The Cascadia Region Earthquake Science Center
Strategic Plan 2023-2027

Building an Earthquake Center and Culture in the Pacific Northwest

Subduction zones host the largest earthquakes on the planet. Their cascading consequences — strong shaking, tsunamis, landslides, liquefaction, fire, and more — make them some of the most devastating natural hazards. As a result, convergent plate boundaries have been the subject of intense scientific scrutiny in the past two decades that has yielded many of the most important recent advances in the physics and impacts of earthquakes. In the USA, the Cascadia subduction zone presents both the greatest hazard of a magnitude 8 or larger great earthquake and tsunami, as well as the greatest risk of loss of life, injury, and physical infrastructure to the nation. At the same time, because no such event has happened in Cascadia in the time since European settlers arrived, and because seismicity is relatively rare in the region compared to California or to other subduction zones, the public and its governmental leaders do not have the earthquake hazard awareness of those in more seismically active regions. The region has not developed an earthquake culture.

We conceived the Cascadia Region Earthquake Science Center (CRESCENT) to fill this need for a subduction-focused earthquake research, education, and partnership building effort.

Vision

CRESCENT envisions a future where the complexities of subduction zone earthquakes and their hazards are well- and holistically understood, where communities are prepared and resilient, and where science and society work hand in hand to mitigate risks and ensure public safety.

Mission

CRESCENT is dedicated to advancing our understanding of earthquakes and their hazards in the Cascadia region, by fostering collaborative basic and applied research, community engagement, and inclusive geoscience education. Our mission is to improve regional resilience through scientific discovery, knowledge synthesis, and community partnership and connections, with a vision of a safer and more informed society.

Values

CRESCENT is committed to inclusive and community-driven science where broad collaboration and diverse perspectives are welcomed and needed to achieve a more holistic understanding of Cascadia earthquakes and their place in Pacific Northwest society and beyond.

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A Call to Action: The Science and Culture of Cascadia's Earthquake Hazards

The Cascadia subduction zone (CSZ) is one of the world's best natural subduction zone laboratories. CRESCENT is pursuing an ambitious shoreline-crossing earthquake hazards research agenda aimed at deepening understanding of the CSZ and subduction zone systems more broadly. The research agenda will draw on many ongoing efforts by the U.S. and global research community to understand subduction processes and resulting hazards, but focus the effort of a large, multi-disciplinary team on advancing science and hazard awareness in Cascadia. Novel, transformative activities in CRESCENT will range from state-of-the-art simulation of earthquake processes within this unique and complexly interacting system to mining of vast quantities of legacy seismic and geodetic data for new insight.

Beyond fundamental discovery, CRESCENT's focus on the CSZ is of regional as well as national importance. Amplified by popular science writing, public awareness has grown that the Pacific Northwest and its residents will face a slew of cascading hazards accompanying the next large earthquake and that resilience of the region is low. Nonetheless, the earthquake culture of the region is still developing. Spanning three states and two countries, the region has yet to come to grips with how to prepare for future events. Inadequate earthquake resilience of built infrastructure, impossibly long tsunami evacuation distances, precarious lifelines, and other fragilities are well known and pose unresolved challenges that reduce resilience and public safety. Hazardous faults in the CSZ are diverse. The crustal faults in its southern terminus, for example, lead to frequent damaging events in California and Oregon. Likewise, the Seattle fault and other crustal thrusts are well known to be capable of up to M7 events. Meanwhile, deep-focus ruptures like the 2001 M6.9 Nisqually earthquake are poorly understood. That event led to losses of $1-4bn in the Puget Sound region. Of course, the megathrust and its capacity to produce up to magnitude 9 events is a major concern – losses of up to $100-$300bn can be expected in such an earthquake (e.g., Belenky et al., 2014) with decades of economic and social impacts reverberating nationally due to business interruption and displaced populations (OSSPAC, 2013).

If the scientific challenge is daunting and the goals ambitious, the parallel challenge of building a more geohazard-resilient society – an earthquake culture – is equally so. CRESCENT will pursue these goals through work with our partners in geohazards risk mitigation and emergency management at all levels (federal, state, local, and industry) and through strategic efforts to foster a robust, diverse, and inclusive community of geoscientists for the future.

