Earthquake Hazards Program

Science Plan for Improving Three-Dimensional Seismic Velocity Models in the San Francisco Bay Region, 2019–24

Open-File Report 2020–1019

U.S. Department of the Interior
U.S. Geological Survey

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Most of the figures were created using Cartopy v0.17.0 (https://github.com/SciTools/cartopy/releases/tag/v0.17.0, accessed September 25, 2019) and Matplotlib v3.1.1 (https://doi.org/10.5281/zenodo.3264781, accessed September 25, 2019).

Reviews by Oliver Boyd, Robert Graves, and Keith Kundsen led to significant improvements in the manuscript.

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Figures

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Conversion Factors

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
kilometer (km)	0.5400	mile, nautical (nmi)
meter (m)	1.094	yard (yd)
	Velocity	
kilometer per second (km/s)	3,281	feet per second (ft/s)

Datum

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Elevation, as used in this report, refers to distance above the vertical datum.

Abbreviations

ANSS	U.S. Geological Survey Advanced National Seismic System
API	Application programming interface
DAS	Distributed acoustic sensing
SCEC CCA	Southern California Earthquake Center Central California Community Velocity Model
SCEC CVM-H	Southern California Earthquake Center Community Velocity Model H
SCEC CVM-S	Southern California Earthquake Center Community Velocity Model S
SCEC	Southern California Earthquake Center
Mw	Moment magnitude
Q_p	Quality factor for (P) wave attenuation
Q_s	Quality factor for (S) wave attenuation
USR	Unified Structural Representation
USGS	U.S. Geological Survey
V_p	Compressional (P) wave speed
V_s	Shear (S) wave speed
V_{s30}	Time-averaged shear wave speed to a depth of 30 meters
Z1.0	Depth, in kilometers, to the 1.0 kilometer per second shear wave isosurface
Z2.5	Depth, in kilometers, to the 2.5 kilometers per second shear wave isosurface

Science Plan for Improving Three-Dimensional Seismic Velocity Models in the San Francisco Bay Region, 2019–24

By Brad T. Aagaard,[1] Russell W. Graymer,[1] Clifford H. Thurber,[2] Arthur J. Rodgers,[3] Taka'aki Taira,[4] Rufus D. Catchings,[1] Christine A. Goulet,[5] and Andreas Plesch[6]

Abstract

This five-year science plan outlines short-term and long-term goals for improving three-dimensional seismic velocity models in the greater San Francisco Bay region as well as how to foster a community effort in reaching those goals. The short-term goals focus on improving the current U.S. Geological Survey San Francisco Bay region geologic and seismic velocity model using existing data. The long-term goals focus on acquiring new data and leveraging better analytic tools to improve the model and characterize the uncertainty. The plan describes opportunities for contributions by members of the community to develop these seismic velocity models, provides current and potential users with general information on where efforts will likely be focused to improve these models and how new versions of the models will be released, and outlines funding needs and obstacles for improving and maintaining such models. Several aspects of this plan, including how to foster a community effort, are independent of the geographic region and apply to other similar efforts.

Introduction

Three-dimensional (3D) ground-motion simulations are playing an increasingly important role in assessing seismic hazards (for example, see Moschetti, Chang, and others, 2018). The simulations provide a means for incorporating complex rupture and geologic effects that are important but difficult to capture in traditional, empirical ground-motion models. Whereas the underlying physics of seismic wave propagation is well understood, the accuracy of the ground-motion simulations is limited by our knowledge of the elastic and anelastic (nonlinear and attenuation) properties of earth materials, which are usually described by 3D seismic velocity models. Constructing and refining these models to a high degree of confidence requires the integration of information from a wide variety of geologic, seismic, geotechnical, and geophysical sources. As a result, sustaining long-term development of 3D seismic velocity models is most effective when it is a coherent effort that pools community expertise and resources. This five-year science plan outlines short-term and long-term goals for improving 3D seismic velocity models in the greater San Francisco Bay region as well as how to foster a community effort in reaching those goals. The plan describes opportunities for contributions by members of the community to the develop these seismic velocity models, provides current and potential users with general information on where efforts will likely be focused to improve these models and how new versions will be released, and outlines funding needs and obstacles for improving and maintaining such models. Several aspects of this plan, including how to foster a community effort, are independent of the geographic region and apply to other similar efforts.

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2018 Workshop

This science plan was developed from presentations and discussions at a workshop held March 21–22, 2018, at the U.S. Geological Survey (USGS) Earthquake Science Center in Menlo Park, California. The workshop included sessions describing the 2008 USGS San Francisco Bay region 3D seismic velocity model (Aagaard and others, 2010; which was the most recently released version at the time of the workshop), related efforts, uses of 3D seismic velocity models, how delivery and accessibility of seismic velocity models to users could be improved, what currently available data could be used to improve seismic velocity models for the greater San Francisco Bay region, what new data offered exciting avenues for improving seismic velocity models, and how a community effort could be fostered to further develop these models. (See Appendix 1 for the workshop agenda and list of participants.) This science plan is an outcome of the workshop as well as additional follow-up discussions, especially in refining ideas into short-term and long-term goals. As part of the implementation of this science plan, a second workshop was held on May 16, 2019, to coordinate activities related to the short-term and long-term goals. (See Appendix 2 for the agenda and list of participants of this second workshop.)

Short-Term Goals

In years 1–2, we recommend focusing on

- Expanding the detailed USGS San Francisco Bay region seismic velocity domain outward by adding adjacent detailed models, such as that for the Sacramento-San Joaquin Delta;
- Refining the model within the existing detailed seismic velocity domain by improving the underlying geologic model and the velocity-depth relationships using available data; target regions include the Hayward Fault zone and adjacent region to the east, and the Napa Valley;
- Assessing the accuracy of the model in areas with high seismic risk and acquiring new data in areas where the model is less accurate;
- Creating datasets for validation and quantifying how changes to the model would improve its accuracy in seismic hazard applications; and
- Establishing a framework for leveraging community resources to reach the short-term and long-term goals.

Long-Term Goals

In years 3 and beyond, the high priority goals include

- Acquiring new data to bridge the gap between local high-resolution observations and regionally sparse or coarse-resolution observations, including making use of new instrumentation such as “nodal” arrays and distributed acoustic sensing;
- Leveraging improved methods for constructing and constraining 3D geologic and seismic velocity models, such as ambient field tomography, sequentially structurally constrained inversion, reverse time migration, and machine learning;
- Improving the resolution of seismic velocity model(s) in the greater San Francisco Bay region, especially for depths less than 1 km;
- Adding uncertainty estimates to the seismic velocity model(s) and developing additional models that reflect alternative interpretations (epistemic uncertainty);
- Cataloging data and models and archiving important models in open, curated repositories; and
- Developing informal and formal collaborations with other related efforts to leverage resources and promote community building.

Synergy with Other Efforts

Several of these long-term goals apply to development of other 3D seismic velocity models as well. Methods for constructing and improving 3D geologic and seismic velocity models are relatively independent of the geographic location. Similarly, archiving data and models is important regardless of the geographic region. The strongest synergy exists within California, due to the overlap in personnel involved in 3D seismic velocity model development in the greater Los Angeles region and the greater San Francisco Bay region, and a general focus in both regions on the San Andreas Fault system. Nevertheless, considerable differences and challenges in the two regions are due to seismic network design, seismicity, regional community organizations, funding availability, and the user community. Other closely related efforts include those in the Pacific Northwest and along the Wasatch Front in Utah. All of these regional models will inform the USGS National Crustal Model.

We recommend that researchers involved in 3D seismic velocity modeling, especially those working in California, actively seek opportunities for collaboration, sharing ideas, and leveraging common modeling infrastructure. These opportunities could include joint meetings of the recently formed SCEC (Southern California Earthquake Center) Technical Activity Group focused on seismic velocity model development, and the working group on seismic velocity model development in the greater San Francisco Bay region, which is discussed in the next section.

Community Building

Several factors would greatly contribute to building an active community of developers and users focused on improving 3D seismic velocity models for the greater San Francisco Bay region. These include

- Curated, open data;
- Leveraging open-source tools for building, analyzing, and improving models;
- An open, efficient organizational structure that fosters guided collaboration;
- Dedicated technical and scientific staff with institutional support; and
- Sustainable, long-term funding.

Leveraging data is most efficient if it exists in curated, open collections with appropriate metadata, versioning, and use of modern standard formats. In the long-term, data collections used to constrain a model become more valuable than the model itself as new models are constructed using improved techniques with previous data or using additional data. Open-source tools lower entry barriers to researchers wanting to contribute to model development while allowing full inspection and reproducibility. Open-source tools also help mitigate against an overabundance of new models simply because, in their absence, it can be easier to create a new model than to update an existing one that first requires obtaining access to the necessary tools.

We recommend forming a working group that balances representation from the various disciplines and core institutions involved to implement this science plan. The working group would be responsible for coordinating research efforts, assessing progress, setting strategic milestones, organizing an annual workshop, and forming short-term, ad hoc technical working groups. The working group could also encourage institutional support, sustained funding and staffing, facilitate integration of research priorities into calls for proposals from various funding sources, and help coordinate collaborative proposals with multi-year funding.

San Francisco Bay Region 3D Seismic Velocity Models

Several 3D seismic velocity models of the San Francisco Bay region have been constructed since the magnitude 6.9 Loma Prieta earthquake in 1989. Frankel and Vidale (1992) constructed a seismic velocity model of the Santa Clara Valley, capturing the variation in alluvium over bedrock. Stidham and others (1999) constructed a regional-scale model that represented the major geologic units and sedimentary basin structures. The model used simple polygons to define rough outlines of the basins and fault-bounding structures. Hole and others (2000) combined travel times from the northern California earthquake catalog and the 1991 Bay Area Seismic Imaging Experiment refraction survey to generate a 3D model with more detail than the model by Stidham and others. This model identified thick low-velocity sediment in the Sacramento-San Joaquin Delta (greater than 12 km), Livermore Valley (6 km), Santa Clara Valley (5 km), and eastern San Pablo Bay (4 km). Hole and others (2000) also identified lateral velocity contrasts of 0.3–0.6 km/s across the San Andreas Fault in the middle crust and across the Hayward, Rodgers Creek, Calaveras, and Greenville Faults at shallow depth. Employing updated datasets and a similar approach, Thurber and others (2007) developed a P-wave velocity model of the San Francisco Bay region using double-difference tomography with earthquake and explosion data, and Hardebeck and others (2007) derived a higher-resolution tomographic P-wave velocity model of the eastern San Francisco Bay region, also using earthquake and explosion data.

At the same time, the USGS developed a 3D geologic model (Jachens and others, 2006) and applied rules to define the elastic properties of geologic units as a function of depth within each unit (Brocher, 2008), resulting in a 3D seismic velocity model (Aagaard and others, 2008a). This latter model, with greater detail than the others, has become the standard 3D seismic velocity model for the San Francisco Bay region and has been used to simulate earthquake ground-motions in the region (Aagaard and others, 2008a,b, 2010; Kim and others, 2010; Rodgers and others, 2018, 2019).

Hartzell and others (2006) and Harmsen and others (2008) developed several alternative 3D seismic velocity models of the southern San Francisco Bay region based on the Jachens and others (2006) geologic model but with some differences in elastic properties from those given by Brocher (2008). The differences are most prominent in the Evergreen basin northeast of San Jose, where simulation with smaller gradients in the elastic properties in the top 1 km provide a better match between synthetic and observed waveforms for moderate earthquakes. These alternatives should be evaluated in the context of the additional data now available for small and moderate earthquakes and potential revisions to the USGS 3D San Francisco Bay region seismic velocity model.

USGS San Francisco Bay Region 3D Seismic Velocity Model

The USGS San Francisco Bay region 3D seismic velocity model was originally constructed to enable 3D ground-motion simulations of the 1906 San Francisco earthquake. The model is composed of a detailed domain spanning a 290 km by 140 km by 45 km volume of the greater San Francisco Bay urban region (fig. 1) surrounded by a coarser regional domain spanning a 650 km by 330 km by 45 km volume that encompasses a broad region around the entire length of the 1906 earthquake rupture.

The 3D geologic model was constructed in 2005 (Jachens and others, 2006), making use of three primary datasets: geologic maps, gravity and aeromagnetic maps from potential-field geophysics, and double-difference relocated seismicity (Ellsworth and others, 2000; Waldhauser and Ellsworth, 2000). A digital elevation model (USGS 300 meter) and bathymetry (National Oceanic and Atmospheric Administration 1 arc-second) define the top surface. The upper crustal structure is defined by the main active faults along with other faults that juxtapose geologic units with significantly different rock types. The surface traces from geologic maps are projected downward to match (in order of priority)

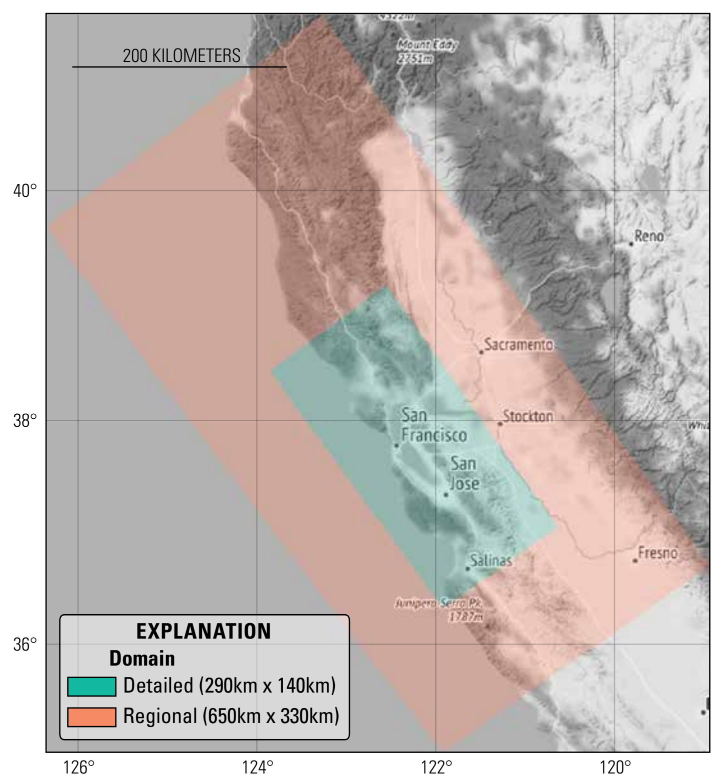

Figure 1. Map of the detailed and regional domains of the U.S. Geological Survey San Francisco Bay region three-dimensional geologic model. The detailed region encompasses the greater San Francisco Bay urban area. Map tiles by Stamen Design, under Creative Commons Attribution 3.0 Unported. Data by OpenStreetMap, under Open Data Commons Open Database License. (km, kilometers)

1. Earthquake hypocenters;
2. Geophysical constraints (primarily gravity and aeromagnetic anomalies with some additional constraints from travel-time tomography and seismic reflection studies); and
3. Regional dip angles based on the sense of offset and regional tectonics.

