Cascadia Subduction Zone Science: Call for the Next Generation Community Seismic Velocity Model

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Abstract

The Cascadia subduction zone (CSZ) hosts major seismic and tsunami hazards, yet key questions persist about the relationship between margin structure, fluid distribution, episodic tremor and slip, shallow megathrust behavior, shaking and tsunamigenesis, and the resulting hazard estimates. Addressing these problems requires an empirically grounded, three-dimensional seismic velocity model to illuminate subsurface structure and properties and to provide a basis for geophysical studies such as earthquake simulations and ground-motion estimation. In May 2024, the National Science Foundation-funded Cascadia Region Earthquake Science Center (CRESCENT) community velocity model (CVM) working group, with U.S. Geological Survey and regional partners, convened a workshop to identify priorities for such a model. Participants emphasized the features necessary for addressing key science questions, including implementing findability, accessibility, interoperability, and reusability (FAIR) access, capturing along-strike and along-dip structural heterogeneity, resolving shallow offshore–onshore structure, constraining elastic properties and quantifying their uncertainties for numerical wave propagation simulations, their validation benchmarks, and supporting associated accurate earthquake ground-motion simulations and hazard assessments. This article describes the priorities defined in the workshop, and a description of how, guided by these needs, CRESCENT plans to develop multiple generations of a CVM to advance CSZ science and improve seismic and tsunami hazard modeling across the Pacific Northwest. The CVM will span the CSZ from the surface to ~100 km depth, offshore and east of the Cascades into Idaho (~132°–110° W) and the southern and northern tectonic regime transitions (~36°–52° N) to capture the entire tectonic system as well as its surroundings.

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The Cascadia subduction zone (CSZ)—the only subduction zone in the conterminous United States and Canada—poses major hazards including strong shaking, tsunamis, and ground failure (Daniell *et al.*, 2011; Kulkarni *et al.*, 2013; Wong *et al.*, 2014; Walton *et al.*, 2021). Major fundamental and applied questions about subduction zone processes and hazards remain and addressing them is one part of societal resilience. For example, what is the interplay between fluids, tremor and slow slip, and the downdip limit of the seismogenic zone? Where do we expect earthquakes to nucleate and propagate, and how does that control resultant splay fault activation and tsunamigenesis (Aslam *et al.*, 2021; Jourdon *et al.*, 2025)? What is the nature of strong ground motions and their seismic hazard implications?

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Addressing these questions necessitates the robust characterization of subsurface properties in three dimensions, which can be obtained through the creation of multiscale and multiresolution seismic velocity models. The U.S. Geological Survey's (USGS) regional-scale velocity model (Stephenson *et al.*, 2017) has been the community standard for tectonic applications and ground motion estimation in the CSZ (Frankel *et al.*, 2018; Roten *et al.*, 2020; Grant *et al.*, 2025; Wirth *et al.*, 2025); however, significant advances in data coverage and methodologies have occurred since its development. A major task of the Cascadia Region Earthquake Science Center (CRESCENT), a National Science Foundation-funded geohazards center (D. Melgar et al., unpublished manuscript, 2025, see Data and Resources; Sahakian *et al.*, 2025), is to produce next generations of three-dimensional (3D) multiscale community seismic velocity models (CVMs).

At a May 2024 topical workshop, experts discussed requirements and desires for CVMs to answer key science questions and develop a community of practice supporting applied science, consistency across state and federal borders, collaborations with other science centers, and model accessibility beyond the scientific community to improve seismic resilience.

Seismic velocities are a window into many foundational tectonic and geodynamic questions, providing constraints on lithospheric and mantle structure and the characteristics of geologic terranes (Gao and Long, 2022; Ashraf *et al.*, 2025), mantle flow patterns (Long, 2016), slab structure, hydration (Horning *et al.*, 2016), and how these properties relate to surface processes and margin segmentation (Bodmer *et al.*, 2020; Delph *et al.* 2021). Sensitive to the presence of fluids (e.g., Canales *et al.*, 2017; Delph *et al.*, 2018), velocity models are one of many tools applied to better understand the extent and nature of conditionally stable and aseismic regions. These regions govern the nature and down-dip edge of seismic slip (Wang, 2024), in turn impacted by rheological properties that promote the existence of slow slip and tremor (Hippchen and Hyndman, 2008; Audet *et al.*, 2010; Wang and Tréhu, 2016; Calvert *et al.* 2020). A CSZ CVM should adequately resolve the depths where we expect dehydration reactions (~20–60 km, Condit *et al.*, 2020) that can be compared with other constraints, such as seismicity (Bostock *et al.*, 2019) low-frequency earthquakes (LFEs; Bostock *et al.*, 2012) and tremor (Ghosh *et al.*, 2015; Wech, 2021), and fluid proxies from electrical conductivity models (Egbert *et al.*, 2022).