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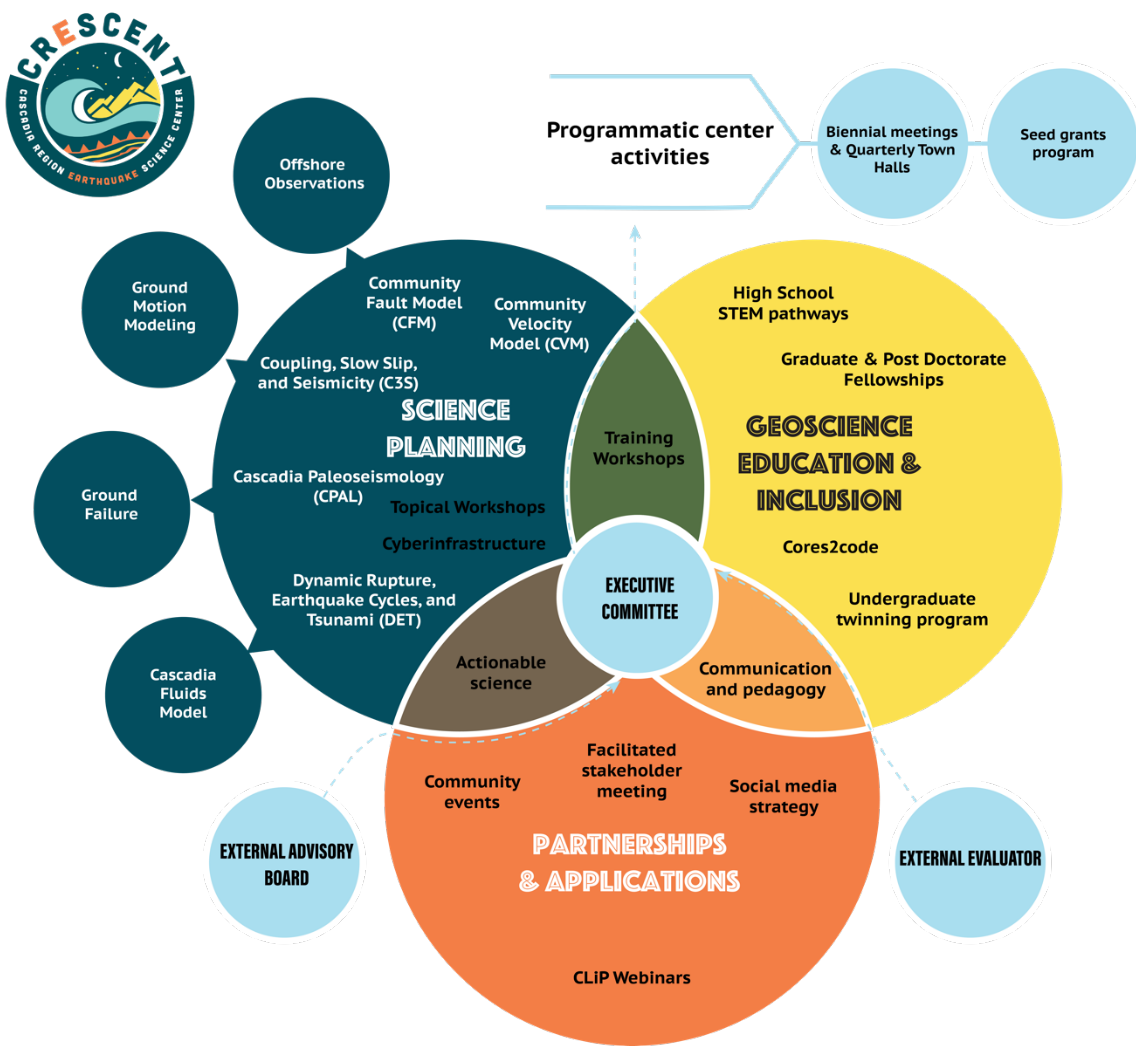
CRESCENT's Architecture: The Three Pillars

Realizing the CRESCENT vision and achieving our mission while adhering to our values relies on dedicated and simultaneous progress on three equally important pillars: conducting foundational scientific research, inspiring and training the next generation of geoscientists, and building a community of practice in the Pacific Northwest. Activities within these three pillars will:

- help close knowledge "gaps" in our understanding of the complex Cascadia Subduction Zone,
- train the next generation of geoscientists in modern and advanced skills and techniques and promote and accelerate the diversification of the field, and
- create and foster collaborations with regional partners and agencies to ensure CRESCENT products are translated to maximize impact and utility.



The three foundational pillars at the core of CRESCENT with various major activities, programs, and groups highlighted.

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To address the knowledge gaps of the CSZ, strategic, decadal-scale planning is an integral part of CRESCENT's structure. Ten major activities span the three foundational pillars. These will be executed by scientists, engineers, and educators from over 15 U.S. institutions. Each activity has been designed with targets and milestones that can be tracked for assessing progress and adjusting as necessary. Guidance and monitoring of milestones and success will be provided by an external advisory board and evaluator. Dedicated management and technical center staff will facilitate the work and coordinate with the scientific, workforce, and community building leadership.

CRESCENT's structure integrates the participating federal, state, and local scientists and professionals, ensuring that our efforts will complement and be in harmony with the work of the mission-driven agencies. In addition, dedicated CRESCENT staff will build partnerships with relevant stakeholders in the region who would both guide and benefit from the science goals and knowledge created by the center. Center scientists already have deep ties in the region thanks to major affiliations with initiatives such as the Pacific Northwest Seismic Network (PNSN), the Cascadia Coastlines and Peoples Research Hub (CoPes), the ShakeAlert earthquake early warning system, the Cascadia Lifelines Program (CLiP). Furthermore, the center will prioritize collaborations with regional tribal nation organizations and seek to involve them in the center's activities.

To foster a vibrant and inclusive geosciences community, CRESCENT will emphasize place-based science and work towards modernizing Earth science education at all levels using the intrinsic interest in the impacts of geohazards as a springboard. Our plan includes a tiered set of activities at secondary, undergraduate, graduate, and postdoctoral levels. Central to this effort are proposed collaborations between the center and minority-serving institutions in the Pacific Northwest and national educational institutions.