The fault surfaces are extended to intersect other faults or external boundaries in order to form closed volumes. The volumes are closed at depth by mid- and lower-crustal boundaries, including the Moho. The structural blocks in the upper crust are subdivided based on a greatly simplified stratigraphy (Cenozoic strata in which Quaternary-Pliocene strata are locally differentiated from the remaining Cenozoic, Cretaceous strata, and various basements). The detailed domain contains 26 fault blocks subdivided by 29 zone surfaces and 25 fault surfaces. The regional domain is much simpler, with 12 fault blocks separated by 11 faults and subdivided into a total of 20 zones. The regional domain extends the outer blocks of the detailed domain in a simple way, adding one additional fault block (Vizcaino) west of the northern San Andreas Fault. The surface contacts are generalized from geologic maps and projected downward, guided by the gravity and aeromagnetic models. The basement continues to the mid-crust except where the gravity and aeromagnetic models require more complex, local adjustments. Near-surface units are not differentiated, and Quaternary deposits are generally lumped into a single unit. Figure 2 shows a perspective view of the detailed 3D geological model.

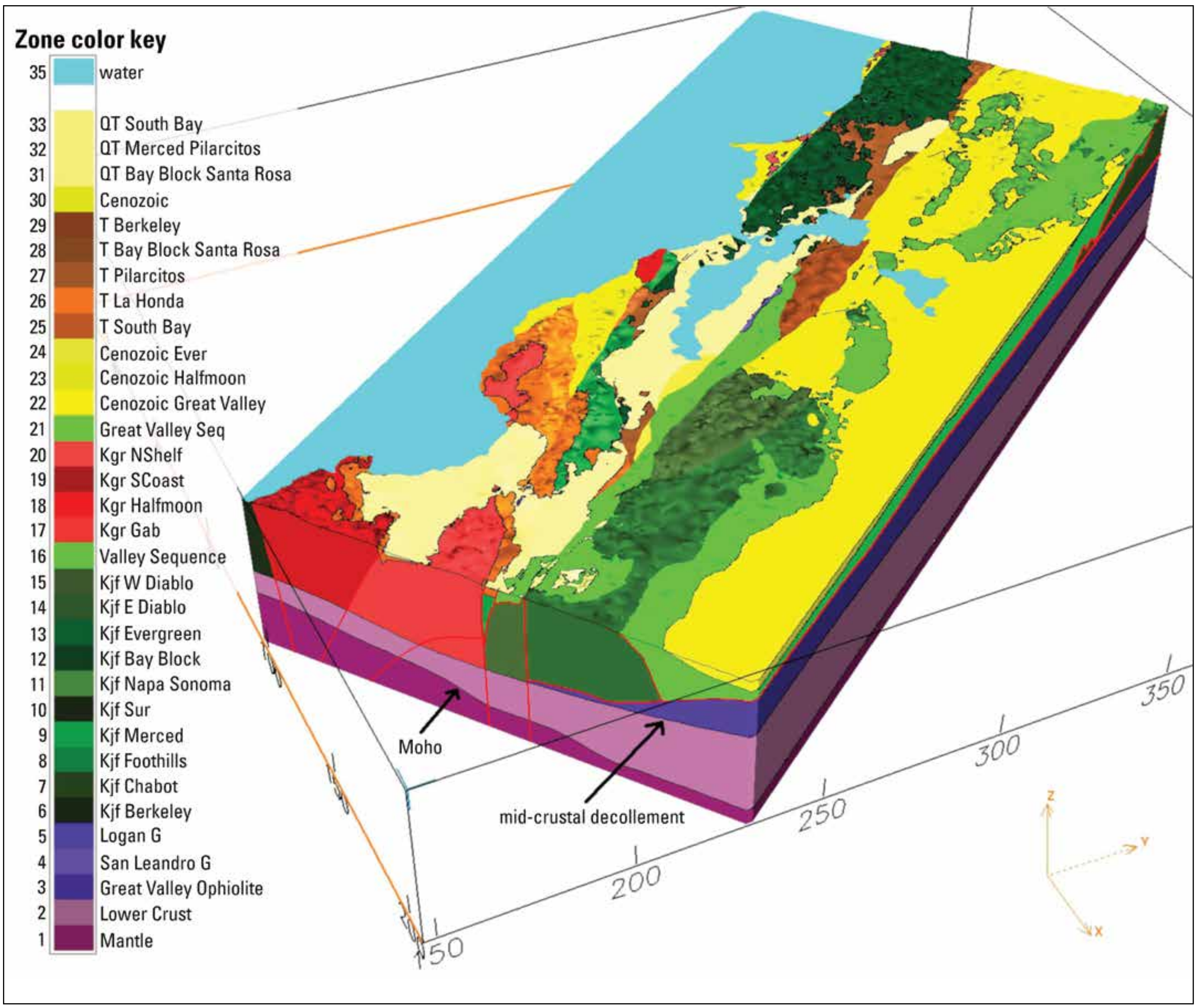

Figure 2. Perspective view of the detailed three-dimensional geologic model from the southeast. The colors show the different geologic units (zones within the geologic model). Zone number 34 corresponds to regions outside the domain, so it is not shown.

The main structural feature of the detailed 3D geologic model is the San Andreas Fault system, including the main active strands (San Gregorio, San Andreas, Hayward-Rodgers Creek-Healdsburg-Maacama, and Calaveras-Concord-Green Valley-Berryessa) as well as other less active strands (Zayante, Greenville, West Napa, and Santa Cruz Mountains Foothills Thrust), and strands that are no longer active but form significant tectonic boundaries (Pilarcitos, Silver Creek, Petaluma Valley, and Palomares-Miller Creek-Moraga-Pinole-Carneros). These faults accommodate a cumulative Neogene right-lateral offset of about 470 km, as well as a significant, more local vertical offset. As a result, the faults form major boundaries between different basement types that demarcate large changes to the depth of basement and the lithology in overlying units.

The model also includes major faults that predate the San Andreas (Coast Ranges, Sierran basement underthrust east of the Greenville, and Nacimiento west of the San Gregorio) that form boundaries between several basement complexes in the region. Within the Salinian basement west of the San Andreas Fault, dense and magnetically susceptible Logan gabbro is bounded below by a nearly horizontal fault and forms a subhorizontal lens-shaped body between the overlying sedimentary rocks and the underlying, more typical Salinian granitic basement.

All these faults are bounded below by a mid-crustal decollement at the brittle-ductile transition, which separates the detailed depiction of the upper crust from a homogeneous lower crust in the model. Although the faults are modeled as through-going to the bottom of the model (the red lines in fig. 2 extend to the bottom of the model), this is just an artefact of the model-building process. The mid-crustal decollement (top of the lower crust) is not offset along any of the faults. The lowest structure in the model is the Mohorovicic discontinuity (Moho), separating homogeneous lower crust from homogeneous upper mantle.

In addition to the fault structures, the model also incorporates a number of Cenozoic basins (Cupertino, Evergreen, San Leandro, San Pablo Bay, Petaluma, Santa Rosa, Suisun, and Livermore). These are volumes of anomalously thick Cenozoic rocks within larger volumes of denser rock. Most of them are fault-bounded, although many of the bounding faults are not incorporated into the model because they have relatively minor offset and no effect on the model geology away from the basin.

As mentioned above, the regional domain generally extends the principal structures of the detailed domain. The one additional structure is the Navarro discontinuity, a basement complex bounding fault between the Salinian and Vizcaino (Franciscan-equivalent) basement west of the northern San Andreas Fault.

Almost all of the structures in the model were included because they form significant lithologic boundaries, and therefore important discontinuities in the seismic velocity model. The few structures that do not form such boundaries are active parts of the San Andreas Fault system that are very young and have not yet accumulated much offset. These faults are included so that all major parts of the currently active fault system are in the model, as this model was also used as a basis for the regional 3D fault model.

Version 05.1.0 of the 3D seismic velocity model was constructed by applying rules, developed by Brocher (2008), which assign elastic properties to each point in the 3D geologic model based on geologic unit and depth. This allows assignment of the compressional wave speed (V_p), shear wave speed (V_s), and density to every point in the volume spanned by the geologic model. The V_p-depth relations are based on borehole, laboratory, seismic refraction and tomography, and density measurements. The V_s-depth relations were derived from V_p-V_s relations. These relations account for increasing overburden pressure and average mineralogical composition but do not account for other factors that generally alter velocities over shorter length scales, such as consolidation, induration, porosity, uplift and burial history, stratigraphic age, and deviations from average mineralogical composition. Density is derived from the V_p and density relations given in Brocher (2005a,b). The attenuation parameters Q_p and Q_s were taken from Olsen and others (2003).

Version 08.3.0 of the seismic velocity model (Aagaard and others, 2010) updates the Brocher (2008) rules based on evaluations of modeling waveforms from moderate earthquakes (Rodgers and others, 2008) and comparison of wavespeeds with a travel-time tomography seismic velocity model (Thurber and others, 2007). The principal changes include

- Reduced V_p and V_s in granites, Franciscan, gabbro, lower crust, and upper mantle geologic units, generally by a few percent;
- Increased V_p and V_s by ten percent in the La Honda basin; and
- Q_p and Q_s as a function of V_p and V_s using the relations given in Brocher (2008) rather than those in Olsen and others (2003).

Figures 3–6 show maps of V_p and V_s on horizontal slices through the regional and detailed seismic velocity domains. The locations of the sedimentary basins, especially the Great Valley that runs along the eastern portion of the regional domain are evident in the local low-velocity zones. The outlines of several sedimentary basins are visible in the jump from pink to purple in the map of V_s at an elevation of −1 km shown in figure 6. These include the Cupertino basin southwest of San Jose and the Evergreen basin northeast of San Jose, the Livermore basin east of Hayward, the San Pablo basin extending south from Vallejo, and the Cotati and Windsor basins south and north of Santa Rosa, respectively. The maps of the depth to the V_s 1.0 km/s and 2.5 km/s isosurfaces given in figure 7 also highlight the locations of the sedimentary basins with greater depths to the isosurfaces. One of the features present in the seismic velocity model is a sharp velocity contrast across the Hayward Fault. Velocities in the surface sediments on the west side of the fault are slower than those in the more competent material in the hills on the east side of the

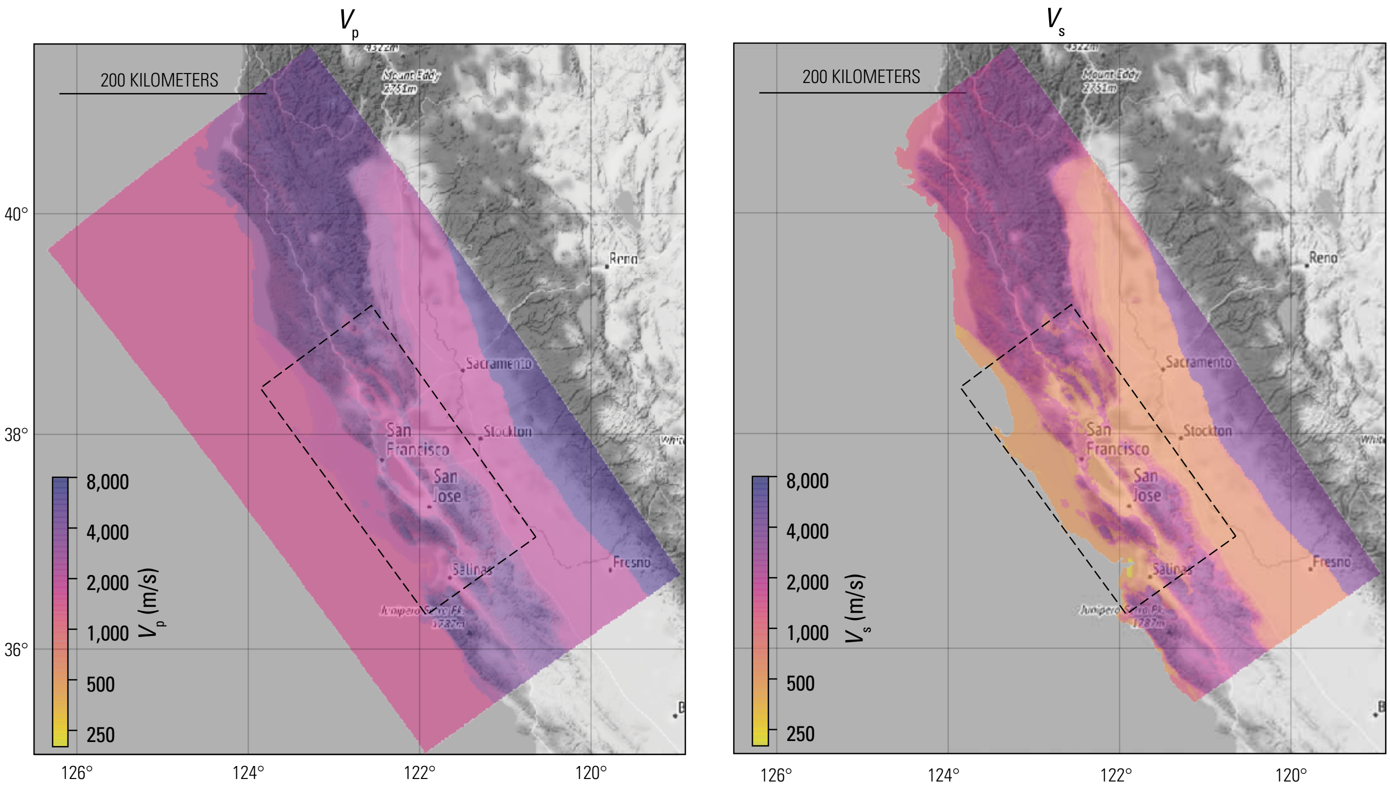

Figure 3. Map of P-wave speed (V_p, left) and S-wave speed (V_s, right) at an elevation of −101 meters in the regional and detailed domains. The dashed line outlines the extent of the detailed model. Map tiles by Stamen Design, under Creative Commons Attribution 3.0 Unported. Data by OpenStreetMap, under Open Data Commons Open Database License. (km, kilometers; m/s, meters per second)

