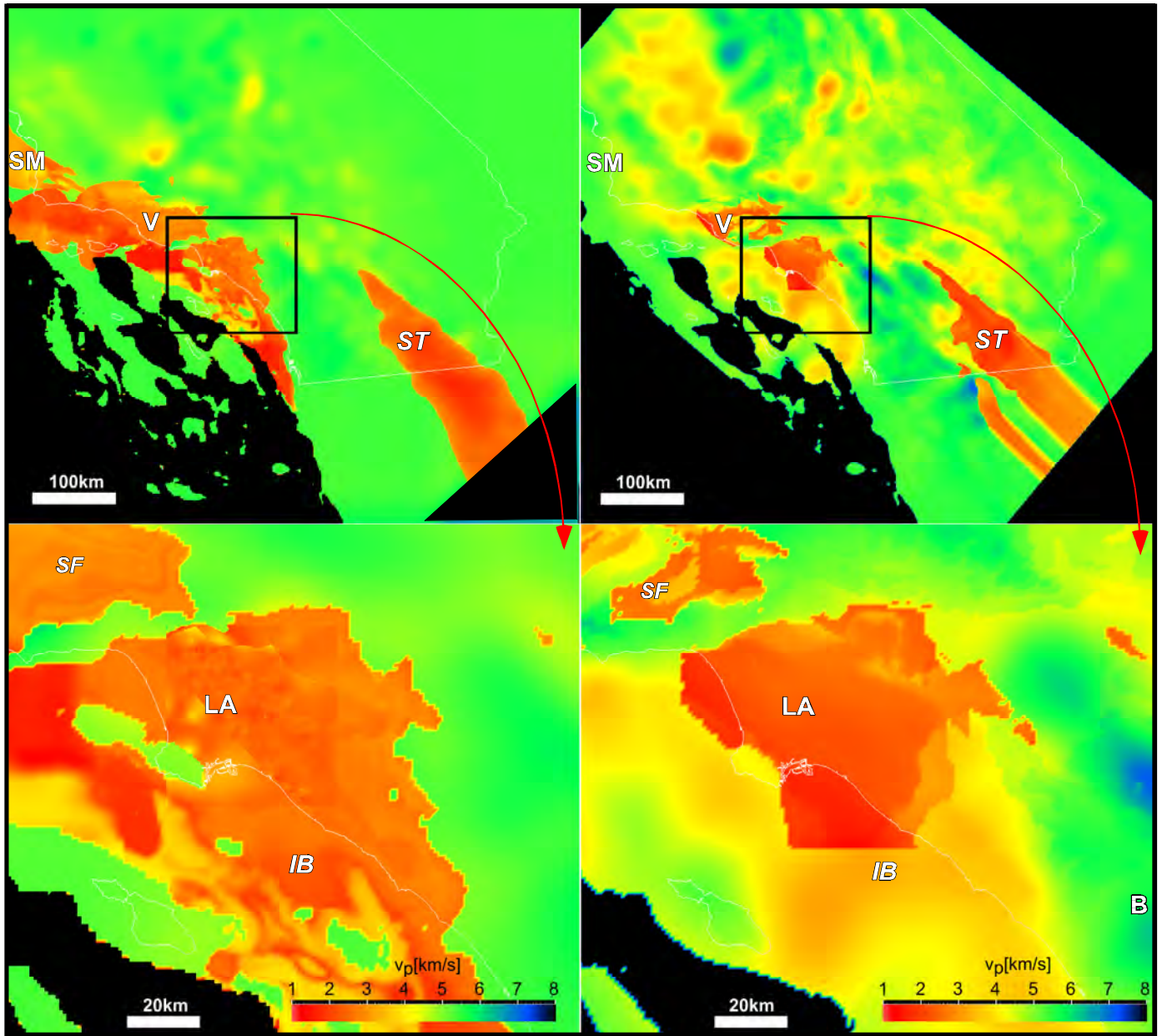
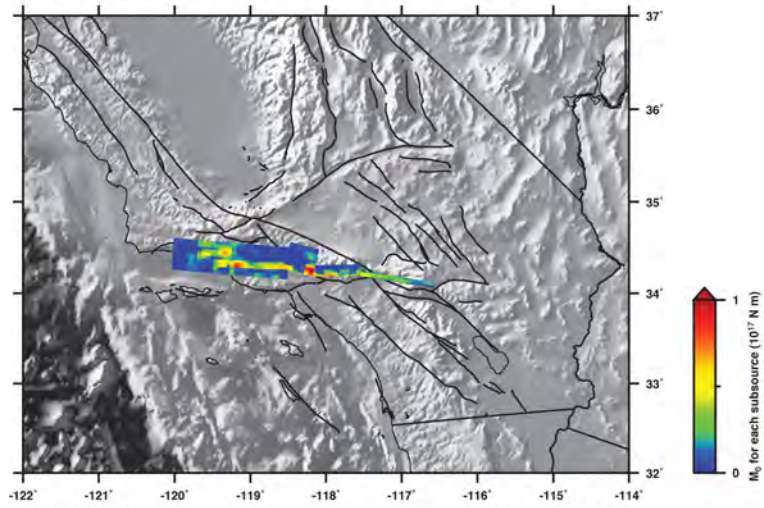
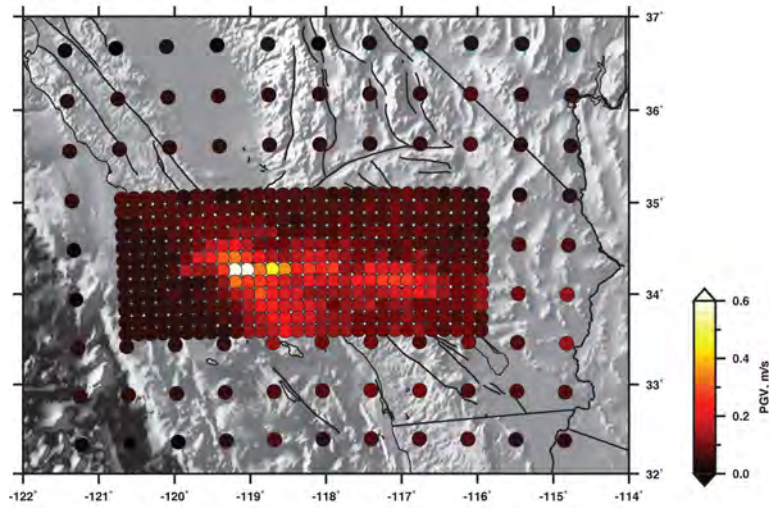