In the following sections, we identify the key strategic activities that the CRESCENT community intends to pursue over this first five-year phase of the Center's existence, with an emphasis on years one and two. We envision and expect that CRESCENT will grow into a nexus for earthquake hazards research, education, and community partnerships in the region and will have impact far beyond the Pacific Northwest.

Innovative Science for a Resilient Society

A solid science foundation is key to CRESCENT's success and will be critical to countless downstream activities and geohazard related efforts in the Pacific Northwest and beyond. Several major activities are focused on laying this foundation and enabling transformative science.

One major activity is the operation of five science working groups (WGs), each tasked with generating scientific products, tools and databases useful for the other CRESCENT groups and the scientific community at large. These working groups will focus on developing community fault and seismic velocity models, computing dynamic rupture, earthquake cycle, and tsunamigenesis simulations, building high-resolution seismicity catalogs, quantifying the stress

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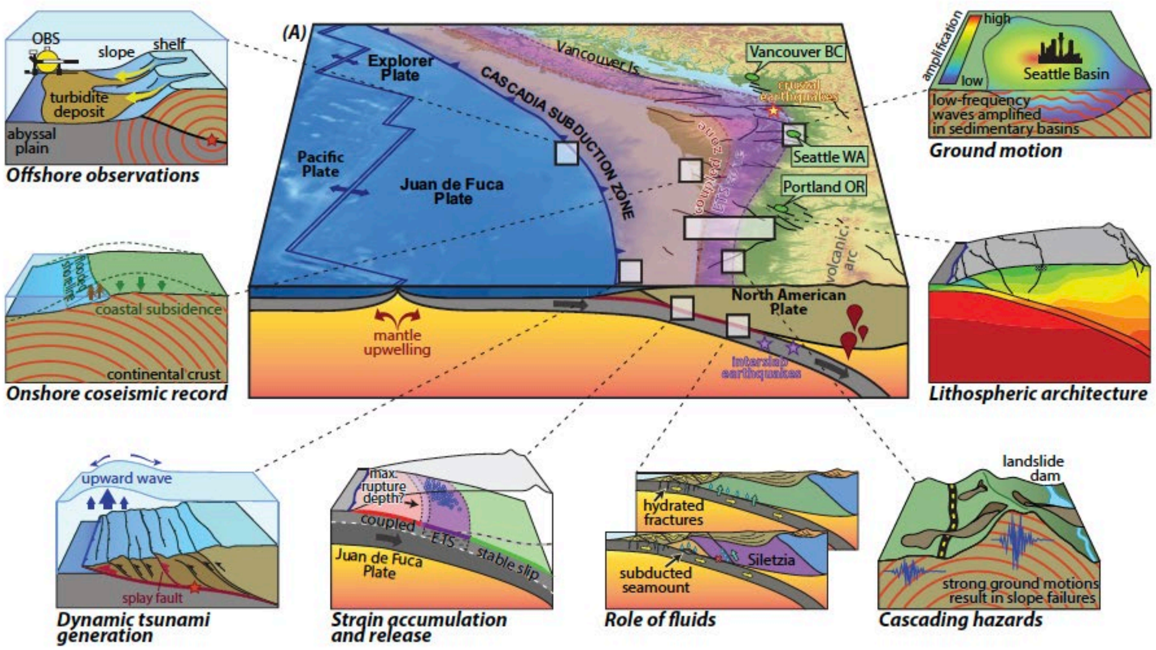
budget of interacting major tectonic structures.", and establishing and expanding world-class paleoseismological databases. These working groups are flanked by special interest groups (SIGs), focusing on emerging frontiers in earthquake science of special importance to the Pacific Northwest. Simultaneous progress on all these fronts is essential for a holistic understanding of the Cascadia Subduction Zone system.

Building proper cyberinfrastructure is essential. Without it, scientific progress along the axes of research named above is impossible. The "CRESCENT Cloud" has as a vision the creation of a high-performance computing (HPC) cloud ecosystem, cloud storage, and dataverse for long term archiving and version tracking of products. The center is collaborating with the EarthScope Consortium to employ several scientific programmers to achieve this vision. The CRESCENT community includes scientists, education specialists, engineers, and other stakeholders with varying interests, and all parties will utilize the cyberinfrastructure in some capacity. For example, members of the DET and C3S working groups (see next sections) will need access to HPC resources with significant storage capacity to develop, test, verify, and validate the new tools, community benchmarks, and training and modular workflows they will develop as part of their respective charges.



The complex Cascadia Subduction Zone with its numerous tectonic manifestations and associated hazards, all interdependent and all incompletely understood (modified from Walton, Staisch et al. (2021)).