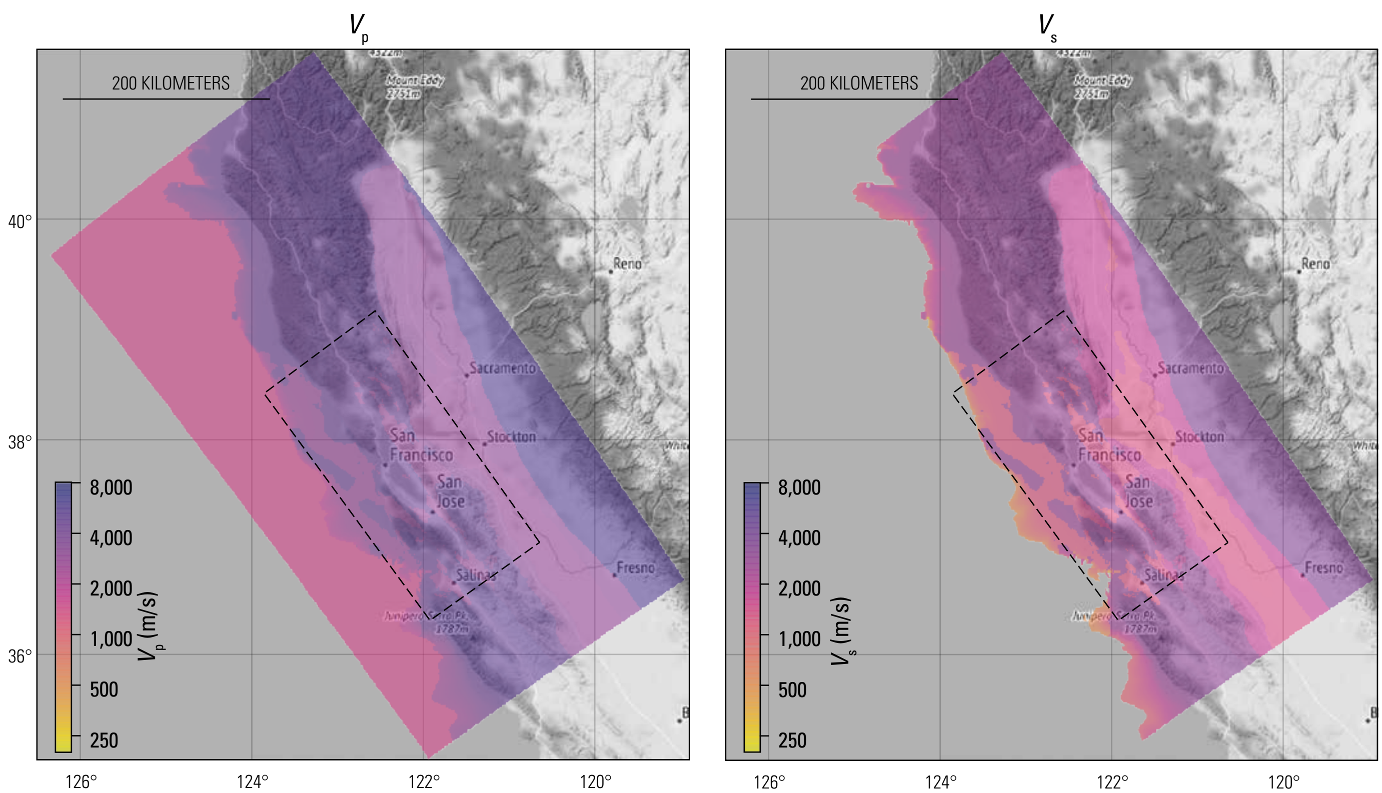

Figure 4. Map of P-wave speed (V_p, left) and S-wave speed (V_s, right) at an elevation of −1 kilometer in the regional and detailed domains. The dashed line outlines the extent of the detailed model. Map tiles by Stamen Design, under Creative Commons Attribution 3.0 Unported. Data by OpenStreetMap, under Open Data Commons Open Database License. (km, kilometers; m/s, meters per second)

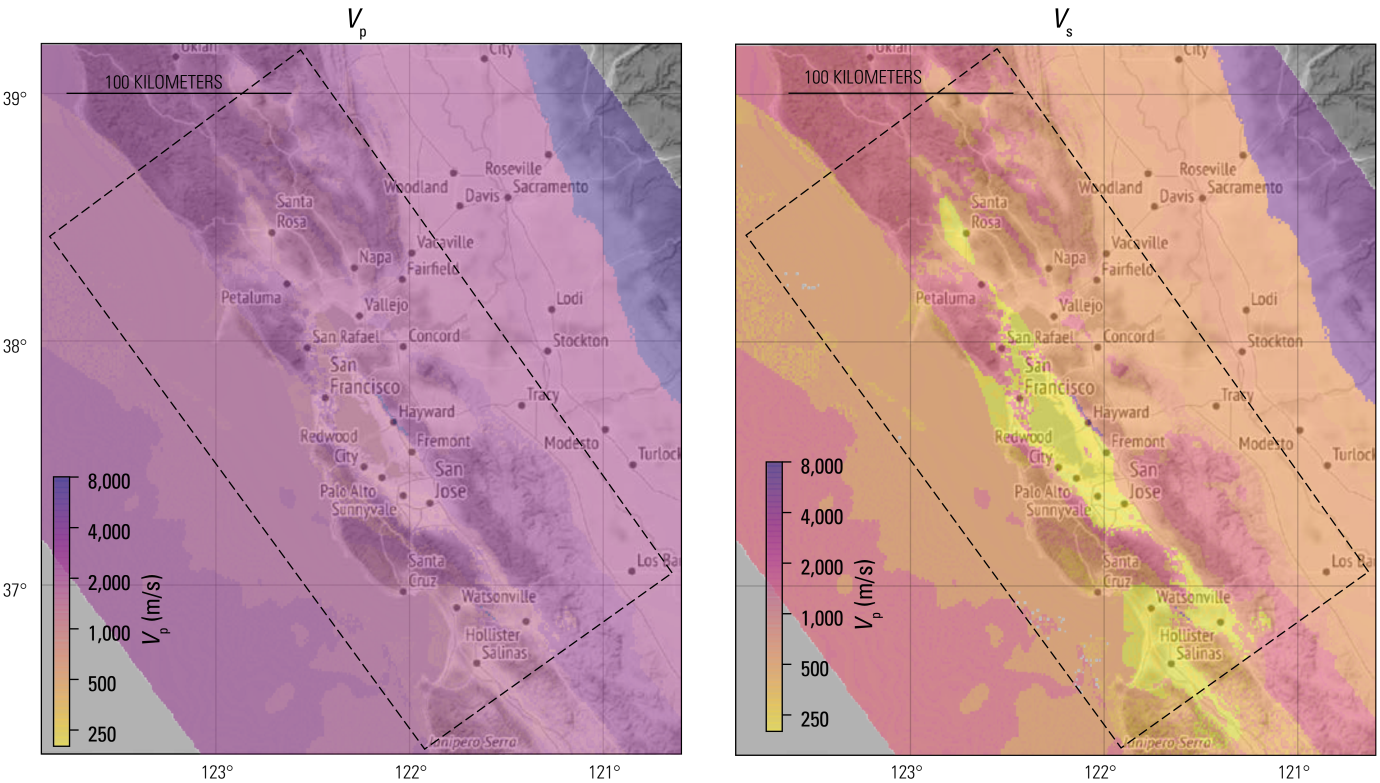

Figure 5. Map of P-wave speed (V_p, left) and S-wave speed (V_s, right) at a depth of 10 meters below the ground surface in the regional and detailed domains, zoomed in to the extent of the detailed model (shown by the dashed line). Map tiles by Stamen Design, under Creative Commons Attribution 3.0 Unported. Data by OpenStreetMap, under Open Data Commons Open Database License. (km, kilometers; m/s, meters per second)

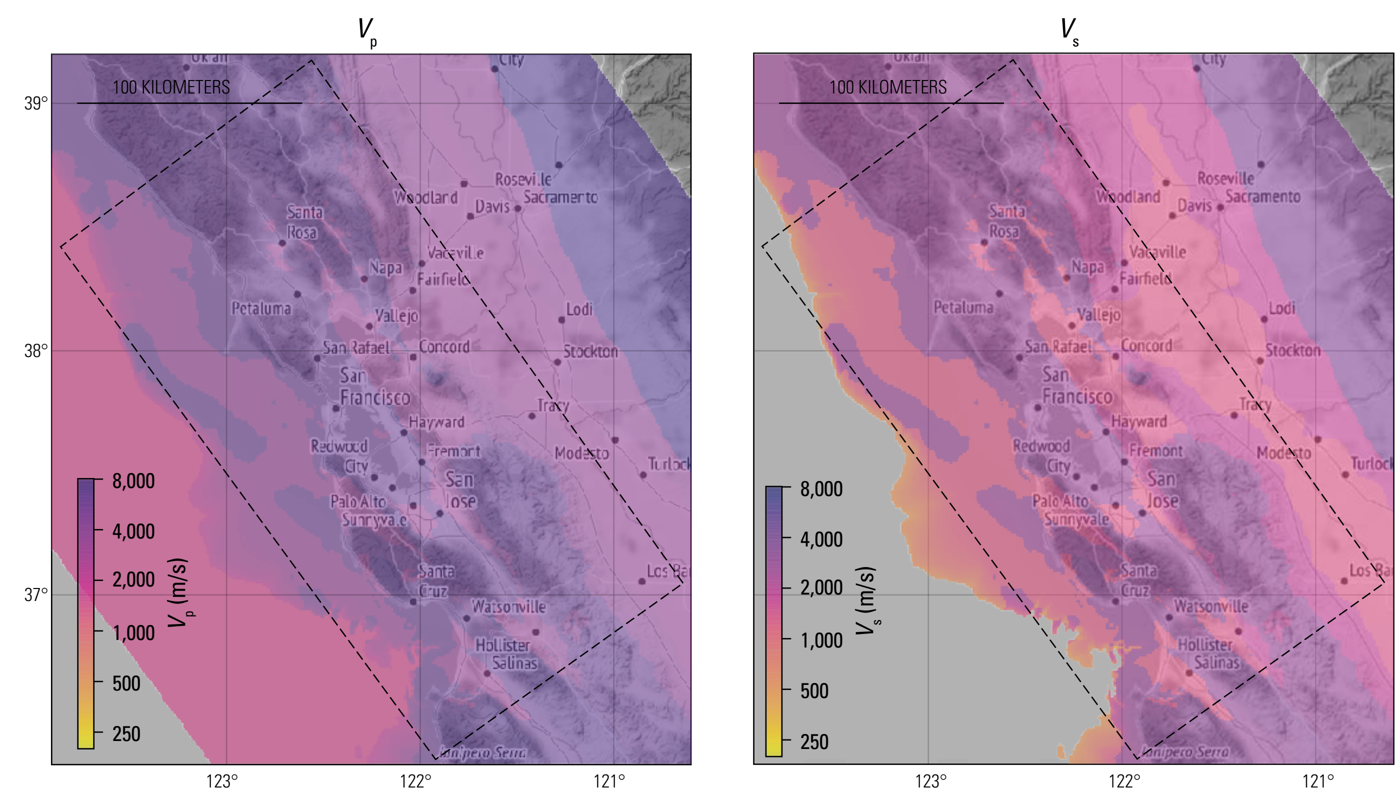

Figure 6. Map of P-wave speed (V_p, left) and S-wave speed (V_s, right) at an elevation of −1 kilometer (km) in the regional and detailed domains, zoomed in to the extent of the detailed domain (shown by the dashed line). Map tiles by Stamen Design, under Creative Commons Attribution 3.0 Unported. Data by OpenStreetMap, under Open Data Commons Open Database License. (m/s, meters per second)

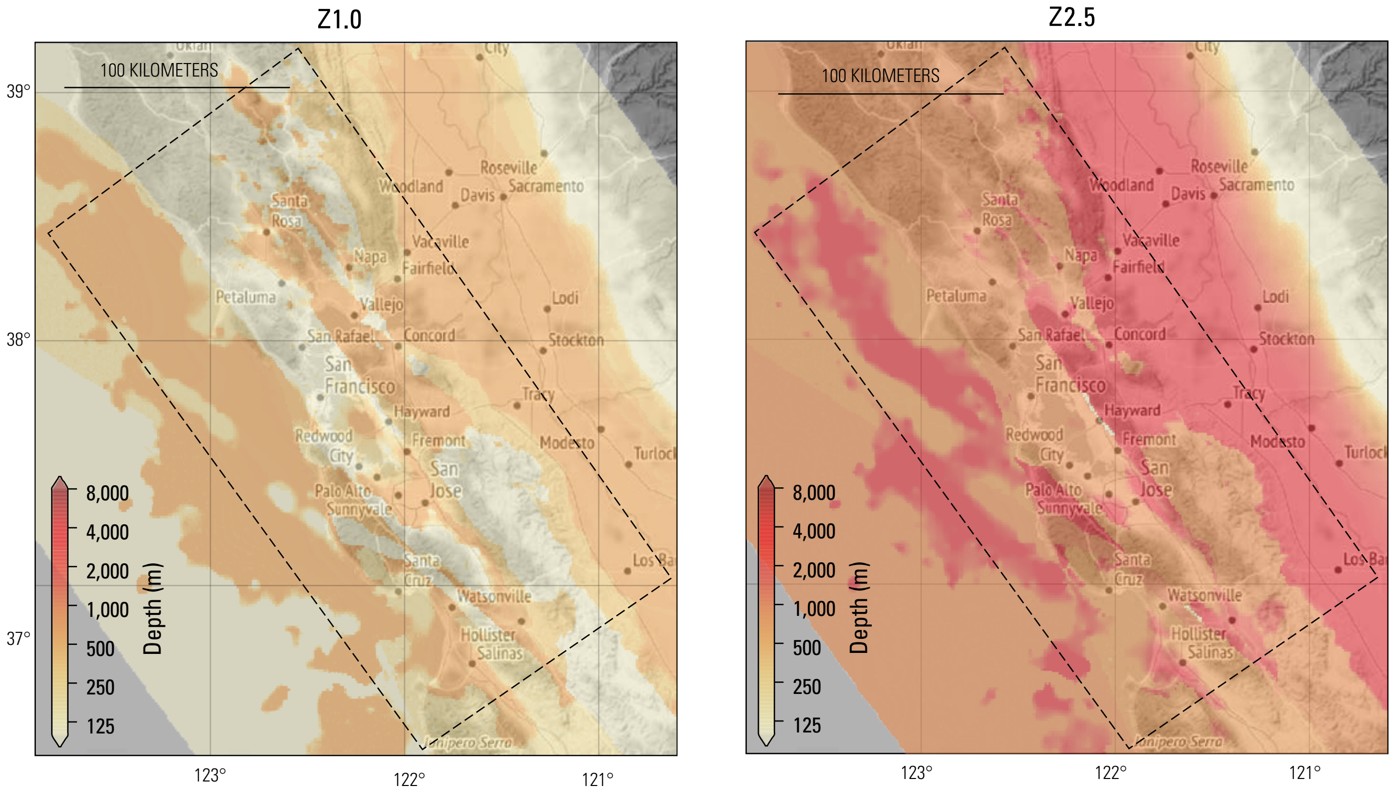

Figure 7. Maps of Z1.0 (depth to 1 kilometer per second S-wave speed isosurface, left) and Z2.5 (depth to 2.5 kilometers per second S-wave speed isosurface, right) in the regional and detailed domains. The dashed line outlines the extent of the detailed domain. These values are commonly used in ground-motion prediction equations to account for amplification in sedimentary basins. Map tiles by Stamen Design, under Creative Commons Attribution 3.0 Unported. Data by OpenStreetMap, under Open Data Commons Open Database License. (m, meter)

fault; this velocity contrast reverses at depth with slower velocities on the eastern side of the fault associated with the presence of Cenozoic and Mesozoic rocks (Graymer, 2000). The map of V_s at an elevation of −1 m in figure 5 shows the relatively soft near-surface material that underlies most of the San Francisco Bay urban area.