Rupture nucleation, propagation, and arrest determine the extent (e.g., along-strike segmentation and down-dip limit of the seismogenic zone) and characteristics of fault slip during megathrust events, informing the range of possibilities of future earthquake source properties and ultimately ground-motion characteristics (Herrendörfer *et al.*, 2015; Corbi *et al.*, 2017; Wirth *et al.*, 2018; Melgar *et al.*, 2022; Wirth *et al.*, 2022; Nye *et al.*, 2024). Similarly, understanding if, how (elastically or inelastically), and where accretionary wedge splay faults may activate and deform is related to rupture characteristics, and critical for modeling tsunamigenesis (Ma and Hirakawa 2013; Aslam *et al.*, 2021; Ledeczi *et al.*, 2023; Biemiller *et al.*, 2025). Determining these *a priori* is still at the forefront of basic seismological research, and dynamic rupture models are one tool with which to explore these CSZ megathrust dynamics. These simulations provide insight into how the state of stress and pore pressure, fault structure, and frictional and material properties may impact extent and kinematics of future CSZ earthquakes and tsunamis (Ramos *et al.*, 2021; Glehman *et al.*, 2024). In particular, there are significant along-strike and down-dip variability in properties, including plate interface morphology (Bletery *et al.*, 2016), the rheological behavior of the interface (Brudzinski and Allen, 2007; Wech, 2021), and coupling or locking in the CSZ (Wang *et al.*, 2013; Schmalzle *et al.*, 2014), which could affect rupture propagation. Dynamic rupture models often use geodetic constraints on fault locking (Yang *et al.*, 2019) to predefine the regional stress state (Madariaga and Olsen, 2000). The stress state relies on inferred elastic properties from a velocity model (Jiang *et al.*, 2022), with literature demonstrating that three-dimensionality of structure matters in modeling crustal deformation (Langer *et al.*, 2019; Fadugba *et al.*, 2024) as well as wave propagation. Dynamic rupture models also inform source physics behavior, making an empirically based CSZ CVM critical input to define material properties and inform questions regarding future earthquake characteristics.

Predicting the impacts of shaking and tsunamis on the built environment allows us to provide hazard estimates to regional users (engineers, utilities, state and federal agencies, and emergency managers) to sufficiently mitigate risk and long-term effects (Kempton and Stewart, 2006; Katsanos *et al.*, 2010; Sajan *et al.*, 2023). Numerical simulations and empirical ground-motion models support this, and a CSZ CVM is essential input to accurately estimating amplitude, duration, and spectral characteristics of future strong ground motions for engineering purposes (Abrahamson *et al.*, 2016; Cremen and Galasso, 2020; Parker *et al.*, 2022). Shallow crustal structure and surface geotechnical properties are critical constraints for these methods (Graves *et al.*, 1998; Nye *et al.*, 2023), and quantifying uncertainties are crucial for ultimately informing probabilistic hazard estimates (Milner *et al.* 2021). Seismic networks and earthquake early warning systems may also use 3D velocity models for locating seismicity and predicting shaking times (Allen *et al.*, 2009).

Across disciplines, a CSZ CVM should support the reproducibility of science, including adhering to findability, accessibility, interoperability, and reusability (FAIR) principles (Lightsom *et al.*, 2022), documenting variabilities and metadata (i.e., model inputs and techniques). Model accessibility can be addressed through good documentation, cyberinfrastructure tools (i.e., cloud hosting and model querying), and adopting output formats for commonly used software (Ni *et al.*, 2025). Addressing model performance requires