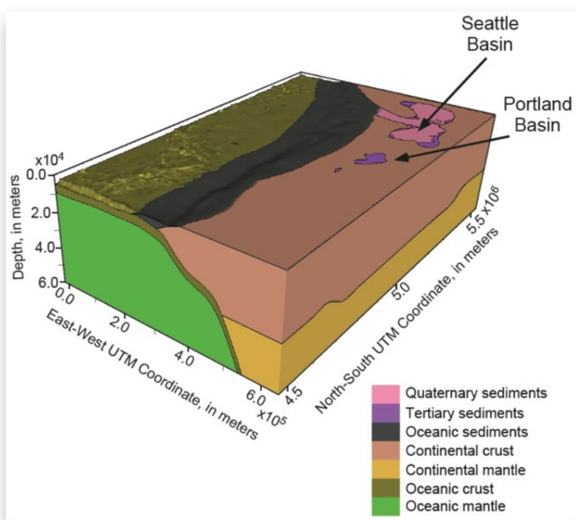
Other major activities for advancing the CRESCENT science goals and broadening community are the annual seed grant program and topical workshops. To truly achieve our goal of transformative subduction zone science will require progress on topics and fronts that are not covered or immediately tractable by the working and special interest groups. The annual seed grant program will broaden community participation and increase the breadth of scientific investigations. We anticipate that 5-10 grants (~$30k each) will be awarded each year.

Ten topical workshops over five years are meant to be "deep-dives" into topics of broad importance to Cascadia geohazards. They will create opportunities for a wide cross-section of scientists, early career researchers, and graduate students to discuss CRESCENT goals and science challenges. These workshops will be an important avenue to interact with the community on topics such as data sources, new findings and observations, synthesis methodologies, product dissemination, and best practices.

CRESCENT Working Groups

Working groups (WGs) are teams of scientists across all career stages working together on developing community products. Each of the five working groups are described below.

Shoreline-crossing Community Velocity Model (CVM)



US Geological Survey Open-File Report 2017–1152.

An accurate multi-scale community velocity model (CVM) of the Cascadia Subduction Zone is essential not only to advance our understanding of large- to small-scale properties and processes in the region but also as a foundational dataset for numerous downstream basic and applied science activities. For example, variations in seismic velocities and densities may provide key insight into the mechanical behavior of the subducting plate as it pertains to variations important physical phenomena. In tandem, all the other CRESCENT working and special interest group activities will directly or indirectly involve CVM products. In the case of C3S, these models will be key in computations of the deformation and state of locking of known faults and for the precise location of all Cascadia earthquakes. The CVM and CFM will share a geographic footprint to ensure shallow velocities are mapped in concert with crustal faults, both of which are key inputs to ground motion and seismic hazard estimates.

In year 1, the CVM team will produce a model of the important variables in a velocity model (P-wave velocity, S-wave velocity, and density) that extends from over the Juan de Fuca Plate to the Idaho-Montana border, and from ~38 degrees N to ~52 degrees, and down to a depth 80 km below sea level. Importantly, this will include topography which is not always the case for velocity models. These 3D models will be based on results obtained from advanced geophysical modeling or "inversion". In addition to these inversions, the geometry of the subducted plate or "slab", critical to many applications will be included. There is some disagreement over aspects of the slab geometry, so, for the CVM, it will be compiled from other studies and undergo careful vetting before integration into the model provided to C3S and DET. In fact, very recent active

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source surveys such as CASIE21 are producing a new image of the slab that will be critical to include in CRESCENT's CVM.

Because CVM serves a varied community of users it needs to be "multi-scale" – this involves high-resolution information nested within volumes that are more poorly resolved, usually because of inadequate data or different methodologies employed. Correctly merging different structural resolutions into a single coherent and sensible CVM is one of the main research thrusts or priorities of this group. Developing ready-to-use tools, software, and technology to merge seismic velocity models across multiple scales and resolutions or stitching or extending existing models to cover the significant footprint planned for the CRESCENT CVM will be a key priority.

Following the year 1 CVM foundation building phase, in year 2 the group will aim to complete the regional-scale model, incorporating results from more modern approaches such as full-waveform inversions. Simultaneously, and continuing into year 3, data and results reflective of upper crustal structures will be incorporated into the CVM with uncertainties increasingly quantified as the model evolves. As the upper crustal modifications are completed, work on synthesizing very shallow geotechnical data into a subduction zone-wide "geotechnical layer" will start and conclude in year 4, at which point waveform/data validation using local and regional earthquakes can begin. Most of year 5 will be focused on broad dissemination of the CVM and metadata.

Shoreline-crossing Community Fault Model (CFM)

Crustal earthquakes in the North American upper plate and the Juan de Fuca lower plate of the CSZ represent the least well-constrained of the earthquake sources in Cascadia. The faults along which they occur are located immediately beneath population centers and have the potential for significant seismic and cascading hazards. Intra-plate slab and shallow crustal earthquakes have the most influence in the U.S. National Seismic Hazard Model for the Pacific Northwest, with a Juan de Fuca plate, Nisqually-type event ranked as by far the most likely future damaging event in coming decades.

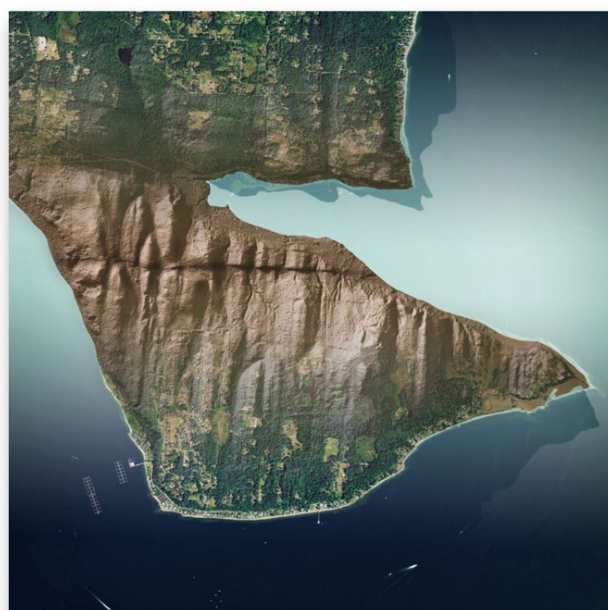

Image from the Washington Geological Survey (Washington State DNR).