The seismic velocity model is delivered to users as a rasterized grid that is encoded as an octree (https://en.wikipedia.org/wiki/Octree, accessed September 25, 2019) stored in a binary file. The octree encoding provides compression and fast lookup of the location in the file for any point in the velocity model domain. A library with C, C++, and Fortran interfaces provides an application programming interface (API) for obtaining the elastic properties and attenuation parameters at any longitude, latitude, and elevation in the model. This high-level library is built on top of the Euclid library (http://www.cs.cmu.edu/~euclid/, accessed September 25, 2019), which provides the octree encoding and decoding with cache support to help reduce input and output bottlenecks. The resolution of the rasterized grid varies with depth as given in table 1. Grid cells above the ground surface are not stored. The rules were applied at the centroids of the grid cells and the API returns the same properties for all locations within each grid cell. That is, the discretization assumes uniform properties within each grid cell. This assumption simplifies queries but linear interpolation would provide a more accurate representation for a given resolution.

The API for querying the seismic velocity model (accessed September 25, 2019, at https://github.com/usgs/earthquake-cencalvm) consists of a handful of functions that allow the user to query for user-specified values at a point in space given by longitude, latitude, and elevation. Many finite-difference seismic wave propagation codes use a flat ground surface, so the API supports both simply ignoring the presence of material above a given elevation (essentially bulldozing all material away above the given elevation) or adjusting the topography up/down (squashing the topography) to create a flat surface at a given elevation.

Table 1. Horizontal and vertical resolution of the seismic velocity model grid.

Elevation range[1]	Horizontal resolution	Vertical resolution
	Detailed	
z > −400 m	100 m	25 m
−400 m > z > −3,200 m	200 m	50 m
−3,200 m > z > −6,400 m	400 m	100 m
−6,400 m > z > −45 km	800 m	400 m
	Transition[2]	
z > −3,200 m	200 m	50 m
−3,200 m > z > −6,400 m	400 m	100 m
−6,400 m > z > −45 km	800 m	200 m
	Regional	
z > −6,400 m	400 m	100 m
−6,400 m > z > −45 km	800 m	200 m

[1]Elevation, z, is with respect to the North American Vertical Datum of 1988 (m, meter; >, greater than).

[2]The transition is a region 3.2 kilometers wide surrounding the detailed domain that extends the entire depth of the model. It provides a smooth transition in elastic properties from the higher resolution detailed domain to the rest of the regional domain.

Accuracy of Simulated Ground Motions for Moderate and Large Earthquakes

The USGS San Francisco Bay 3D seismic velocity models (versions 05.1.0 and 08.3.0) have been used to model waveforms and ground-motion intensity measurements from the 1989 Loma Prieta earthquake as well as more recent moderate earthquakes. These earthquakes provide ground-motion data to evaluate predictions from the model using 3D wave propagation codes.

Two studies have examined the performance of the models at the regional scale. Rodgers and others (2008) used version 05.1.0 of the model to simulate long-period (4–33 seconds, 0.03–0.25 Hz) waveforms for 12 moderate earthquakes (Mw 4.0–5.4) recorded at Berkeley Digital Seismic Network (BDSN) broadband stations. They used an elastic finite-difference, time-domain code without topography (ignoring material above sea level) or attenuation. They found a systematic bias with phase delays dominated by surface wave increasing with distance, suggesting that the nominal shear wave speeds in the upper crust were 4–5 percent too fast in the model. However, wave speeds were too slow in some areas of the model, such as in the Santa Rosa area. The Rodgers and others (2008) study was limited to broadband stations and 12 earthquakes; path coverage heavily sampled the East Bay Hills. They obtained good fits to waveform shapes in this period band if synthetics were aligned by cross-correlation with delays of up to 5 seconds for long paths (50–200 km). Seismic wave paths sampling different geologic units (for example, sedimentary basins or crossing major faults) produced complex, late arriving waves that were commonly predicted by the 3D model. Results from this study provided encouragement that long-wavelength 3D structure in version 05.1.0 of the model produced reasonable fits for long-period waveforms. Rodgers (2015, with further reporting on the work completed in 2007–08) computed delay times and waveform fits for model versions 05.1.0 and 08.3.0 for a subset of events recorded at Berkeley Digital Seismic Network stations. Rodgers found that travel-time biases are reduced for version 08.3.0 relative to 05.1.0 by about 20–30 percent, and waveforms fits are better for version 08.3.0 compared to version 05.1.0.

Kim and others (2010) used a different finite-difference, time-domain computer code to compare predictions from the 05.1.0 and 08.3.0 versions of the model for arrival times and ground-motion intensity measures for 10 moderate earthquakes (Mw 4.1–5.4) at broadband and strong-motion stations. They also focused on relatively long-period waves (33–2 seconds, 0.03–0.5 Hz). Kim and others (2010) also found an arrival time bias in version 05.1.0 of the model similar to that described by Rodgers and others (2008), but this bias was reduced in version 08.3.0 of the model for the P- and S-wave arrivals. They analyzed peak ground velocity and spectral accelerations and found good agreement between the observations and predictions over a range of 4 orders of magnitude, with version 08.3.0 of the model producing smaller residual amplitudes compared to version 05.1.0. Kim and others (2010) noted that most of the misfits in peak ground velocity are less than a factor of 2, but some sites did have misfits as large as a factor of 4.

Studies have also examined the accuracy of the seismic velocity model for two well-recorded, large earthquakes in the San Francisco Bay region, the 1989 magnitude 6.9 Loma Prieta earthquake and the 2014 magnitude 6.0 South Napa earthquake. Aagaard and others (2008a) used version 05.1.0 of the model to simulate ground motions from the Loma Prieta earthquake using rupture models from the Beroza (1991) and Wald and others (1991) kinematic source inversions. The four different modeling groups used slightly different parameters related to attenuation and topography. All of the modeling groups were able to capture the large-scale spatial variations in shaking associated with rupture directivity and geologic structure. On average, the broadband simulations underpredicted the peak velocity by about 16 percent, and in a variety of locations found greater variability in ground motions arising from differences in the two rupture models compared with the variations in waveforms associated with local spatial variability in the seismic velocity structure.

Graves and Pitarka (2018) simulated the 1989 Loma Prieta earthquake using version 08.3.0 of the model. Instead of an earthquake rupture model from a source inversion, they selected a kinematic rupture model that produced the best goodness-of-fit to recorded ground motions in a one-dimensional (1D) seismic velocity model from a suite of random realizations. The model simulated a flat ground surface (no topography) at sea level, in essence bulldozing away the material above this elevation. They compared synthetic motions with recorded motions at frequencies up to 4 Hz at 34 sites, all within 40 km of the fault rupture. The simulations fit the observed motions reasonably well, capturing the pulse-like character of the waveforms associated with rupture directivity and generally matching the large amplitude motions at these sites. However, they noted that the seismic velocity model includes low velocity structures that cause significant amplification and channel energy horizontally along the San Andreas Fault. One low velocity zone, west of the San Andreas Fault along the western side of the Santa Clara Valley, causes the peak velocities in the simulation to be 2–3 times larger than those observed at station LGP (Los Gatos Presentation Center). The other low velocity zone they noted is southeast along the extension of the rupture near Gilroy. Due to the significant effects these low velocity zones have on the simulated motions, it is important to determine how well resolved these structures are and to constrain the elastic properties within them.

The August 24, 2014, magnitude 6.0 South Napa earthquake provided a rich collection of ground-motion records in the northern San Francisco Bay region, including within the sedimentary basins that underlie the Napa and Sonoma Valleys and San Pablo Bay. Dreger and others (2015) compared observed waveforms with 1D and 3D simulations using version 08.3.0 of the model. The earthquake rupture model was estimated from regional strong-motion data at hard rock sites using 1D Green's functions; however, near-fault stations with paths sampling the sedimentary basins and topography near the source were better fit with the USGS 3D model than the 1D model, particularly late-arriving scattered waves.

Johansen and others (2017) and Rodgers and others (2018, 2019) used version 08.3.0 of the model to simulate ground motions for a magnitude 7.0 Hayward Fault scenario earthquake at frequencies up to 2.5–5.0 Hz. Rodgers and others (2018, 2019) found good agreement between simulated ground motions and ground-motion models from the Pacific Earthquake Engineering Research Center's Next Generation Attenuation models. Ratios of ground motion intensity measures for the 3D model and a reference 1D model identify path and site effects that are correlated as expected with higher intensities, where wave speeds are lower. These and earlier simulations of large scenario earthquakes (for example, Aagaard and others, 2010) have found large ground motions in the East Bay Hills, where low wavespeed sedimentary rocks associated with the Great Valley Sequence are present at depths of several kilometers, although fault dip may also play a role in causing large amplitude ground motions in this area.

Allam and others (2014) used measurements from fault zone head waves to constrain the velocity contrast across the Hayward Fault to 3–8 percent, with velocities in the Franciscan rocks southwest of the fault faster than those in the sedimentary Great Valley rocks on the northeast side of the fault. Version 08.3.0 of the model has a larger contrast of about 10–20 percent. This provides further evidence that the model seismic velocities in the Cenozoic and Mesozoic geologic units on the east side of the Hayward Fault are too slow.

Hartzell and others (2016) studied site response in the Livermore Valley and identified basin-edge generated surface waves by material heterogeneity across the Calaveras Fault. They performed 3D ground motion simulations for paths crossing this interface and proposed some modifications to version 08.3.0 of the model in order to better reproduce amplifications along the basin edge. They applied the rules from Brocher (2008) for seismic velocities in the Great Valley Sequence deeper than a depth of 4 km (the rules appear to have been incorrectly applied in version 08.3.0 for this geologic unit) and reduced the minimum shear wave velocity at the surface from 550 m/s to 350 m/s. These improvements need to be fully incorporated and further evaluated as part of the process for updating the seismic velocity model.

Related Efforts

Other Regional 3D Seismic Velocity Models in California

Southern California Earthquake Center Community Velocity Model H

The Southern California Earthquake Center (SCEC) Community Velocity Model H (CVM-H) 15.1.0 (fig. 8) by Shaw and others (2015) provides a model of the crust and upper mantle velocity structure in southern California. It is implemented as a Unified Structural Representation (USR). A USR brings together structural information from geology, tectonics and geodynamics with geophysical data in a self-consistent manner. The southern California USR comprises detailed basin velocity descriptions that are based on tens of thousands of direct velocity (V_p and V_s) measurements and incorporates the locations and displacement of major fault zones that influence basin structure. These basin descriptions were embedded in 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 based on V_{s30} measurements and consistent with the underlying velocity descriptions was also developed as an optional model component. The resulting model reflects the complex tectonic history of the region. The crust thickens eastward as Moho depth increases 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.

The model was constructed in a top-to-bottom manner. Shallower crustal data from well logging, seismic reflection surveys, and lithology were used to constrain deeper tomographic imaging, which in turn was used as input to model upper mantle velocity. Other key characteristics include the incorporation of borehole velocity log information and seismic reflection constraints on P-wave seismic velocities (V_p) and basement depths. Potential field data were primarily used to constrain the geometry of sedimentary basins. The deeper velocity structure is constrained by tomographic methods for velocities and by receiver functions for the Moho. S-wave velocity is derived from empirical relationships of Brocher (2005a,b).

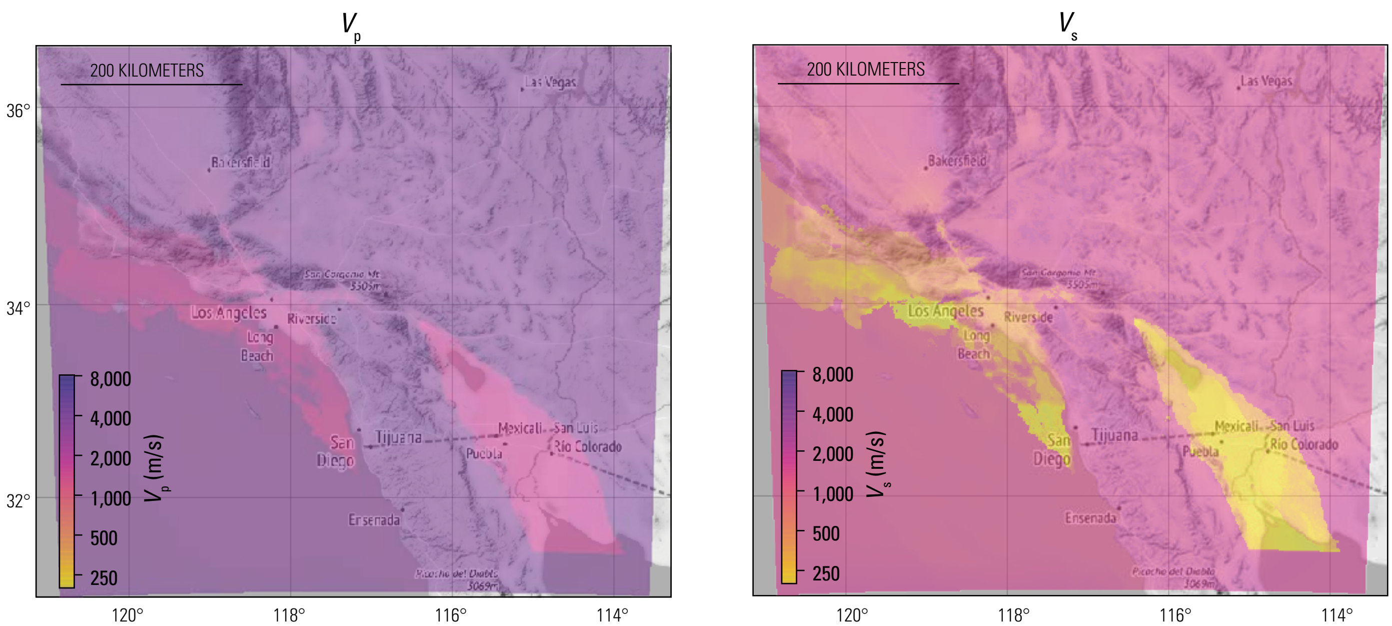

Figure 8. Map of P-wave speed (V_p, left) and S-wave speed (V_s, right) at a depth of 100 meters below the ground surface in the Southern California Earthquake Center Community Velocity Model H 15.1.0. Map tiles by Stamen Design, under Creative Commons Attribution 3.0 Unported. Data by OpenStreetMap, under Open Data Commons Open Database License. (km, kilometers; m/s, meters per second)

Southern California Earthquake Center Community Velocity Model S

The SCEC Community Velocity Model S (CVM-S) was originally a geology-based model (Magistrale and others, 1996) that used empirical rules to assign elastic properties, similar to the general construction of the USGS San Francisco Bay region seismic velocity model. It captured the sedimentary basin under Los Angeles as well as those in the San Gabriel and San Fernando Valleys. The original model was updated by Magistrale and others (2000). Kohler and others (2003) improved the San Bernardino Valley and the Salton Trough regions of the model and incorporated a new V_p-density empirical relation to create version 4 (CVM-S4). Subsequently, CVM-S4 was updated using a sequence of 26 full waveform tomography inversions at frequencies up to 0.2 Hz, producing model CVM-S4.26 (Chen and others, 2007; Lee and others, 2014). CVM-S4.26 includes V_s, V_p, and density on a 500 m grid, with minimum V_s values of 900 m/s. An additional version (CVM-S5) integrates CVM-S4.26 with the CVM-S4, near-surface geotechnical layer. The desired effect is that the integrated model captures the low, near-surface seismic velocities while smoothly adding positive and negative perturbations (fig. 9). Versions of CVM-S4 have been used for ground-motion simulations for seismic hazard estimation (for example, Graves and others, 2011).

