## 2022 SCEC Report

# Support of next generation Statewide Community Velocity Models through enhanced basin representations

**SCEC Award 22060**

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**Proposal Categories:**

Data Gathering and Products; Collaborative Proposals

**SCEC Science Priorities:** P4.b

**Project Duration:**

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## 1. Summary

We improved 3D descriptions of sedimentary basins in California to support the development of next-generation SCEC Community Velocity Models (CVM's). First, we evaluated new probabilistic approaches to parameterize the basin velocity structure (Vp & Vs) using wellbore, seismic reflection, and other direct velocity constraints. This effort focused on the Los Angeles basin, which is the most data rich and mature basin velocity representation in the current CVM's. Our analysis included formal assessment of model uncertainties as well as provide statistical measures of spatial variability in the sedimentary velocity structure. In a second phase of the project, we developed new, detailed basin surfaces for the complete Central Valley (San Joaquin and Sacramento basins) to provide for continuity and consistency in velocity modeling. The Central Valley is the largest sedimentary basin structure in California, yet is not directly represented in CVM-S or CVM-H. Development of the new Central Valley model is critical for SCEC's efforts to move toward encompassing the entire San Andreas plate boundary system. This study region also helps to improve hazard assessment in an area that includes the city of Sacramento, the California state capital, which has a population of more than 2.4 million. Sacramento is one of the fastest growing regions of the United States and is at risk from earthquakes on numerous active faults in the region (e.g., WGCEP, 2007; Ward, 2007; Field et al., 2013). This year we focused on improving the Central Valley basin structure, which is now represented by a top-basement surface and a more detailed base Tertiary geologic horizons along its entire, ca. 650 km long extent. We also developed a database that provides the basis for developing a base Quaternary geologic horizon for the complete basin. Finally, we identified a list of wells which have extensive sonic logs and cover large portion of the Sacramento Valley. With these efforts complete, we plan to further improve the 3d descriptions of sedimentary basin velocity representations in the CVM.

## 2. Improved methods for velocity modeling in sedimentary basins

Sources of information for velocity modeling in the commercially explored sedimentary basins include hundreds of kilometers of seismic reflection profiles, industry well logs, and other sources. Nevertheless, parts of the subsurface remains unsurveyed and can only be included by models based on geological rules, indirect geophysical observations, inversions and reconstructions. All these methodologies come with uncertainty. When regional velocity models such as the CVM's are applied to model seismic events, the forecasts of strong ground shaking are directly impacted by these uncertainties. Our research is focused on trying to assess and reduce uncertainty on the structure of the deeper (below geotechnical level) parts of basins in Southern California.

In our project we developed a new workflow to study the impact of structural uncertainty on seismic response based on implicit modeling of a sedimentary basin. Implicit geological modeling techniques have been developed since the turn of the millennium (Mallet, 2004) and the methodology has since had significant impact with increased computational power. Various implementations in commercial software exist, but no open-source implementation for non-commercial use and research was available prior to the development of Gempy (de la Varga et al., 2019), an open-source geostatistics based Python-Library. Implementations of these approaches are generally characterized by high computational costs and numerical complexity. De la Varga et al. circumvented some of this complexity by solving the problem on a regular grid and based on established geostatistical methods. Hence the method was developed for larger structures and whole basins with relative sparse data distribution, which is typical for large parts of the sedimentary basins in California.

A common methodology applied to describe deep spatial uncertainty of geophysical measurements is provided by kriging and derived geostatistical methodologies which represent uncertainty with a distance dependent least square estimator (Deutsch & Journel, 1997). Here we use a sequential Gaussian simulator, a Monte-Carlo based sequential modeling method to distribute correlated spatial uncertainty and modify the structural model based on best estimate conforming realizations of the velocity structure (as implemented by Mueller et al. (2022) in Python). For our study, we selected the northern part of the Puente Hills area where the Whittier fault juxtaposes younger low velocity older basement rocks, including local inversions (higher over the lower velocity sediments) (Süss et al., 2003). While the structure of the area is relative well known and has been penetrated by wells to a depth of more than 4,000 m, we can easily study the impact of uncertainty on the distribution of earthquake energy at the surface. In our pilot study we use simwave, a python library for finite difference solutions of p-wave propagation that is highly parallelized and provides seismic simulations at reasonable resolutions with performance suitable for uncertainty and sensitivity studies (de Souza et al. 2022). It is clear that these simulations do not represent an accurate representation of earthquake wave dynamics, but in the frame of our project the implementation is sufficient to demonstrate the impact of spatial uncertainty.