A community fault model (CFM) will assist in evaluating these and other sources of seismic hazards, serving at least three critical functions:

(1) it will provide well-constrained fault geometries and paleoseismic histories that are required for appropriate characterization of upper plate fault hazards,

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(2) through construction of this database and associated stress modeling, it will help improve understanding of fault interaction (e.g., stress transfer and earthquake triggering), and
(3) by incorporating splay faults in the accretionary prism off-shore, it will shed light on the likely size and nature of near-field and far-field tsunami waves.

The CFM working group will develop a comprehensive topological and multi-earthquake cycle activity model of crustal faults in the upper plate of the Cascadia subduction system. The topological model will combine both on and offshore fault systems (in collaboration with the United States Geological Survey). In year 1, a simplified CFM will be built based on the National Seismic Hazard Model fault database. Off-shore wedge faults and upper plate faults constrained by new data will be reviewed and prioritized for incorporation into the CFM. This part of the model will include fault name, location, subsurface geometry, lengths, and other attributes of fault shape and position within the seismogenic crust. Fault activity will be as comprehensive as data allows. Desired attributes include slip per event, slip rate, paleoseismic event chronology, recurrence interval, earthquake size, sense of slip, and other quantities used to constrain fault behavior on multi-earthquake time scales.

Compatibility between CRESCENT and SCEC CFM products will be a key priority throughout, as will be the development of new data and/or analytical methods that constrain on- or off-shore crustal fault activity in space and time (especially for northern and southern Cascadia). Moreover, there are gaps in existing on- and off-shore fault and fold databases and slab models that the CFM team would like to fill. All these efforts will be made in concert with the other CRESCENT working groups keeping the compatibility of products as a high priority.

In year 2, the CFM v. 1.0 will be presented to the CRESCENT community for review, discussion, and updates. The CFM team will hold annual community meetings alternating between remote and in-person. Beginning in year 2, the CFM working group will collaborate with C3S to assess consistency between geodetic block model boundaries and the locations of known fault systems and their slip rate and sense. Through annual community CFM review and C3S verification, we will identify high-hazard or other geodynamically-important faults for which event chronology, slip rate, slip sense, or other important information are unknown, for prioritization in the annual small grant program.

In year 3, the CFM will hold a training workshop titled "Geophysical and geological characterization of active faulting structures." A remote one-day workshop will be held in year 5, edits will be incorporated in the CFM and the final CFM source model for the PNW will be launched. Also in year 5, a joint training workshop will be held with CPAL, CFM, DET, and C3S.

Dynamic Rupture, Earthquake Cycle, and Tsunamis modeling (DET)

The Dynamic Rupture, Earthquake Cycle, and Tsunamis (DET) group is tasked with advancing computational modeling of earthquakes and tsunamis. This is done both to make progress on fundamental understanding of subduction zone dynamics and to assess and quantify hazard. At the heart of the group's efforts will be dynamic rupture models. These models integrate

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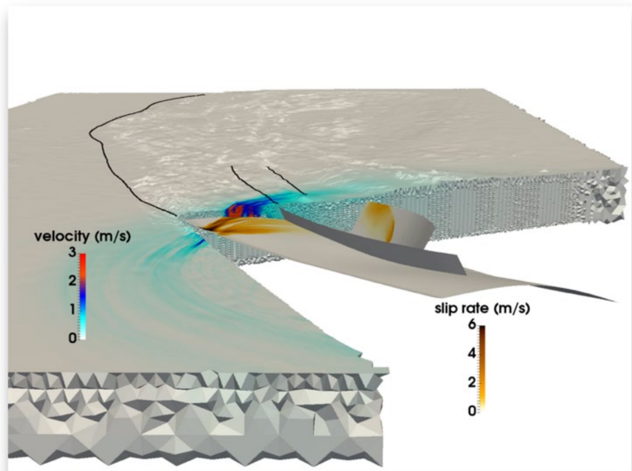
constraints on friction, stress, pore pressure, and the deformation behavior of subduction rocks to simulate fault slip and rupture propagation during earthquakes. Such models complement kinematic source models that compute the wavefield and crustal deformation from a user-specified slip history. Dynamic rupture models can be used to study controls on rupture path selection in geometrically complex fault systems. This is of critical importance for Cascadia which features numerous splay faults offshore. The DET group will utilize the fault geometries and material properties provided by the CFM and CVM groups.

Will ruptures propagating toward the seafloor continue along the decollement, jump to a splay fault, or slip both faults simultaneously? The partitioning of slip onto these structures with different dip angles affects seafloor uplift and tsunami generation. Another possibility to be investigated is that of distributed inelastic deformation caused by yielding of sediments in response to the stress concentration at the rupture front. Again, this affects seafloor uplift and tsunami generation. The DET group will tackle this problem using state-of-the-art dynamic rupture simulations that fully couple the ocean response with the solid mechanics problem, thereby providing not only the seismic wavefield but also the ocean acoustic and tsunami wavefields. The group will compare different earthquake-tsunami modeling workflows to determine if some of the simpler approaches (e.g., using static seafloor displacements to set tsunami initial conditions) are sufficiently accurate.