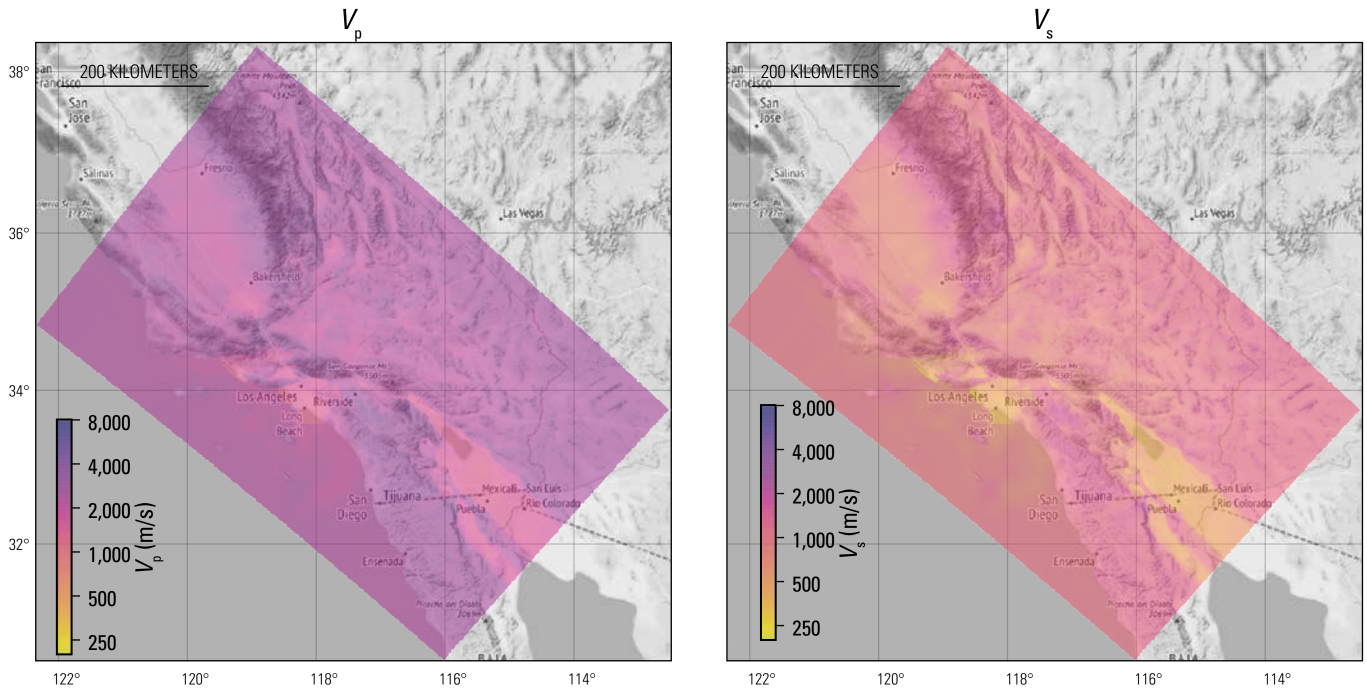

Figure 9. Map of P-wave speed (V_p, left) and S-wave speed (V_s, right) at a depth of 100 meters below the ground surface in the Southern California Earthquake Center Community Velocity Model S5. Map tiles by Stamen Design, under Creative Commons Attribution 3.0 Unported. Data by OpenStreetMap, under Open Data Commons Open Database License. (km, kilometer; m/s, meters per second)

Southern California Earthquake Center Central California Community Velocity Model

The SCEC Central California (CCA) seismic velocity model fills the region between SCEC models focused on the Los Angeles region (CVM-S and CVM-H) and the USGS model focused on the San Francisco Bay region. The current version, CCA06, corresponds to the 6th iteration of a tomographic model. The initial model consisted of a combination of the USGS San Francisco Bay region model (08.3.0) for northern CA and the CVM-S4.26 for southern CA. The same full waveform tomography approach used for CVM-S4.26 was utilized to refine the model in six subsequent iterations, each using sets of ambient-field Green's functions and earthquake waveforms. The 6th iteration included 59,000 ambient field Green's functions and 78,000 frequency-dependent waveform measurements. CCA06 provides V_p, V_s, and density (which is not changed from the starting model) on a 500 m grid, with minimum *V*s values of 900 m/s. The inversions reveal the presence of several basins (see fig. 10) and provide a more refined representation of the Great Valley relative to CVM-S4.26. It does not capture near-surface structure with the same resolution as the USGS San Francisco Bay detailed domain or SCEC CVM-S4.26 M01 due to the relatively coarse resolution of the grid and minimum shear wave speed of 900 m/s.

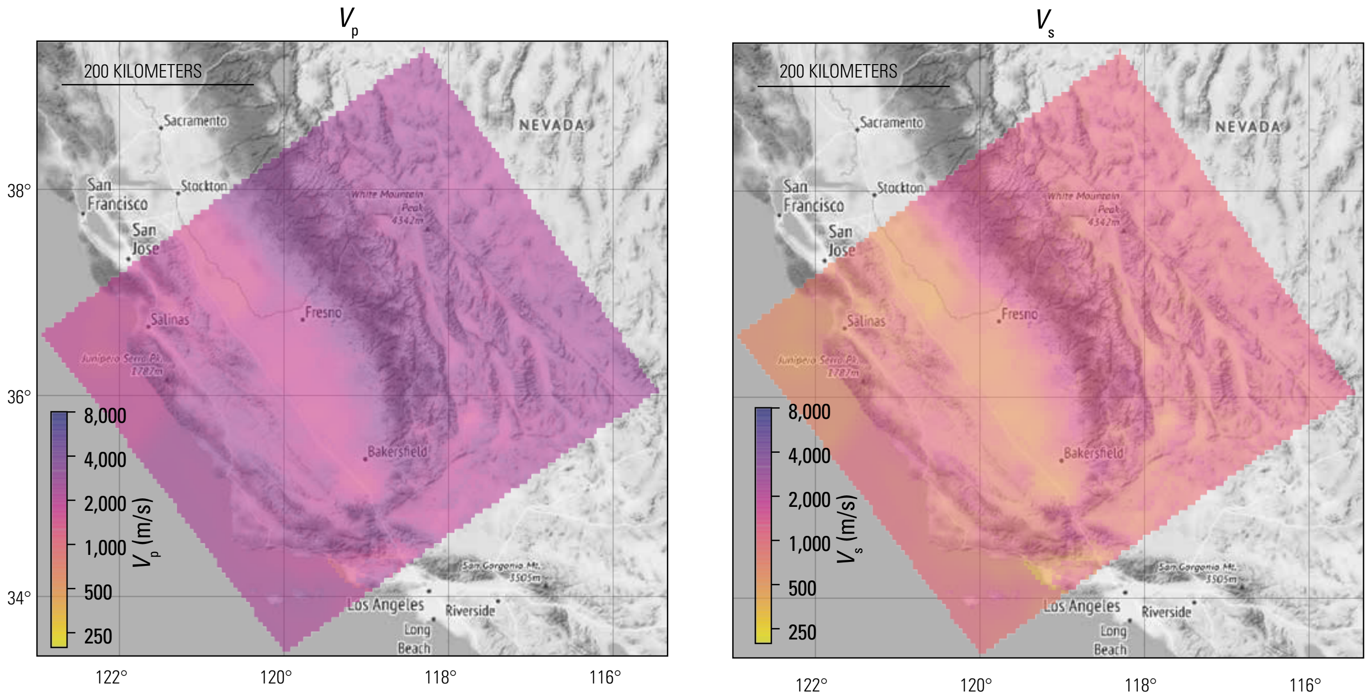

Figure 10. Map of P-wave speed (V_p, left) and S-wave speed (V_s, right) at a depth of 100 meters below the ground surface in the Southern California Earthquake Center Central California Community Velocity Model. Map tiles by Stamen Design, under Creative Commons Attribution 3.0 Unported. Data by OpenStreetMap, under Open Data Commons Open Database License. (km, kilometers; m/s, meters per second)

USGS Central California Geology-Based Model

In addition to the SCEC tomographic model, a new effort has begun to create a geology-based model of the Central California Coast Ranges, similar in method and level of detail to the present San Francisco Bay regional domain. This effort builds on the previous work (geologic map compilation, potential-field geophysics, and construction of a 3D fault model) accomplished as part of USGS and Pacific Gas and Electric Cooperative Research and Development Agreement studies to improve understanding of regional seismic hazards.

USGS Sacramento-San Joaquin Delta Shear Wave Model

Fletcher and Erdem (2017) developed a 3D shear wave velocity model for the Sacramento-San Joaquin Delta using the dispersion of Rayleigh waves with periods between 4.0 and 18.5 s at 31 stations from ambient field tomography. This dispersion is sensitive to a depth range from about 1–2 km down to 20 km. The model images a broad asymmetrical sedimentary basin located close to the western edge of the Great Valley. Additionally, it includes the Rio Vista basin nestled between the Kirby Hills and Midland faults. Other spatial variations in shear wave speed appear to be correlated with other geologic structures, such as the Stockton Arch and the faults bounding the western edge of the Great Valley. Figure 11 shows the shear wave speed at a depth of 1–3 km in this model (Fletcher and Erdem, 2017).

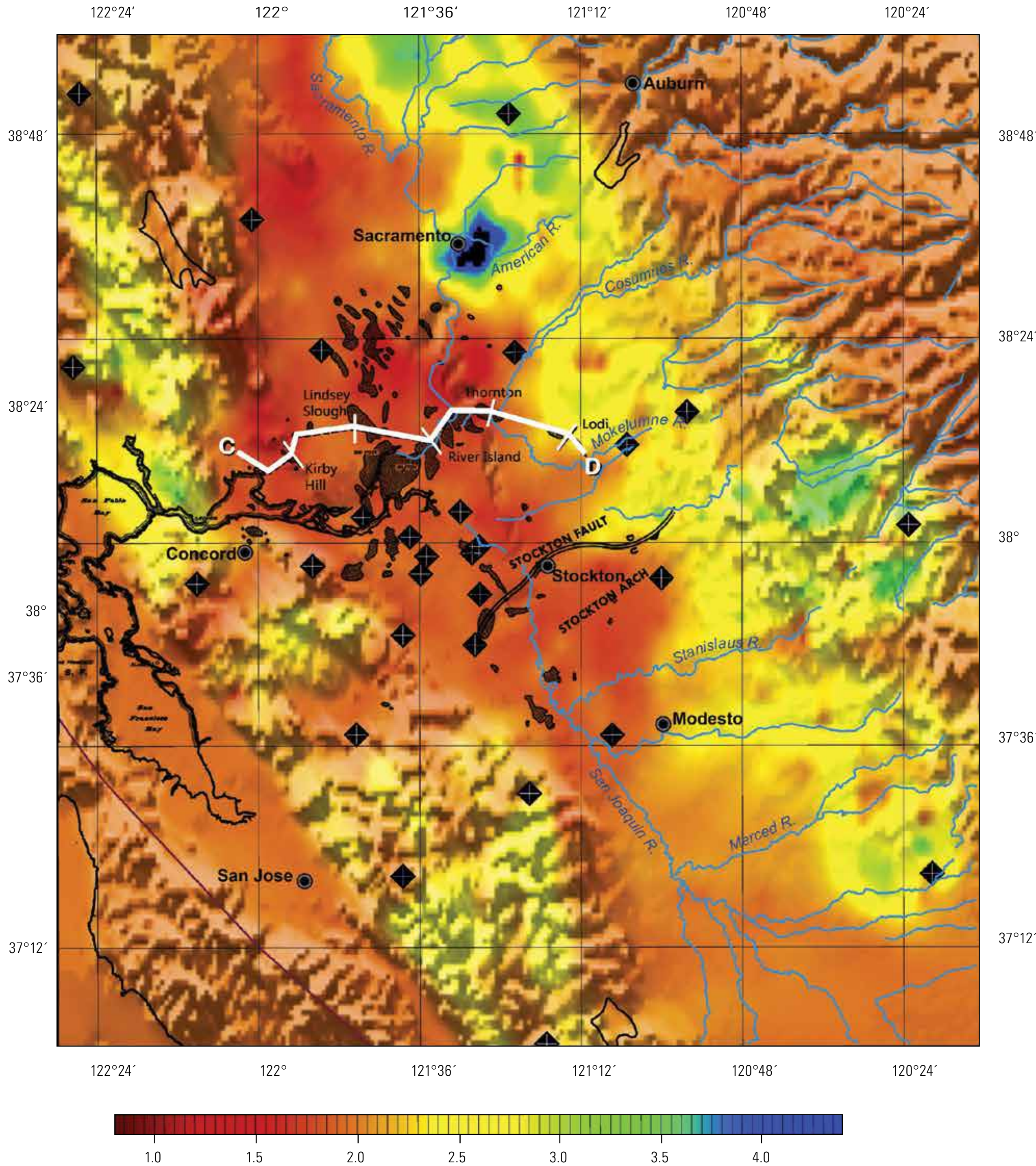

Figure 11. Map view of the S-wave speed at a depth of 1–3 kilometers below the ground surface in the Sacramento-San Joaquin Delta region (Figure 9 from Fletcher and Erdem, 2017).

USGS National Crustal Model

The USGS National Crustal Model (NCM) is being developed (Boyd, 2019a, 2019b; Shah and Boyd, 2018) to assist in the modeling of seismic hazards across the conterminous United States, initially by improving estimates of site response. This model is based in part on existing geologic and geophysical models and is composed of geophysical profiles, devoid of discontinuities across constituent model boundaries and county, state, and country borders. Metrics needed for ground-motion models can be extracted, including the depths to 1.0 and 2.5 km/s shear wave isosurfaces. As ground-motion models develop, other metrics can be extracted such as fundamental frequency, other S-wave or P-wave velocity metrics, velocity profiles for frequency-dependent horizontal and vertical site response functions, or 3D geophysical volumes for wavefield simulations. The NCM could be extended to account for spatial variability in geometric spreading and seismic attenuation as applied in ground-motion models or for improved estimates of earthquake source parameters including hypocentral location, magnitude, and stress drop.