Our model is based on basic work presented by Süss et al. (2003) which integrated hundreds of wells and thousands of kilometers of industry seismic to build a regional seismic velocity of Southern California. Due to computational costs, we concentrate on an area of approximately 45x44 km and model only the role of the Whittier fault as a structural element that impacts wave reflectivity and focusing in the basin. The area is modeled with a resolution of 200x200x160 meters and input data for our model was substantially reduced compared to the original dataset. Still, both resolution and data are sufficient for a realistic representation of the structure. In general, spatial uncertainty has two sources: uncertainty in data precision due to method resolution (in example data repositioning by seismic processing) and uncertainty of the estimator of spatial modeling algorithm. While it is in principle possible to treat both separately, we focus in our model on the impact of data precision by adding spatially correlated noise using Sequential Gaussian Simulation to the impact data. We assume that total uncertainty increases with depth by simulating a relative positioning uncertainty which adds approximately 1% of spatial noise (2 $\sigma$) to the depth values, which approximates typical vertical positioning uncertainty at depth from seismic surveys in areas without direct well control (eg. $\approx$10 m uncertainty at $\approx$ 3,000 m depth). While at the first glance, such uncertainties appear minor, they can impact dip angle of structures and positioning of reflected seismic energy as shown in our experiments. After we generate a realization of the structure of the basin we calculate a linear velocity models based on a velocity estimate for the sedimentary layer derived from the original model with a gradient of 0.35 m/sec increase per m and a $v_0$ of 1800 m/sec. For the deeper basement units we apply a lower gradient of 0.12 m/sec per meter and a $v_0$ of 4800 m/sec which implements a significant velocity contrast at the based of the sediments and causes focused reflectivity in the area of the fault. After the seismic velocity model is calculated, we simulate seismic waves sourced from an event (p-wave only) at approximately 10 km below the sedimentary basin west of the Whittier Fault. Waves traveling from below through the basement are disperse and reflected in the sedimentary units. We record the seismic amplitudes at the surface and compute the total seismic energy distribution by the summation of amplitudes in the model. The shape of the randomized subsurface is directly influencing both the direct amplitude above the event and the distribution of waves. To illustrate this result, we calculated the standard deviation of fifty realizations which allows to be better understand the variability of energy distribution in our model (Figure 1).

In summary, this component of our study demonstrates the impact of structural geological uncertainty on seismic energy distribution. While our pilot modeled only a small area of the Los Angeles basin, we demonstrated that is possible to study the impact of uncertainty with available techniques. Time and computational memory demand remains a crucial component of realistic uncertainty evaluations. We carried out our studies on modest of-the-shelf hardware and were able to simulate an area of approximately 1600 square kilometers in reasonable times. However, being a volumetric problem, memory and time consumption increases at least by the square or even more. We therefore recommend to investigate further computational improvement of the code (which appears feasible), which will enable us to increase area and complexity of our models. Further we stress that uncertainty evaluations of this kind require a closer integration of geological and geophysical uncertainty understanding as well as the reporting and determination of structural and methodological uncertainty of our data which form the base of the models. Further, more state-of-the-art seismic simulations should be investigated in future uncertainty quantification studies.

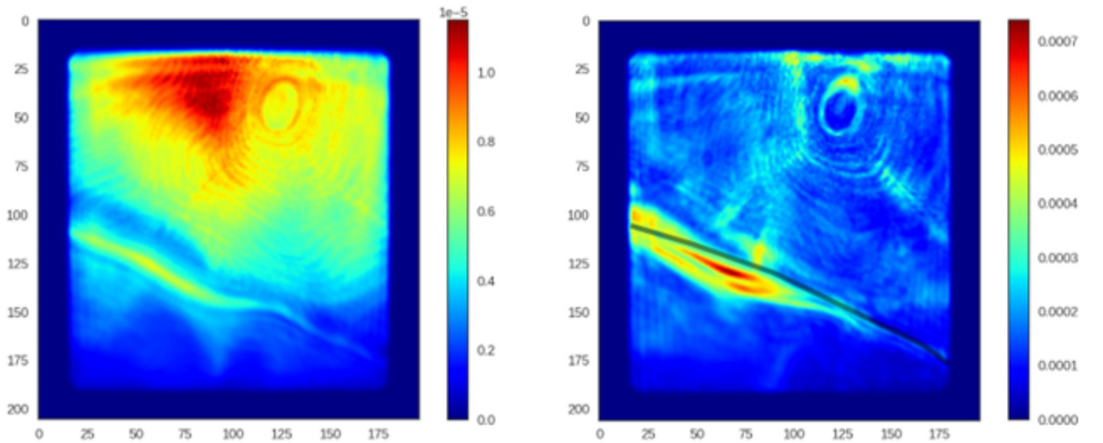


**Figure 1**: Left: Total vertical excitation at the surface of one simulation run. The source is at about 11 km in the East at the model boundary. Right: standard deviation of 50 uncertainty runs. In black the surface trace of the fault in the model. Note the area along the fault shows the highest uncertainty of seismic excitation.