Dynamic rupture simulation of a subduction zone megathrust rupture, including activation of seaward and landward verging splay faults. Colors show slip rate on the faults and particle velocity (shaking) in the solid (Uphoff et al., SC'19).

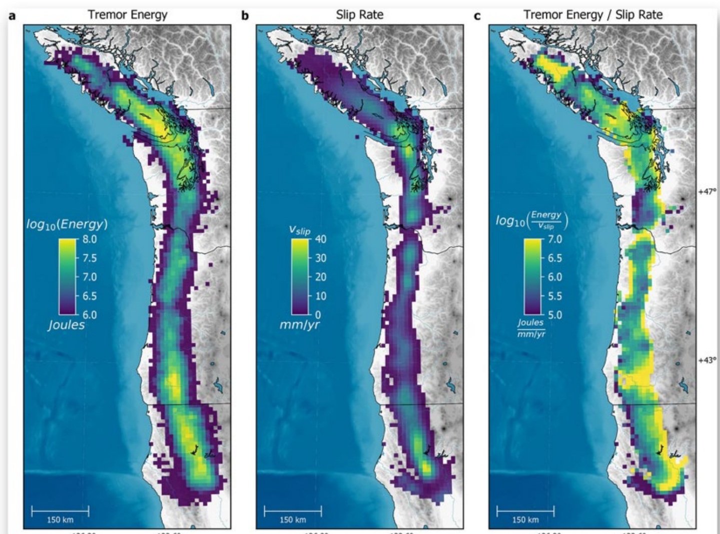
A second focus will be earthquake cycle models. DET will develop a sequence of increasingly complex models that will eventually account for fluid production and transport, which controls pore pressure and fault strength, and viscoelastic deformation, which affects strain accumulation and stress transfer. Cascadia is famous for episodic slow slip and tremor below the seismogenic zone, but the cause of this deformation behavior remains unknown. Cascadia provides one of the best opportunities to develop and test hypotheses for slow slip and tremor.

Furthermore, the down-dip extent of slip in megathrust ruptures remains uncertain. Can ruptures penetrate the partially coupled transition zone or even down to slow slip depths, or will they arrest at the lower boundary of the fully coupled seismogenic zone? This has huge implications for ground motion at population centers in the Pacific Northwest. The DET group will integrate earthquake cycle models with constraints provided by the C3S group to tackle these problems. They will also use earthquake cycle models to investigate the evolution of stress and pore pressure over the earthquake cycle. These evolving conditions determine whether ruptures remain confined along strike or propagate across changes in frictional properties or stresses that might be set by geology and long-term geodynamical processes.

Model validation is critical, but the paucity of events in the instrumental period makes this challenging. The DET group will turn, therefore, to paleoseismic constraints provided by the CPAL group. Models must be consistent with coastal subsidence, the extent of tsunami inundation caused by megathrust events, and the recurrence interval of sizeable earthquakes.

All models will be developed and released using open-source codes, documentation, and training to facilitate the adoption and extension of these models by the community. Furthermore, the DET group will lead a community code verification effort focused specifically on subduction zone megathrust ruptures, tsunami generation, and earthquake cycles. They will design benchmark problems that exercise and test relevant code capabilities, with comparisons between codes made through an online visualization platform.

Coupling, Slow Slip and Seismicity (C3S)



Maps of tremor properties along the Cascadia margin (Wech, 2021, JGR – Solid Earth).

The overarching goal of (C3S) is to obtain a time-dependent view of strain accumulation and release. C3S is comprised of three core scientific foci: (1) time-dependent coupling along the subduction interface and other crustal faults in the region, (2) a high-resolution seismicity catalog, and (3) developing a complete slow-slip catalog. Achieving these core goals will allow us to refine other products, such as a community geodetic model, which will provide a revised interseismic velocity field to be used in estimating which faults are locked and thus are more hazardous. Global Navigation Satellite System (GNSS) and other geodetic estimates of strain accumulation shows that Juan de Fuca-North American interplate coupling varies considerably both along-strike and through time. The known spatial correlation between the depth dependence of coupling, tremor density, and fluid distribution as inferred from electrical resistivity imaging all suggest fault fluids may control much of coupling patchiness and transient strain release. Because strength of coupling appears to correlate with seismogenic rupture, slow slip, tectonic tremor perturbations, steady-state deformation measured geodetically, and seismicity must all be modelled together.

The year 1 goals for C3S primarily consist of compiling the pertinent datasets and setting up the framework/workflows for the coupling model and the seismicity catalog. On the geodetic data side, CWU will expand the reach of their standard daily processing to include stations west of 100° W longitude to allow for a better constraint on viscoelastic deformation within the coupling and block model. Additional datasets, such as historic leveling data, will be investigated and validated for use in our models. An initial framework for detecting transients will be developed to extract the inter-ETS velocity field. This framework will allow for the community to test different detection and characterization algorithms to be compared systematically against all

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other community algorithms. The coupling model will also need inputs from the CFM for fault geometries, so the initial models will be generalized using the formats agreed upon by that working group. For the seismicity catalog, all datasets will be compiled, including raw seismic waveform data and existing seismic catalogs and their associated metadata. All the models and data will be set up to be run in a cloud environment.