The NCM incorporates several primary elements in its construction:

1. Depth to bedrock and basement (Shah and Boyd, 2018; fig. 12);
2. A 3D geologic framework (Boyd, 2019a);
3. A petrologic and mineral physics database (Sowers and Boyd, 2019);
4. A 3D temperature model (Boyd, 2019b); and
5. A porosity model.

These elements make use of a host of geology, borehole, gravity, thermal, and seismic datasets. The model is defined on a 1−km^2 grid and, when combined with Biot-Gassmann and mineral physics theory, describes how density and seismic velocities change as a function of porosity, saturation, composition, temperature, and pressure. Future refinements of this model could include tomographic inversion as has been done in southern California (Lee and others, 2014; Shaw and others, 2015).

Uncertainty and resolution in the NCM are highly variable as the datasets used to produce each element are not uniformly distributed. Uncertainties in model parameters are being tabulated and a full assessment of model uncertainty will be accomplished as the project progresses. The effort is currently focused on the western United States and on the production of maps showing the depths to 1.0 and 2.5 km/s S-wave velocity for application in ground-motion models and seismic hazard analyses.

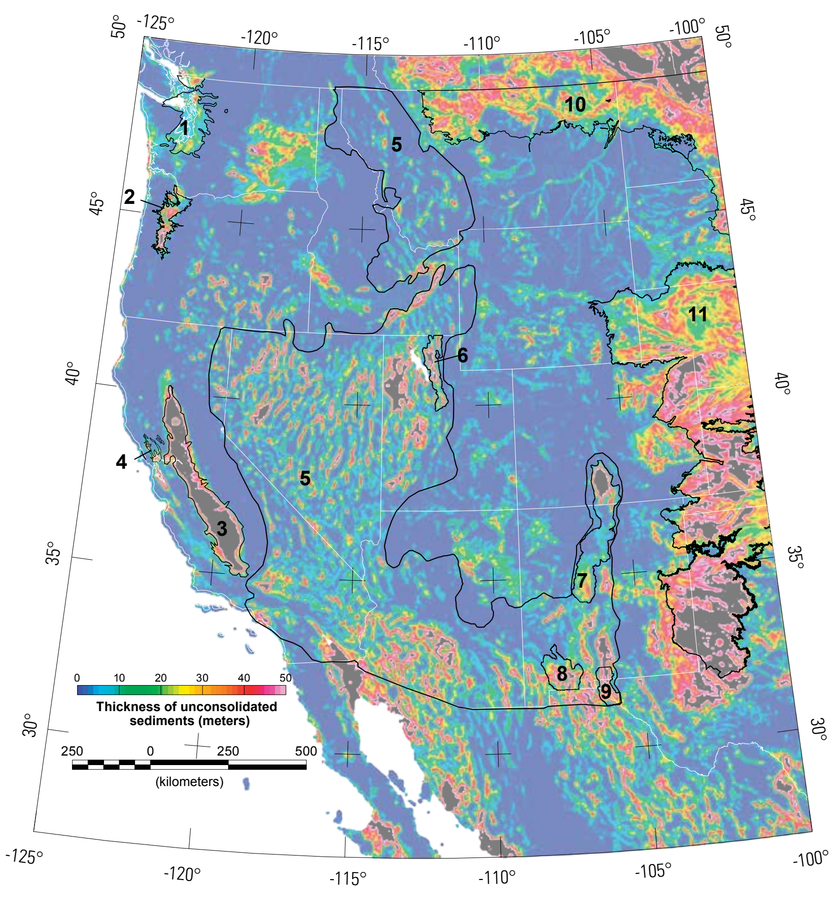

Figure 12. Thickness of unconsolidated sediments in the western United States from Shah and Boyd (2018). Numbered polygons show the bounds of regional models superimposed on top of the background model of Pelletier and others (2016).

Next Generation SCEC Community Seismic Velocity Models

A recent SCEC workshop (October 2, 2018) brought together a group of 22 scientists to discuss the historical development and status of the SCEC Community Velocity Models (CVMs) and the Unified Community Velocity Model (UCVM) framework that provides access to these models, and potential avenues for continued development and assessment of the SCEC community seismic velocity models. The workshop report is available at https://www.scec.org/proposal/report/18118 (accessed September 25, 2019). The discussion highlighted new promising data sources, such as dense nodal arrays and distributed acoustic sensing to obtain high-resolution constraints on near-surface structure, sedimentary basins, and fault zone structures. In regions with lower seismic activity, ambient field Green's functions can provide important constraints. The potential action items included

- Develop end-to-end full waveform tomography software and workflow tools;
- Develop the methodology and tools for integrating new localized seismic velocity models into existing larger regional seismic velocity models and quantifying the accuracy of the modified model;
- Develop strategies for dealing with topography in creating, comparing, and assessing models with and without topography with codes that can accommodate topography and codes that cannot;
- Explore strategies for embedding high-resolution, near-surface structure and fault zone models into seismic velocity models;
- Pursue the potential of joint geophysical inversions to improve seismic velocity models;
- Establish data repositories for (1) data used to develop SCEC community seismic velocity models and (2) observed and synthetic Green's functions; and
- Develop approaches for assessing model uncertainty.

Several of these items overlap with topics discussed in the March 21–22 workshop in Menlo Park and short-term and long-term priorities discussed in this science plan.

Seismic Velocity Model Representation and Access

In order to address the community's needs for 3D seismic velocity models, we first identify potential uses of the models. This leads to some basic requirements for how the models are represented and accessed, as well as how the resulting products are delivered to users.

3D Seismic Velocity Model Use Cases

Breakout discussions at the March 21–22, 2018, workshop identified five important uses of 3D seismic velocity models:

- 3D simulations of earthquake ground motions;
- Earthquake location and moment tensor solutions;
- Seismic hazard analyses using ground-motion prediction equations;
- Analysis of site effects and microzonation; and
- Strain accumulation and postseismic deformation modeling.

In the following sections, we summarize how a 3D seismic velocity model is used in each of these cases and how a seismic velocity model could be validated for each of these applications.

3D Simulations of Earthquake Ground Motions

A primary use of 3D seismic velocity models is simulating earthquake ground motions for historical and hypothetical future earthquakes. Research activities include studies of earthquake sources, wave propagation in heterogeneous media, development of earthquake early warning algorithms, and including finite-source and 3D seismic wave propagation effects in seismic hazard assessments (see for example, Moschetti, Luco, and others, 2018). These kinds of simulations require density, V_p, V_s, Q_p, and Q_s data at high resolution over domains spanning tens to hundreds of kilometers in the horizontal and vertical directions. A parallel C/C++ API for accessing this information with good scalability on large clusters used to run such simulations is critical. Validating seismic velocity models for this application generally involves matching synthetics with recorded waveform features (travel time, peak amplitude, frequency content, and duration) within some tolerance for a suite of moderate earthquakes.

Earthquake Locations and Moment Tensor Solutions

Earthquake catalogs (hypocenter locations, focal mechanisms, and moment tensor solutions) are one of the most widely used products of earthquake seismology. They provide basic information for a broad range of earthquake studies and applications, such as constraining fault geometry and fault constitutive behavior, analysis of wave propagation, and earthquake triggering. Migrating from using simple 1D depth-dependent seismic velocity models in construction of earthquake catalogs to 3D seismic velocity models remains a challenge due to the computational resources required; however, continued increases in computational power are making this tractable (see for example, Lin and others, 2010). Multiple algorithms and inversion techniques are involved in constructing earthquake catalogs. Locating earthquakes relies on travel times from 3D ray tracing, whereas moment tensor solutions rely on 3D Green's functions. Nevertheless, they have similar access requirements to 3D ground motion simulations, which are met by an efficient API for extracting elastic properties throughout a large volume. Validating seismic velocity models for use in constructing earthquake catalogs is best done with active source experiments in which the mechanism, location, and origin times are known. Additionally, the accuracy of the velocity model can be assessed through misfits in moment tensor inversions of earthquake sources and ambient field tomography that were not used in constraining the seismic velocity model.

Seismic Hazard Analysis Using Ground-Motion Prediction Equations

Some ground-motion models used in seismic hazard analysis (for example, the ground-motion models used in the construction of the USGS National Seismic Hazard Models) include functions that depend on the depth to the 1.0 and 2.5 km/s V_s isosurfaces (also known as Z1.0 and Z2.5). These values are frequently available only from 3D seismic velocity models. The isosurfaces are currently used in conjunction with V_{s30} to model amplification in sedimentary basins. As a result, we need the seismic velocity models from which the isosurfaces are extracted to resolve the geometries of sedimentary basins. This application requires less fine-scale detail in the near surface and spatial resolution outside sedimentary basins than do ground-motion simulations. The isosurfaces can be provided as a standard derivative product from a 3D seismic velocity model. One challenge that has yet to be addressed by the ground-motion modeling community is what depth should be used in cases in which the isosurface is present at multiple depths. Direct validation of the isosurfaces is possible in some areas for which well logs are available; well logs are most useful in constraining the basin edges, which are important for capturing amplification from converted phases at basin edges. In the middle of the sedimentary basins where amplification is thought to be most significant, the isosurfaces lie farthest from the ground surface and below the depths to which most wells are drilled. Therefore, for the central portion of sedimentary basins, validation would need to be indirect and could be cast in the form of simulations matching amplification in recorded waveforms.

Analysis of Site Effects and Microzonation

Three-dimensional seismic velocity models that capture fine scale, near-surface structure can be used to characterize site effects and perform microzonation analyses. Including this level of detail in velocity models is challenging due to the lack of uniform fine-scale data needed to constrain the elastic properties in the upper 1 km to 100 m at a vertical resolution of 10 m or less. For example, the bay mud that covers most of the San Francisco Bay is generally only a few meters thick and can significantly affect shaking intensities and frequency content. The current USGS San Francisco Bay region 3D seismic velocity model (version 08.3.0) does not include this level of detail.

Including this near-surface information in 3D seismic velocity models helps bridge the gap between analysis of site effects using simple proxies such as V_{s30} and more comprehensive two-dimensional (2D) and 3D analyses. Any site effects or microzonation study would generally query for the elastic properties in the topmost 1 km or less of a seismic velocity model at vertical resolutions approaching a few meters, and, in some but certainly not all cases, might be limited to similar horizontal scales. Validation of the seismic velocity models for this purpose may involve direct observations with cone penetrometer tests as well as comparison of synthetic and recorded waveforms at frequencies above 1 Hz; validation should also leverage observations from borehole instrumentation, dense sensor networks, and short baseline arrays via horizontal to vertical spectral ratios and active and passive analysis of surface waves.

Strain Accumulation and Postseismic Deformation Modeling

Models of crustal strain accumulation and postseismic viscoelastic deformation and afterslip can benefit from incorporating lateral variations in elastic structure provided by 3D seismic velocity models (for example, Cho and Kuwahara, 2013). These quasistatic models are driven primarily by geodetic observations and tend to include variations in elastic properties across faults and variations in lower crustal and upper mantle structure. Accessing the bulk rheological properties for this application is virtually the same as in earthquake ground-motion simulation applications; these models typically also need viscoelastic relaxation parameters, such as viscosity. Validation of the seismic velocity model for wave propagation applications also constrains the elastic properties used in strain accumulation and postseismic deformation modeling applications. Extension of seismic velocity models to include viscoelastic relaxation parameters would require additional validation specific to geodetic modeling, such as criteria for synthetic postseismic relaxation displacements matching recorded values for datasets not used to constrain the properties.

Representation of Geologic Structures and Elastic Properties

In general, geologic structure and elastic properties are inherently related. Geologic structures, especially faults, form significant lithologic boundaries, and often delineate important discontinuities in the elastic properties. At smaller length scales, we find lower rigidities and amplification of ground motions within fault damage zones. The vertical variations in elastic properties commonly follow a much more complex relationship due to deposition, increasing confining pressures and temperatures with depth, and deformation history (uplift, folding, and so forth). Thus, in defining the elastic properties within a 3D seismic velocity model, we need to honor sharp discontinuities across geologic structures that form significant lithologic boundaries while incorporating complex spatial variations across other regions.

On the basis of these relationships between geologic structures and elastic properties, simultaneously representing the geologic structure and elastic properties within the same framework is desirable to achieve self-consistent descriptions. This includes representation of the lithologic boundaries and the relationships among them as well as the variation of elastic properties within each block. Commercial geologic modeling software, such as EarthVision (used by the USGS in the development of the USGS San Francisco Bay region seismic velocity model) and GOCAD (used by SCEC in the development of CVM-H), provides frameworks for unified structural representation. These software packages, however, have a steep learning curve and are quite expensive. More work is needed to identify open-source tools suitable for this purpose.

Frameworks that provide self-consistent representation of the geologic structure and elastic properties may provide tools suitable for quantifying the uncertainty of the elastic properties. Quantifying the uncertainties becomes especially challenging when incorporating constraints from disparate observations.

Accessibility

Our discussion of use cases for seismic velocity models in the previous sections illustrates a wide range in the size and scale of queries of the elastic properties in a 3D seismic velocity model. The end members range from users extracting a relatively short 1D profile of elastic properties at one or a small number of locations on a laptop or desktop computer to users extracting the elastic properties of a large 3D volume in parallel on some of the largest supercomputers in the world.

The domain size and resolution of 3D seismic velocity models result in model components requiring several gigabytes or more of storage. As a result, it is often not possible to load an entire model into memory when accessing the model via laptops and desktop computers. This is especially true when the user is accessing the model from another software application that itself may be using a significant fraction of a computer's memory. Consequently, the interface for querying 3D seismic velocity models must limit its memory footprint to support accessing the model while loading only a portion of it into memory. This is often most efficient by caching a small chunk of a model in memory, so that access to points located close in space minimize file system access, which is in general the most significant bottleneck. This is the model supported by the cencalvm (query software) and Euclid libraries used to access the USGS San Francisco Bay region seismic velocity model (https://usgs.github.io/earthquake-cencalvm/, accessed September 25, 2019).

At the other end of the spectrum, efficient parallel access of seismic velocity models for large, high-resolution volumes from large supercomputers necessitates alternative strategies. Filesystems cannot support simultaneous reads from thousands to hundreds of thousands of processes. Instead, filesystem bottlenecks are avoided by reads from designated input/output processes that distribute the information to the other processes. For seismic wave propagation codes that rely on domain decomposition for parallel processing, this means a small number of processes each read in separate chunks of the model, and each of the other processes receives the properties for its small volume from the processes that read in chunks of the model. Lawrence Livermore National Laboratory developed a specialized interface to the USGS San Francisco Bay region seismic velocity model using this approach (Petersson and Sjogreen, 2017).

Products and Delivery

Supporting the use of 3D seismic velocity models outlined in the previous sections requires distributing the seismic velocity model data file(s) along with libraries to query them from a variety of platforms, as well as derivative products.