Fig. 8

(a) Mw 7.9 scenario thrust earthquake



(b) Peak ground velocity using SoCal-1D



(c) Peak ground velocity using CVM-H

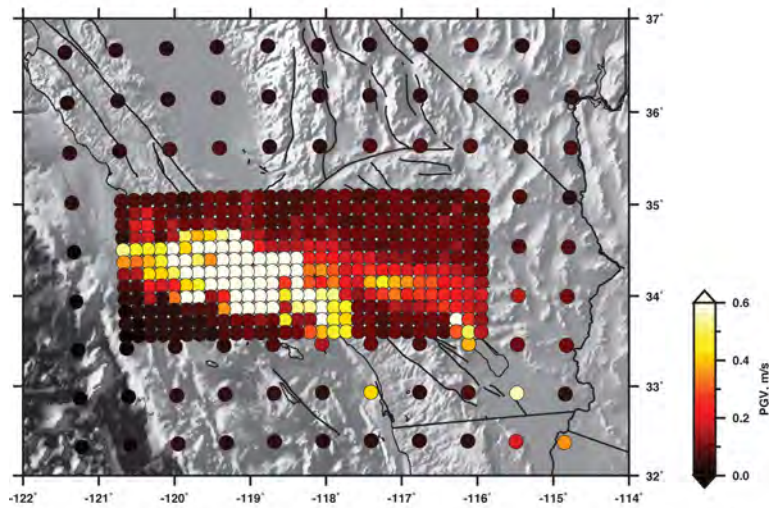


Figure 9

SoCal1D

USR/CVM-H

t = 108 s

t = 72 s

t = 36 s

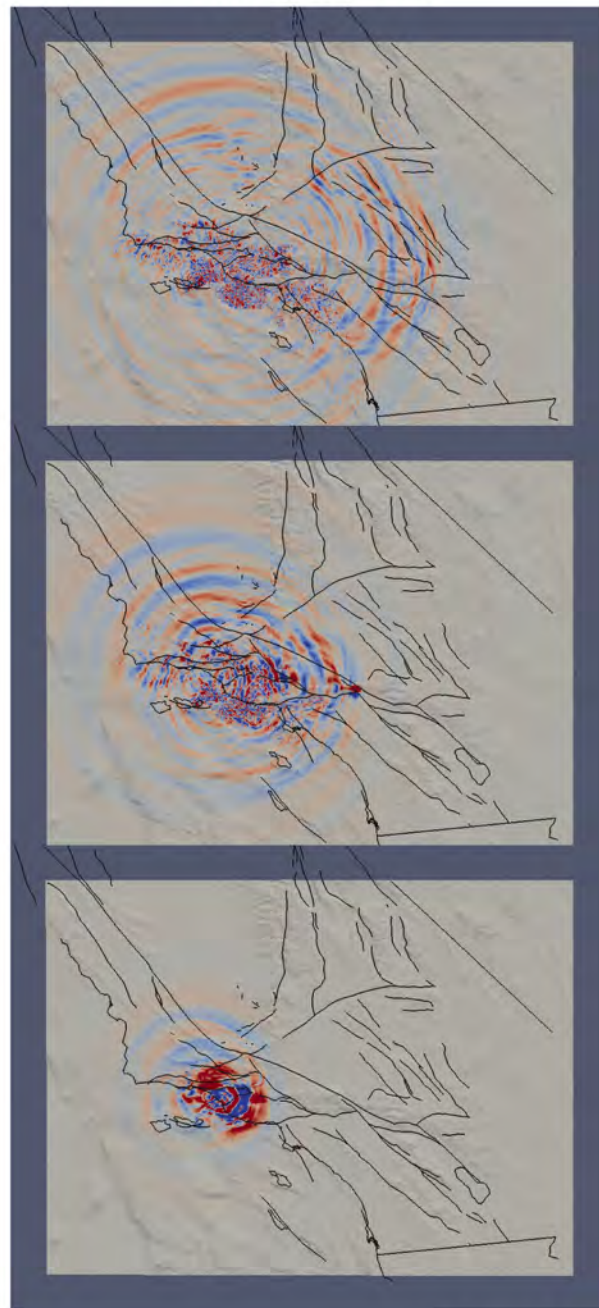
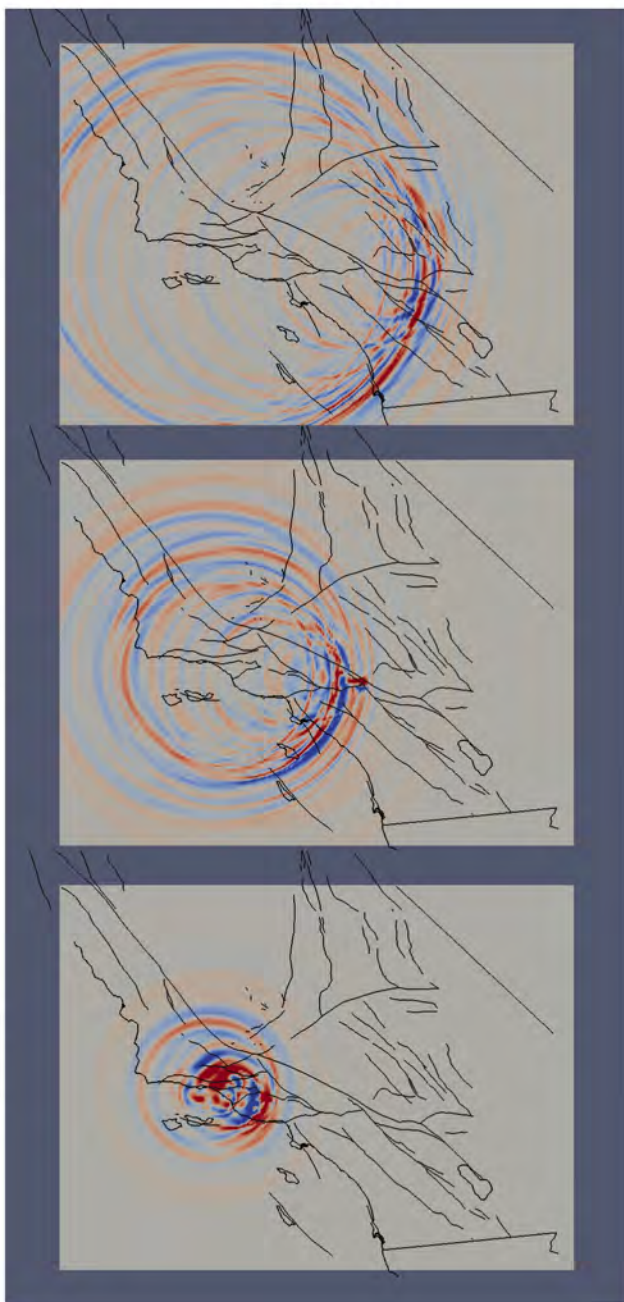


Figure 10

# Unified Structural Representation of the southern California crust and upper mantle

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## 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 Earth's surface in the voxel.  $V_P$ , 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:

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

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

where  $z'$  is depth,  $V_{ST}$  and  $V_{PT}$  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

$$z = z'/z_T \quad (\text{S3})$$

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

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

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*).

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