The key priorities for the C3S group in the realm of coupling are to fully characterize the time-dependent coupling along the megathrust and explore the role of viscoelastic deformation. Moreover, fully characterizing the deformation budget of crustal faults is a high priority. With regards to seismicity, we aim to create the most complete event catalog, building a framework to systematically test and compare different seismic detection algorithms as a means to that end. For geodesy, building a full transient deformation catalog will allow us to properly characterize the full range of seismic and aseismic behaviors prevalent throughout the earthquake cycle in Cascadia. We also aim to enable the holistic integration of all potential datasets from geodesy, seismology, and geology.

The goals for years 2-5 will be reassessed based upon community scientific progress; however, we aim to fully build up complexity in the three core areas of C3S. For coupling models, this will include full viscoelastic Green's functions, incorporation of a complete fault catalog and a revised subduction interface (CFM), incorporation of 3D velocity structure (CVM), and a revised time-dependent community geodetic model based upon many datasets. For seismicity catalogs, the goal will be to obtain full catalogs of unusual seismicity such as low frequency earthquakes and tremor. On the slow slip side, we will fully merge the seismic catalog to build a seismogeodetic detection framework to build the most complete catalog of transient deformation in the region. We will also finalize the community geodetic model by merging other geodetic datasets with GNSS.

Cascadia Paleoseismology (CPAL)

A fundamental challenge in characterizing hazards along the Cascadia subduction zone is the lack of an instrumentally recorded megathrust earthquake. Due to this limitation, we must rely on paleoseismic studies to characterize the frequency, timing, and associated coseismic displacement of prehistoric Cascadia earthquakes. The Cascadia Paleoseismology Working Group (CPAL) will employ detailed stratigraphic mapping of subsidence and tsunami evidence and new high-resolution analysis of cores including CT scanning, microfossil, geochemical, and microfossil analyses to reconstruct coseismic land-level change and tsunami inundation during past Cascadia subduction zone earthquakes. To help build larger quantitative paleoseismic datasets of subsidence along the Cascadia subduction zone, CPAL will develop a shared, community-built diatom and foraminifera database that will increase accessibility and standardize microfossil analysis. CPAL will also work with the members of the USGS Powell Center Cascadia Earthquake Hazards group to develop and expand an online database of geologic observations that provide evidence for subsidence, shaking, and ground failure from past Cascadia subduction zone earthquakes and inundation from associated tsunamis. CPAL will directly collaborate with modelers to integrate the new and improved quantitative paleoseismic datasets and utilize the database of geologic observations to validate numerical models of subduction zone earthquakes and tsunamis and better assess hazards along the Cascadia subduction zone. With these tools, CPAL will establish the frequency, timing, total slip, slip rate, and other diagnostic features that reveal details of earthquake processes and can inform fault rupture models of past and future earthquakes in the CSZ region (crustal, megathrust, and slab).

In year 1, CPAL will collect new paleoseismic data in data-poor areas (e.g., sites that need quantitative subsidence estimates and sites where upper plate structures may influence subsidence estimates and rupture patch distribution). The new data collection will be informed by discussions with DET to identify sites that are most advantageous to modeling objectives. CPAL will conduct fieldwork at coastal sites in Oregon, including Salmon River, Coquille estuary, and Sixes River. Research objectives are to expand quantitative estimates of coseismic subsidence and mapping the inland extent of tsunami sand deposition. Laboratory analysis (e.g., CT scanning, radiocarbon dating, grain size and microfossil analysis) will be conducted on samples collected during year 1 fieldwork. In addition to fieldwork and laboratory analysis, CPAL will begin developing the microfossil database. By the end of year 1, diatom and foram plates will be posted on the CRESCENT website and integrated into community built taxonomic and photo websites and databases. Finally, CPAL will refine the plan for the Cores2code Summer School, developing and recruitment strategy and curricula, selecting and scouting sites, and planning logistics for the summer school to be held in year 2.

Paleoseismologists extract a sediment vibracore from the Siletz River estuary along the central Oregon coast (Photo Credit: Tina Dura).

In years 2-5, CPAL will continue to conduct high-resolution, quantitative field and laboratory paleoseismic analysis at sites strategically targeted to help modeling efforts. In addition, CPAL will build a community of practice that involves direct collaboration between paleoseismologists and modelers (e.g., the DET, CFM, and C3S WGs) with the shared goal of improving the integration of paleoseismic data and rupture modeling, providing the framework to test theoretical approaches that use paleoseismic data. In years 2 and 3, CPAL will develop and expand an online database of geologic observations that provide evidence for subsidence, shaking, and ground failure from past Cascadia subduction zone earthquakes and inundation from associated tsunamis to make paleoseismic data readily available to modelers in collaboration with the USGS Powell Center Cascadia Earthquake Hazards group. Finally, CPAL will host the Cores2code Summer School at Cal Poly Humboldt in years 2 and 4.