The primary deliverables for a 3D seismic velocity model include

- 3D seismic velocity model defining the elastic properties (density, V_p, and V_s) and seismic attenuation (Q_p and Q_s) in a standard, self-describing binary format with access via portable, open-source software. The software used to access the model should support both serial and massively parallel access and queries for small portions of the model or the entire model; serial and massively parallel access could be implemented in different libraries as part of the overall framework for accessing the model. We expect these query tools to be incorporated into the Unified Community Velocity Model tool (Small and others, 2017) developed by SCEC.
- Maps of the depth to the 1.0 and 2.5 km/s V_s isosurfaces (also known as Z1.0 and Z2.5) for the region spanning the seismic velocity model domain in a standard, geographic information system format.

Model releases should include release notes describing changes relative to earlier versions. Substantial updates via major releases should be accompanied by publications with detailed descriptions of the changes, such as those to the elastic properties and methodologies used.

Model releases should be accompanied by results of benchmarks assessing model accuracy. The benchmarks should include ground-motion predictions for a suite of well-recorded moderate earthquakes that were not used in model development. Similar comparisons should be made for other suites of observations, such as gravity measurements and ambient field Green's functions. For example, a researcher could randomly select all earthquakes from 10 percent of the stations and all stations from 10 percent of the earthquakes for use as independent data in testing following model updates that make use of the other approximately 80 percent of the data.

Seismic velocity models should also quantify the uncertainty of the values delivered. Given the variety of methods used to constrain the elastic properties at any given point, it is difficult to assign a strict uncertainty estimate. A very simple metric for quantifying the relative uncertainty of the material properties at a point is the number of observations used to constrain the values. An inherent problem with this metric is that some observations may provide much tighter constraints than others, so that more observations constraining a point does not necessarily translate into less uncertainty. More work needs to be done to identify practical and meaningful ways to quantify the uncertainty of the elastic properties at any given point within a 3D seismic velocity model.

Many other research applications would benefit from extending seismic velocity models to include additional bulk properties. For example, SCEC is developing community thermal and rheology models. Such models can be used to constrain the anelastic and plastic behavior. These extensions significantly increase the complexity and observations required and are beyond the scope of this five-year science plan for seismic velocity model development in the greater San Francisco Bay region.

Short-Term Goals (Years 1–2)

Short-term goals for improving the USGS San Francisco Bay region seismic velocity model include several kinds of modifications, such as

- Expanding the inner, detailed domain outward by adding adjacent detailed models;
- Refining the model within the existing detailed domain by improving the underlying geologic model and the velocity-depth relationships;
- Assessing the accuracy of the model in areas with high seismic risk and acquiring new data in such areas where the model is less accurate;

- Creating datasets for validation and quantifying how changes to the model improve its use in seismic hazard applications; and
- Establishing a framework for leveraging community resources to reach the short-term and long-term goals.

The existing model should be evaluated systematically to identify problem areas by comparing parts of the existing model to independent datasets, such as refraction tomography models, local and regional earthquake tomography models, and comparing synthetic earthquake ground-motion waveforms derived from the model to observed waveforms. The existing model can also be improved and tested by acquiring additional data in select areas, as discussed in the next sections.

Most short-term goals, possible in the 1–2-year time frame, fall into two main categories. The model can be improved by integrating existing models and incorporating additional constraints using existing data, and new data can be prioritized and gathered to improve future iterations of the model (as discussed in the next section detailing the long-term goals). Integration of new data into model updates might be possible in the 1–2-year timeframe, but it would require a focused collaborative effort.

Outward expansion of the inner, more detailed domain is now possible because new geologic and geophysical data are available in several locations where only limited data were previously available. In particular, significant new work on the geologic framework and seismic velocities of the Sacramento-San Joaquin Delta (Fletcher and Erdem, 2017) would provide detail comparable to that in the existing inner model. Temporary seismic deployments in the region east of the Hayward Fault and a 10-km seismic profile across the Hayward Fault provide new constraints on the seismic velocities along the central portion of the Hayward Fault, an area that has been identified as needing improvements.

Sacramento-San Joaquin Delta

Multiple studies have recently focused on refining the geologic and seismic velocity models in the Sacramento-San Joaquin Delta. The USGS is developing a new 3D geology-based, P-wave seismic velocity model using geologic mapping, potential field geophysics, seismic reflection profiles, and borehole logs. This model will capture the complex geometry of the Cretaceous, Paleogene, and Neogene geologic units and features such as the Rio Vista basin. This geologic model is designed to be consistent along its western boundary with the geologic model underlying the detailed portion of the USGS 3D San Francisco Bay seismic velocity model. The shear wave velocity model of Fletcher and Erdem (2017), based on ambient field tomography, focuses on depths greater than 1–2 km. Regional estimates of Q_p and Q_s can be included leveraging the regional attenuation model of Eberhart-Phillips and others (2014). These three complementary models should be integrated while resolving any discrepancies and merged into the detailed portion of the USGS San Francisco Bay region seismic velocity model.

Other datasets also available for this region could help further constrain the structure and elastic properties. This includes oil industry reflection data, long-range V_s profiles developed from ambient field correlations by Kiochi Hayashi (http://seisimager.esy.es/index.htm), a regional travel-time tomography model by Thurber and others (2009), and the hybrid velocity models of Lindeman and others (2017). Leveraging these additional datasets and models will require careful consideration of the different resolutions, footprints, and depth sensitivities, making it a long-term goal.

New shallow-depth tomography/surface-wave data are needed in select locations to fill in regions lacking sufficient coverage from boreholes to constrain the models in the top few hundred meters to a kilometer. This could be tied into the marine shallow seismic reflection profiles recently collected along a few river transects in the delta region (Klotsko and others, 2018).

Napa Valley

Abundant new and older data are available to improve the current USGS San Francisco Bay region 3D geologic model and seismic velocity model in the Napa Valley area. The current geologic model relies on regional scale datasets; however, the geology of the Napa Valley has been mapped in greater detail by a number of researchers, including Helley and Herd (1977), Pampeyan (1979), Bryant (1982), Wagner and Bortugno (1982), Fox (1983), Wagner and others (2004), Clahan and others (2005), Graymer, Bryant, and others (2006), Graymer, Moring, and others (2006), Graymer and others (2007), Wesling and Hanson (2008), Brossy and others (2010), Wagner and Gutierrez (2010), Dawson and others (2014), Ponti and others (2014), and Lienkaemper and others (2016). Some of this more recent work followed the August 24, 2014, magnitude 6.0 South Napa earthquake. New subsurface fault models are also now available for the west Napa Valley from a number of studies preceding and following the South Napa earthquake, including those by Langenheim and others (2006), Waldhauser (2009), Langenheim and others (2010), Brocher and others (2015), Dreger and others (2015), Ji and others (2015), Wei and others (2015), Catchings and others (2016), Hardebeck and Shelly (2016), and Li and others (2016). Seismic velocity structure can also be constrained using available refraction tomography profiles from Catchings and others (2017) and surface-wave profiles from Chan and others (2018a,b).

The USGS has initiated development of a detailed geology-based seismic velocity model for the Napa Valley region. These various datasets should be leveraged in applying a unified structural representation approach to improving the USGS San Francisco Bay region 3D geologic and seismic velocity models for the Napa Valley region.

Hayward Fault Zone

The Hayward Fault zone is another target for leveraging existing data to add more detail to the USGS San Francisco Bay 3D geologic and seismic velocity models. Phelps and others (2008) constructed a 3D geologic model of the Hayward Fault zone. As in the Napa Valley, the geologic mapping efforts should be integrated with 3D earthquake-based tomography models for the Hayward Fault zone and the East Bay (for example, Zhang and Thurber, 2003; Hardebeck and others, 2007) and 2-D refraction tomography profiles within the San Francisco Peninsula and East Bay regions (Catchings and others, 2004, 2006, 2017). Additionally, recent work by Watt and others (2016) on the connection of the Hayward Fault to the Rodgers Creek Fault has not been incorporated into the geologic model. Many of these data span complementary scales, so the most accurate model of Earth structure should integrate the results from these studies.

Assess Other Locations and Acquire New Data

Some regions within the detailed portion of the USGS San Francisco Bay region seismic velocity model are less well resolved than others, as a result of the paucity of earthquakes and seismic instrumentation in those areas, a lack of active-source seismic data, and incomplete surface mapping. These regions include those west of the San Andreas Fault along the coast between Santa Cruz and San Francisco and various regions north of the San Francisco Bay between the major faults. Some initial evaluation of the model in these regions in the context of the seismic risk will help prioritize areas for targeting focused studies, including collection of new active and (or) passive source seismic data and surface mapping.

The northern and southern portions of the Hayward Fault zone are a high priority target for acquisition of new active/passive seismic data due to the high seismic risk associated with the Hayward Fault and the lack of high-resolution seismic data for constraining the near-surface elastic properties in those regions.

Validate and Quantify Improvements

Revisions to the 3D seismic velocity model require careful analysis to ensure that they, on average, improve the accuracy of the model for intended applications, such as modeling earthquake ground motions. In parallel with the other short-term goals to improve various regions of the model, independent data—primarily ambient field and earthquake ground-motion recordings—will be needed for validation. These data should be assembled, along with the workflows for performing the validation, and made publicly available so others can independently quantify the accuracy of the model. In addition to data independent of those used to construct the model, including regional-scale data will be helpful, even if it has been used to constrain the model, in order to facilitate assessment of the entire seismic velocity model.

Long-Term Goals (Year 3 and Beyond)

For the long term, we need a sustainable approach to assessment, improvement, and evaluation of uncertainty in the 3D seismic velocity models for the San Francisco Bay region. Even as new data are acquired and analytical techniques change, we want to maintain a unified structural representation approach that insures self-consistency between the geologic structure and the elastic and anelastic properties.

Acquire New Data

We anticipate that continued collection of conventional data to fill in gaps in current coverage via the regional seismic network, reflection/refraction and ambient field temporary deployments, geologic mapping, well logs, and potential field geophysics will lead to additional improvements in the model. However, new types of instrumentation could lead to more significant improvements in constraining the geologic structures and elastic properties.

Major improvements in the accuracy of 3D seismic velocity models entail bridging the gap between local high-resolution observations and sparse regional or coarse-resolution observations. Dense seismic observations are becoming more affordable through lower cost, scientific quality sensors and new measurement techniques.

Short-term, very dense deployments of hundreds to thousands of three-component "nodal" instruments provide continuous seismic data that can be used for a range of passive and active imaging techniques. Such deployments offer a practical means for obtaining structural and site response information with high spatial resolution at a reasonable cost (Lin and others, 2013).

Another potential alternative for acquiring new data is distributed acoustic sensing (DAS) using existing or purpose-deployed, fiber-optic cable. DAS systems have been shown to be able to record useful earthquake data on a scale of meters for nearby earthquakes down to a magnitude of about 1, to regional distance earthquakes above about magnitude 4, and to teleseisms above about magnitude 5.5 (Lindsey and others, 2017; Wang and others, 2018). Recent studies also show the potential of DAS data for passive seismic imaging (Dou and others, 2017; Zeng and others, 2017). Practical issues with DAS systems include access to cables, the limited directional response of the cable, and very high data volumes. However, the potential of these systems for providing extremely high resolution sampling of the seismic wavefield is transformational.

Other potential transformational observations include crowdsourcing seismic instrumentation through the use of cell phones (Kong and others, 2019) and accelerometers integrated into electrical power smartmeters (Davis and Nguyen, 2019).

Improve Data Analysis Techniques

Application of more advanced analysis techniques will help improve the seismic velocity model resolution using available and new data. This includes broader use of current state-of-the-art techniques, such as ambient-field, full-waveform tomography, and reverse time migration, as well as exploration of new techniques, such as further development of machine learning algorithms to 2D and 3D seismic imaging.

Currently, the USGS San Francisco Bay 3D seismic velocity model is constructed by assigning elastic properties to geologic units of a 3D geologic model. Geologic mapping, boreholes, well logs, and potential field geophysics constrain the geologic model, whereas seismic data constrain the rules assigning the elastic properties. This approach could be improved by simultaneously using all of the data to constrain both the geologic structure and elastic properties. For example, standard arrival-time or waveform tomography models typically do not include structural discontinuities, but the potential for including them in arrival-time tomography models does exist (Bleibinhaus and Gebrande, 2006). Sequentially structurally constrained inversion (Gao and Zhang, 2018) could also be used to integrate the geologic and seismic tomographic models, perhaps in conjunction with faults defined by seismicity as an additional constraint on discontinuities in elastic properties.

Improve Model Resolution

Another key task is to bridge the gap between meter-scale resolution at the ground surface and kilometer-scale resolution at the Moho. Boreholes and well logs provide fine spatial sampling in the vertical direction, but they are sparse in the horizontal direction. At the other end of the spectrum, regional- and local-scale tomographic and potential field studies provide broad horizontal spatial coverage but cannot adequately represent or resolve the near-surface structure. Observations from dense seismic deployments (for example, nodal arrays) can help bridge these gaps, especially when deployed in a leap-frogging fashion as was done for the EarthScope Transportable Array (http://www.usarray.org/researchers/obs/transportable, accessed September 25, 2019).

A high-priority initial step for improving the near-surface resolution is to refine the model in the upper kilometer by leveraging V_{s30} observations and proxy methods as well as ambient field Rayleigh wave horizontal to vertical amplitude (H/V) information from three-component seismic stations (Berg and others, 2018). Incorporating seismic data from geotechnical arrays, such as those operated by the California Geological Survey, also provides additional constraints on shallow velocity structure. This will improve the values at the finest discretization size in the current USGS San Francisco Bay region detailed seismic velocity domain, which is 100 m in the horizontal direction and 25 m in the vertical direction. As data become available to introduce finer scale structure than this current smallest scale, the discretization size can be reduced accordingly.

Quantify Uncertainty

Developing uncertainty estimates for the seismic velocity models will permit better quantification of uncertainties in downstream products. The seismic velocity model uncertainties should include aleatory (uncertainty due to unknown effects) estimates for each individual model and epistemic (uncertainty due to known gaps in data and knowledge) estimates based on alternative models.

The uncertainty in the elastic properties of a seismic velocity model at any point depends on many factors, including the number of independent observations at that point, the quality of those observations, and the uncertainty in determining the elastic and attenuation properties from those observations. Formal methods for uncertainty quantification in large numerical models are gaining traction, but they would be challenging to implement in the context of 3D seismic velocity models constrained by the wide range of geophysical, geologic, and seismological observations currently used. A practical solution is to implement simpler methods for quantifying the uncertainty in the near future and work towards implementation of more complete, formal methods in the long term. These simpler methods could include assigning quality factors, indicating the number of independent constraints, and estimating errors in V_p and V_s from travel time residuals.

Different analysis techniques and interpretations can produce different seismic velocity models from the same data. Such a suite of viable alternative models can provide an estimate of the epistemic uncertainty. A key issue is that the alternative models should reflect gaps in knowledge, not simply different scientific studies. The ground-motion modeling community has used Sammons maps to help estimate the true epistemic uncertainty from multiple models that have a range of variability in commonality (Scherbaum and others, 2010). Similar analyses could be applied to seismic velocity models.