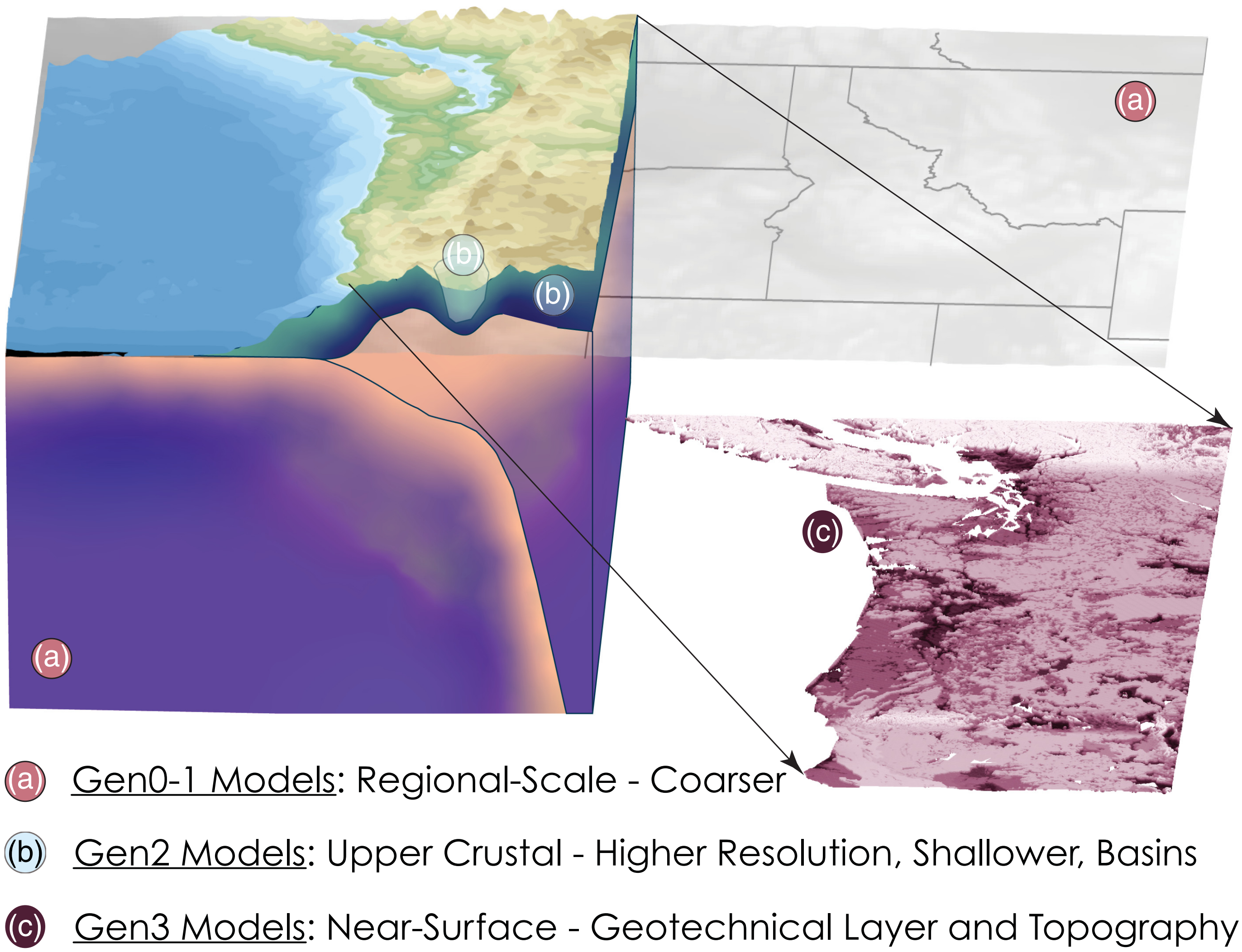

Figure 1. Schematic showing the extent, resolution, and components of Gen 0–3 models. (a) The Generation 0–1 models with coarse, regional-scale resolution and coverage, spanning beyond the Cascadia subduction zone (CSZ) tectonic regime by extending west of the spreading ridge offshore (~132° W) and east into Idaho (~110° W) and south of the tectonic transitions into California (~36° N) and Canada (~52° N). The warm purple to orange colors qualitatively represent seismic velocities from fast to slow, respectively. (b) The contributions from Generation 2 velocity models, incorporating both higher resolution, shallow upper crustal and basin structure in the region. (c) The near-surface, geotechnical layer and topography, with darker purple colors indicating softer material (lower surface velocities or V_{S30}) and lighter colors representing harder rock (faster surface velocities).

consistent validation and scoring systems across model generations, accompanied by an online repository of community-contributed velocity models, accessible with the same tools. Finally, the community expressed the importance of building a collaborative community of practice with the CVM group.

To accommodate the aforementioned science needs, the CVM group is developing a regional-scale coarse model (~20 km horizontal resolution), that extends the CVM east of the CSZ volcanic arc (Fig. 1). To serve key partner agencies, the northern and southern extent of the model should extend past the Mendocino triple junction and into British Columbia, consistent with Statewide California Earthquake Center and other California community models (Aagaard *et al.*, 2025). Work with Canadian partners would serve as a collaborative endeavor with existing institutions of knowledge, producing Generation 0 and 1 models (Fig. 2).