### 3. Central Valley basin structure

The most conspicuous regions of the SCEC CVM's that need further model development are the San Joaquin and Sacramento basins, which together comprise the Central Valley structure.

In order to develop a detailed basin representation for the Central Valley, we start by defining a basin shape for the entire basin. Geologically, the base of the Jurassic-Cretaceous forearc basin section, corresponding locally to the top of the Mesozoic accretionary and plutonic complex, is one of the most important boundaries (Wentworth et al., 2005). Sonic logs show that this "acoustic" basement horizon represent an abrupt change in compressional wave velocity, shear wave velocity, and density. Moreover, other major geologic horizons within the sedimentary section represent important velocity interfaces (Brocher, 2005), and thus can provide constraints on our model. These surfaces include the base Tertiary, top Eocene, and base Quaternary horizons. Here, we present new top basement and base Tertiary horizons.

Our new top basement surface (figure 2) incorporates a comprehensive compilation by Wentworth et al. (1995) which covers the San Joaquin basin and the eastern margin of the Sacramento basin. We extend the surface to the western margin of the Sacramento basin using interpretations of seismic reflection profiles by Unruh et al. (2004) and inversions by Godfrey and Klemperer (1992). We then further extend the surface in a generalized manner under the Coast Ranges at a depth of ca. 15 km acting as basal detachment.

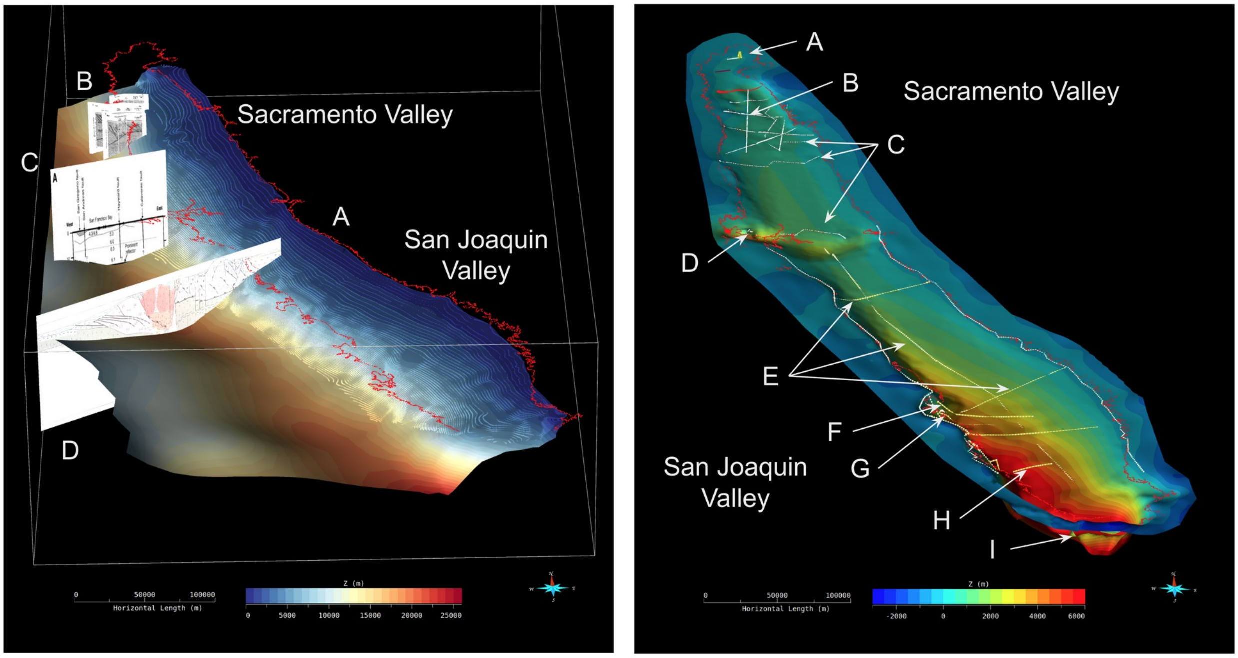


**Figure 2:** Left: A perspective view of the top of crystalline basement surface for the entire Central Valley basin. The interval of the color contours is 1000m. Letters point at major data sources: A: structure contours by Wentworth et al., (1995), B: Unruh et al. (2004), C: Brocher et al. (1994), D: Fuis & Mooney (1990); Right: A perspective view of the detailed base Tertiary surface for the entire Central Valley basin. The interval of the color contours is 500m. Letters point at major data sources: A: Well Tucker-1 (API 0408900003), B: cross-sections in CA DWR (2014), C: AAPG correlation sections (Cross et al., 1954, Edmondson et al., 1967, Rennie, 1987), D: Cherven, 2020, E: Bartow (1991), F: Walter, 1990, G: Guzofski et al. (2007), H: Wentworth et al., 1984, I: Namson & Davis, 2017