Catalog Data and Models

One of the primary long-term goals of the plan described in this report is to coordinate research efforts in order to leverage a broader range of data and analysis techniques to improve the 3D seismic velocity models for the greater San Francisco Bay region. An important aspect of leveraging previous and current efforts is the construction and maintenance of curated, open repositories for the relevant data and models. The Northern California Earthquake Data Center (http://ncedc.org/, accessed September 25, 2019) and the Incorporated Research Institutions for Seismology (https://www.iris.edu/hq, accessed September 25, 2019) fulfill these needs for seismic waveform data. Less comprehensive repositories exist for other data, such as gravity and aeromagnetic surveys. Regrettably, such central repositories generally do not exist for derived products, such as tomographic models, seismic profiles, and density models in California. Models constructed on the basis of results in previous and ongoing studies, as well as their associated data, should be catalogued and assessed for their usefulness in improving 3D seismic velocity models. The most useful models and data not yet in existing open, curated repositories should be added to such repositories first. Expanding and building such long-term repositories requires considerable resources. As a result, these efforts are best provided by such institutions as the USGS, which can commit institutional technical and scientific support and is already committed to archiving a wide variety of scientific data.

Community Model Building

We want to build an active community of developers and users contributing to improvement of 3D seismic velocity models for the greater San Francisco Bay region. Important factors related to building this community include

- Curated, open data;
- Leveraging open-source tools for building, analyzing, and improving models;
- An open, efficient organizational structure that fosters collaboration;
- Dedicated technical and scientific staff with institutional support; and
- Sustainable, long-term funding.

Curated, Open Data

Abundant, high-quality data are the foundation for building accurate, high-resolution 3D seismic velocity models. As additional data are collected, we want to retain constraints provided from existing data. In the long-term, data collections used to constrain a model become more valuable than the current version of the model as improved versions are constructed with new techniques from previously collected data or new data. Leveraging data is most efficient if it exists in curated, open collections with appropriate metadata, versioning, and use of standard formats. Curated collections also facilitate generation of digital object identifiers for providing attribution when making use of these data. Identifying and supporting a site to store existing datasets would facilitate the long-term goal of archiving data.

Open-Source Tools for Building, Analyzing, and Improving Models

Use of commercial software with annual license fees of several thousand dollars for building and improving models creates a significant barrier to contributing to model development. For example, the current USGS San Francisco Bay geologic model, which underlies the seismic velocity model, was developed using commercial software (EarthVision); researchers who want to contribute to further development of the geologic model would need a license for EarthVision. As a result, only a few people have contributed to model development, thereby creating an impediment in incorporating new data to improve the model and releasing new versions. This also generally leads to a tendency for a proliferation of models simply because it is easier to create a new model using tools a researcher already has access to than to update an existing model that requires obtaining access to different tools. Open-source tools lower entry barriers to researchers who want to contribute to model development.

Ideally, we want a modular, open-source framework for assembling seismic velocity models from a wide variety of geologic, geophysical, geotechnical, and seismic data. Several research groups within the seismology community actively maintain open-source software for seismic wave propagation and provide training in their use. Although some include extensions for full-waveform tomographic inversions, the workflows are generally fragile and poorly documented. Researchers should be encouraged to contribute toward improving these tools or developing new generations of tools that make use of modern software engineering practices. Additional effort should be made to identify open-source or low-cost alternatives to commercial software for integrating geologic, geophysical, and seismic data.

An Open, Efficient Organizational Structure

Making substantial progress in characterizing Earth structure through 3D seismic velocity models will involve a multidisciplinary effort leveraging researchers from a variety of institutions. An open, agile organizational structure will be required for effective use of these resources. We recommend forming a working group, with a chair and vice chair, that balances representation from the disciplines and core institutions involved, to guide seismic velocity model development. The chair and vice chair would serve as leaders of the overall effort and occupy their positions for sufficient duration so as to ensure sustained progress. Some community collaboration may require additional technical expertise or more extensive collaboration than what can be done efficiently by the whole working group. As a result, the working group will likely need to form short-term, ad hoc technical working groups to make progress on specific issues. We anticipate that the working group would be most effective with quarterly meetings to coordinate research efforts, assess progress, and set milestones.

Annual workshops, potentially held in conjunction with the annual Northern California Earthquake Hazards workshops, would be the primary opportunity for community coordination and scientific exchange of ideas related to seismic velocity model development and their use in seismic hazard assessment for the greater San Francisco Bay region. The workshops would be used to showcase results to users and obtain feedback, discuss integration of newly available data, and discuss obstacles and priorities associated with further development of the seismic velocity models. The annual workshops would also serve as a tool for recruiting additional researchers, identifying potential funding sources, and maintaining an open collaboration.

The working group should develop a community web portal to serve as the main hub for engaging the community. The community portal would include links to the model and data repositories, host a meeting calendar with agendas, meeting summaries and slides from presentations, reports with the outcomes from ad hoc technical working groups, and list past and target release dates of seismic velocity models and other project milestones. This would require long-term institutional support and resources.

Sustainable, Long-Term Funding

Characterizing Earth structure at sufficient resolution to accurately predict ground shaking in damaging earthquakes at frequencies of engineering interest will require sustained, long-term investment to improve 3D seismic velocity models. The long-term nature of this research effort and wide variety of institutions involved (academic, federal and state agencies, national labs, and lifeline organizations) necessitates funding this work using a variety of sources. Engaging current and potential funding sources would help to ensure the priorities of institutions are consistent with the priorities identified in this science plan and to develop mechanisms for providing funding across multiple years. As discussed in the previous sections of this document, curated data repositories and a community web portal require dedicated staff with institutional support. In general, we expect that researchers involved in this collaborative effort to improve seismic velocity models in the greater San Francisco Bay region will seek their own funding, leveraging collaborative proposals when feasible.

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Appendix 1. 2018 San Francisco Bay Region Seismic Velocity Models for Seismic Hazard Assessment Workshop

Agenda

Workshop: San Francisco Bay Region Seismic Velocity Models for Seismic Hazard Assessment

March 21–22, 2018
USGS Menlo Park Campus
Rambo Auditorium (Building 3 Main Conference Room)
Financial support provided by the USGS Earthquake Science Center and Pacific Gas and Electric.

Objective: Develop a five-year plan for leveraging community resources to systematically and continually improve one or more 3D seismic velocity models for the San Francisco Bay Area and surrounding region for use in seismic hazard assessment.

Wednesday, March 21

10:00	Welcome/Introduction, Brad Aagaard (USGS)
	Session I: Current USGS San Francisco Bay Area 3-D Seismic Velocity Model
10:15	3-D Geologic Model, Russell Graymer (USGS)
10:25	Elastic Properties, Thomas Brocher (USGS)
10:35	3-D Seismic Velocity Model, Brad Aagaard (USGS)
10:45	Validation of Synthetic Ground-Motions using 1989 M6.9 Loma Prieta Earthquake, Robert Graves (USGS)
10:55	Accuracy of Synthetic Ground-Motions for the 2014 M6.0 South Napa Earthquake and Moderate Earthquakes, Arthur Rodgers (LLNL)
11:10	Discussion
11:45 - 12:45	Lunch (on your own)
	Session II: Related Efforts
12:45	SCEC Central Coast Seismic Velocity Model, Tom Jordan (USC)
13:05	San Joaquin-Sacramento Delta 3-D S-Wave Model, Joe Fletcher (USGS)
13:15	USGS National Crustal Model, Oliver Boyd (USGS)
13:30	Discussion
	Session III: Model Refinement: What additional geologic, geophysical, and seismic data are currently available that could be readily used to improve the model?
13:45	Seismicity and Seismic Networks, Lind Gee (USGS)
13:55	Geologic data and well logs, Russell Graymer (USGS)
14:05	Gravity and Aeromagnetic Data, Vicki Langenheim (USGS)
14:15	Active and Passive Seismic Data, Rufus Catchings (USGS)
14:25	Discussion
	Breakout Discussion I: Seismic Hazard Assessment Use Cases for 3-D Seismic Velocity Models
14:55	Breakout Groups
15:35	Group Reports

Session IV: Model Representation and Access

16:00	Unified Structural Representation Workflow for Updating the SCEC CVM-H, Andreas Plesch (Harvard)
16:15	SCEC Unified Community Velocity Model Interface, Philip Maechling (USC)
16:25	LLNL R Interface: Querying the USGS Seismic Velocity Model on a Massively Parallel Supercomputer, Anders Petersson (LLNL)
16:35	GeoModelGrids: Query Interface and Self-Describing Storage Scheme, Brad Aagaard (USGS)
16:45	Discussion
17:15	Dinner (self organize)

Thursday, March 22

Session V: Frontiers in Geologic, Geophysical, and Seismic Data

9:00	Discussion: New Data Sources for: Geologic, Geophysical, and Any Other Useful Non-Seismic Information (Moderator: Geoffrey Phelps, USGS)
9:20	Discussion: New Analysis Techniques For Constraining Geologic Structure and Crustal Properties (Moderator: Arthur Rodgers, LLNL)
9:40	PG&E SmartMeter Seismometer Project, Jeff Bachhuber and Katie Wooddell (PG&E)
9:55	Discussion: Augmentation/Expansion of existing seismic networks (Moderator: Valerie Sahakian, USGS)
	Breakout Discussion II: Community Model Building
10:15	Part 1: How do we maintain a coherent model while leveraging constraints on geologic structure and elastic properties from a wide range of data and analysis techniques?
10:55	Group reports for Part 1
11:30 - 13:30	Lunch (on your own; Snow and Avalanche Science Public Lecture 12:00-13:00)
	Breakout Discussion II (continued): Community Model Building
13:30	Part 2: Resources
14:00	Group reports for Part 2
14:30	Discussion
15:00	Wrap-up
15:30	Adjourn

Registered Participants

Names and affiliations of people who registered for the March 21-22, 2018, workshop.

Aagaard, Brad	(USGS)
Abrahamson, Norm	(UC Berkeley)
Bachhuber, Jeffrey	(PG&E)
Baltay, Annemarie	(USGS)
Barall, Michael	(Invisible Software)
Boyd, Oliver	(USGS)
Brocher, Tom	(USGS)
Catchings, Rufus	(USGS)
Celebi, Mehmet	(USGS)
Craig, Mitchell	(CSU East Bay)
Di Alessandro, Carola	(GeoPentech, Inc.)
Erdem, Jemile	(USGS)
Fernandez, Alfredo	(Fugro)

Registered Participants—Continued

Fletcher, Joe	(USGS)
Flinders, Ashton)	(USGS)
Gee, Lind	(USGS)
Goldman, Mark	(USGS)
Goulet, Christine	(SCEC/USC)
Grant, Alex	(USGS)
Graves, Robert (	(USGS)
Graymer, Russell	(USGS)
Hanks, Tom	(USGS)
Hardebeck, Jeanne	(USGS)
Harris, Ruth	(USGS)
Hickman, Steve	(USGS)
Jordan, Thomas	(SCEC/USC)
Knudsen, Keith	(USGS)
Kottke, Albert	(Pacific Gas and Electric Company)
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Miah, Mamun	(Lawrence Berkeley National Laboratory)
Nihel, Kurt	(Lawrence Berkeley National
Nishenko, Stu	(Pacific Gas and Electric Company)
OConnell, Daniel	(Tetra Tech)
Ogbidi, John	(Albert Services Nigeria Limited)
Petersson, Anders	(Lawrence Livermore National Lab)
Petrone, Floriana	(Lawrence Berkeley National Laboratory)
Phelps, Geoffrey	(USGS)
Pitarka, Arben	(Lawrence Livermore National Laboratory)
Plesch, Andreas	(Harvard University)
Rector, Jamie	(UC Berkeley, Lawrence
Retailleau, Lise	(Stanford)
Rodgers, Arthur	(Lawrence Livermore National Laboratory)
Sahakian, Valerie	(USGS)
Spica, Zack	(Stanford)
Taborda, Ricardo	(University of Memphis)
Taira, Taka'aki	(UC Berkeley)
Thurber, Cliff	(Univeristy of Wisconsin-Madison)
Tsiaousi, Dimitra	(Fugro)
Vidale, John	(USC)
Woddell, Katie)	(Pacific Gas and Electric Company
Yong, Alan	(USGS)
Yuan, Siyuan)	(Stanford University

Appendix 2. 2019 San Francisco Bay Region Seismic Velocity Models for Seismic Hazard Assessment Workshop

Agenda

Workshop: San Francisco Bay Region Seismic Velocity Models for Seismic Hazard Assessment

May 16, 2019
USGS Menlo Park Campus
California Conference Room, Building 3

Objective: Provide updates on recent science activities associated with the 3-D Bay Area geologic and seismic velocity models. Discuss draft of five-year science plan for improving seismic velocity models in the San Francisco Bay region.

Thursday, May 16

9:00	Welcome/Introduction, Brad Aagaard (USGS)
9:05	Participant Introductions
9:15	Summary of Five-Year Science Plan, Brad Aagaard
	Session I: Evaluating the Current USGS San Francisco Bay Area 3-D Seismic Velocity Model
9:30	Arben Pitarka (LLNL), *Comparison of 3D and 1D wave propagation effects in the San Francisco Bay Area on simulated long period ground motion from the 1989 Loma Prieta earthquake*
10:00	Artie Rodgers (LLNL), *Evaluating the current USGS 3D seismic velocity model with moderate earthquakes*
10:30	Evan Hirakawa (USGS), *Revising the USGS 3D seismic velocity model in the East Bay*
11:00	Break
	Session II: Incorporating Site and Path Effects in Seismic Hazard Assessment
11:15	Christine Goulet (USC/SCEC), *Preliminary CyberShake results for the greater San Francisco Bay region*
11:45	Grigorios Lavrentiadis (UC Berkeley), *Comparison of non-ergodic GMPEs and earthquake simulations in the San Francisco Bay region*
12:15	Lunch
	Session III: Constraints from 3D geologic models and potential field geophysics
13:30	Russell Graymer (USGS), *Central California Coast Ranges 3-D geologic model*
14:00	Geoff Phelps (USGS), *Validating elastic properties using potential field geophysics*
	Session IV: Discussion
14:30	Discussion of five-year science plan, Brad Aagaard
15:00	Wrap up, Brad Aagaard

Registered Participants

Names and affiliations of people who participated in the May 16, 2019, workshop.

Aagaard, Brad	(USGS)
Bachhuber, Jeffrey	(PG&E)
Baltay, Annemarie	(USGS)
Barall, Michael	(Invisible Software)
Boyd, Oliver	(USGS)

Registered Participants—Continued

Catchings, Rufus	(USGS)
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Graves, Robert	(USGS)
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Nishenko, Stu	(Pacific Gas and Electric Company)
Phelps, Geoffrey	(USGS)
Pitarka, Arben	(Lawrence Livermore National Laboratory)
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Aagaard and others—**Science Plan for Improving Three-Dimensional Seismic Velocity Models in the San Francisco Bay Region, 2019–24**—Open-File Report 2020–1019

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