For earthquake rupture simulations, accurate onshore–offshore models are necessary to characterize the shallow megathrust interface properties and surrounding velocities (Hicks *et al.*, 2014; Huang *et al.*, 2014; Yamamoto *et al.*, 2014), as well as accretionary wedge structure. Due to inconsistencies in the density and longitudinal location of seismic stations used to constrain velocity models, the trench to shoreline structure is usually poorly constrained. In addition, shallow crustal features such as basins (Cruz-Atienza *et al.*, 2016) and sharp lithological contrasts across crustal faults (Ma and Beroza, 2008) represent key structural features that control ground-motion characteristics. The CRESCENT CVM should produce models of shallow

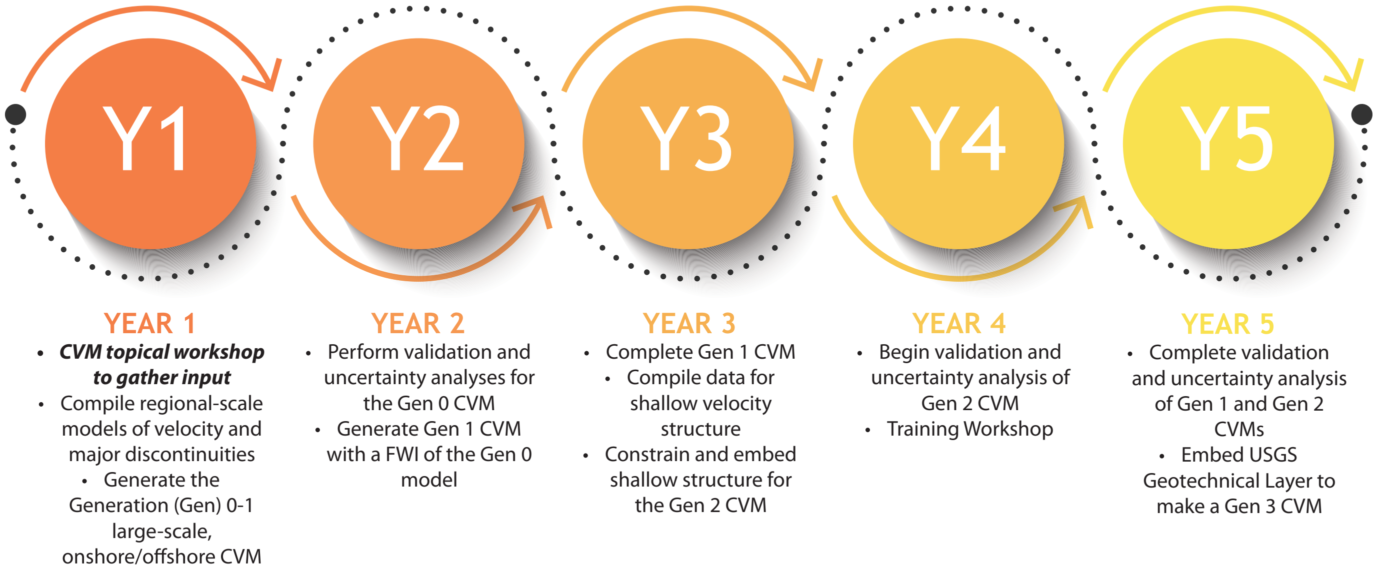

Figure 2. Diagram of the Cascadia Region Earthquake Science Center (CRESCENT) Community Velocity Model (CVM) timeline.

(<20 km depths) and finer-scale (<1 km resolution) velocities by incorporating constraints from basins and offshore data sets (e.g., Carbotte *et al.*, 2024), embedding them into the deeper and coarser Generation 0 and 1 models such as with merging techniques (Ajala and Persaud, 2021). This would produce the class of Generation 2 models, accompanied by the depths and characteristics of key interfaces such as the plate interface (Ashraf and Hooft 2026; Figs. 1 and 2).

Generation 3 CVMs should integrate shallow geotechnical and site characteristics, including the USGS Pacific Northwest soil velocity model and topography at sufficient resolutions (Grant *et al.*, 2025; Wirth *et al.*, 2025). These models should have smooth and continuous velocities across state and federal borders for unified hazard forecasts based on ground-motion simulations (Fig. 1). Each CVM generation should include the characterization of uncertainties of model parameters and validation metrics, reporting both uncertainties of the velocities in each grid cell (intramodel variability), and, if possible, between other existing models at that grid (intermodel variability). These are crucial for understanding how models impact resultant simulated ground motions and probabilistic seismic hazard analyses (Milner *et al.*, 2021). Later iterations of the CVM could include accurate estimates of seismic anisotropy and anelasticity.

Finally, model accessibility is supported via cyberinfrastructure tools and metadata documentation; this same cyberinfrastructure hosts a repository of other models from researchers, to support a community of practice (Bahavar *et al.*, 2025).

Declaration of Competing Interests

The authors acknowledge there are no conflicts of interest recorded.

Data and Resources

All data used in this paper came from published sources listed in the references. The unpublished manuscript by D. Melgar et al., 2025, "The Cascadia Region Earthquake Science Center (CRESCENT): Advancing understanding of Cascadia's earthquake hazards," submitted to Seismol. Res. Lett.

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