In the Central Valley largely Cretaceous fore-arc basin sedimentary, marine rocks lie above the top basement surface. Their upper limit - the base Tertiary - is in many places an unconformity separating marine rocks from terrestrial clastics and volcanics. These Tertiary units have varied facies and are dominated by paleo-drainage systems along the axis of the basin (Harwood and Helley, 1987). In the San Joaquin Valley, we constructed a detailed base Tertiary surface (figure 2) from many sources, including Bartow (1991), Walter (1990), Wentworth et al. (1984), Guzofski et al. (2007) and Scheirer (2007). In the Sacramento Valley, we incorporated American Association of Petroleum Geologists correlation sections (Cross et al., 1954, Edmondson et al., 1967, Rennie, 1987), a digital map by the Department of Water Resources, Northern Region Office (2014), and references therein, in particular Helley and Harwood (1987) with accompanying geologic cross-sections supported by a number of recent research wells by the DWR, and interpretations of seismic reflection data by Unruh et al. (2004). Contacts between Tertiary or younger units with Cretaceous or older units on the geologic map of California define the limit of the base Tertiary surface, outlining the modern Central Valley and marking interior structures such as the Capay Hills. All sources were precisely geo-referenced using GIS software, digitized and combined by discrete-smooth interpolation (Mallet, 2002). This method allows for secondary constraints on the interpolation such as respecting longitudinal trends or faulting. The resulting surface shows a deepening of the Tertiary basin from north to south where sediment thicknesses reach >6 km. The eastern margin is characterized by steady, gradual thinning in a monocline towards the basin boundary. The western margin is marked by contractional deformation which in places involves faulting and folding of the Tertiary.

We also developed a database for base Quaternary consisting of water well based maps and cross-sections. The database includes maps by Scheirer (2007), and cross-sections by Cal. DWR (2014) and Bartow (1991).

There are hundreds of oil and gas wells and associated well logs in the Sacramento Valley. Logging frequently focuses on specific sedimentary units to define their reservoir quality, and is therefore often limited to those intervals. Thus, we focused on identifying deep wells in the Sacramento basin with long continuous sonic logs which are plotted in figure 3.

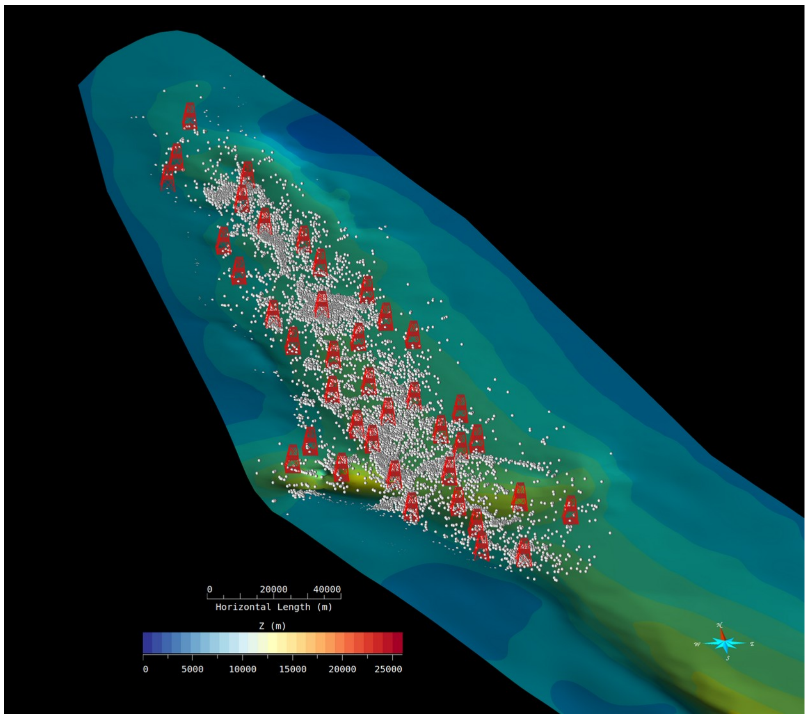


**Figure 3:** Well coverage in the Sacramento Valley. White dots show oil and gas wells in the region. Red derricks mark wells with extensive sonic log availability. Color contoured surface is Base Tertiary.

The California Geologic Energy Management Division (CalGEM) provides a web-based query interface to scans of paper well logs provided by operators of wells. We developed a workflow to automate accessing batches of sonic logs from the system with little user interaction.

## 4. Application to SCEC5 Goals

This proposal represents a primary effort to address the following SCEC priority: P4.b.
Develop multi-scale velocity models, with high-resolution information around faults and near the surface embedded in the regional models, and validate the merged multi-scale models.
Moreover, through the development and delivery of the CFM this project contributes to the CXM modeling effort and a range of other SCEC goals.

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