Emerging Frontiers: CRESCENT's Special Interest Groups

Special Interest Groups (SIGs) are teams of scientists working together on emerging areas of inquiry. Each of the four SIGs are described below.

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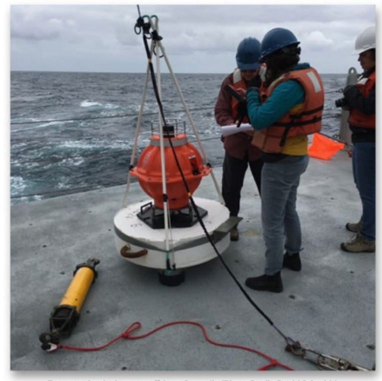
Offshore Observations

The source region of the next large subduction zone earthquake in Cascadia is offshore where instrumentation, imaging, and sampling studies are often sparse. Enhancing the quality and quantity of offshore observations in Cascadia is critical to long-term efforts of advancing CRESCENT science goals and estimating the seismic hazard. The Offshore Observations Special Interest Group seeks to gather broad community input on observational needs and priorities and identify specific areas for accelerated progress through coordination and the development of collaborations that link the academic community, federal agencies, private companies, and international partners.

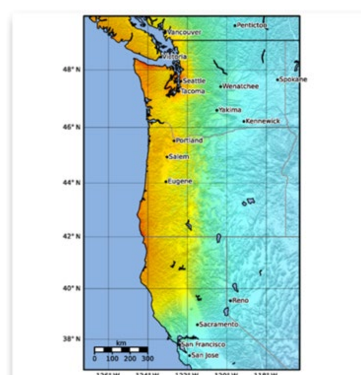


Transponder deployment offshore Cascadia (Photo Credit: David Schmidt).

At the CRESCENT kickoff meeting, the Offshore Observations breakout group enumerated a long wish list of desirable observations including enhanced offshore geodetic and seismic observations, subsurface imaging, improved seafloor characterization, sampling, and monitoring for earthquake, and tsunami early warning. The group also discussed specific ways in which CRESCENT could help make progress toward these goals through training, coordination of planning, and developing partnerships outside the science community. The priority for this working group is to use this initial input to plan a workshop in year 2 that can galvanize the community to build upon these ideas, identify funding sources, and develop a prioritized list of CRESCENT activities.

Ground Motion Modeling

Seismic hazard, or the likelihood of exceeding a specific level of ground shaking, relies heavily on estimates and models of ground motions in a region, which in turn benefits from CRESCENT's more fundamental science products and advances. The Ground-Motion Modeling Special Interest Group aims to translate such fundamental scientific advances into implications for ground motions in the region. In year 1, our goals are to have conversations with key partners (e.g., USGS) to identify areas of collaboration and to survey the community to identify priorities and needs. This SIG will additionally serve as a vehicle to bridge gaps and collaborations between WGs (e.g., DET and CVM), as well as between WGs and key collaborators and partners interested in more applied science questions relating to seismic hazard in the region.



SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
DAMAGE	None	None	None	Very light	Light	Moderate	Moderate/heavy	Heavy	Very heavy
PGA (%g)	<0.0464	0.297	2.76	6.2	11.5	21.5	40.1	74.7	>139
PGV (cm/s)	<0.0215	0.135	1.41	4.65	9.64	20	41.4	85.8	>178
INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Scale based on Worden *et al.* (2012)

Shaking expected for a M9 earthquake, from "Ensemble ShakeMaps for magnitude 9 earthquakes on the Cascadia Subduction Zone" by Wirth et al. (2021).

We will pursue funding on several fronts: (1) computational and data infrastructure for physics-based simulations, (2) empirical studies, and (3) collaborations with partners. Towards (1), we will pursue DOE and NSF ACCESS grants for computational resources to develop a turn-key computational infrastructure. Additionally, this will enable utilization of the dynamic rupture

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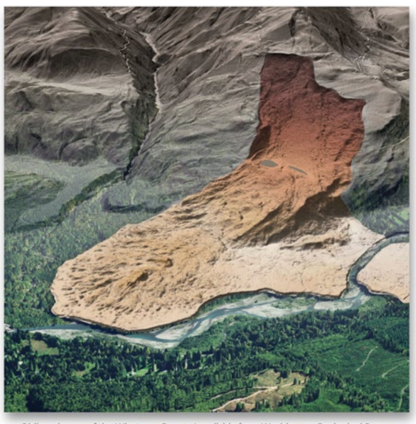
models produced by the center, as well as other simpler kinematic sources, to be seamlessly utilized in wave propagation codes. This will allow computation of ground motions that meet the needs of addressing the priorities and vision identified above. We will also pursue opportunities to connect with and seek funding for infrastructure projects within the NSF Engineering directorate, such as connections with DesignSafe and NHERI facilities.

Landslides, Liquefaction and Ground Failure



Oblique image of the Whatcom County Landlside from Washington Geological Survey (Washington State DNR).

The state of structure and strain within the shallow Cascadian subsurface, which will be a key focus of the CVM and CFM teams, is an important driver of ground motions from moderate to large earthquakes and essential to realistic simulation efforts. Moreover, the characteristics of realized ground motions impact all cascading hazards from such events, e.g., landslides, liquefaction, lateral spreading, ground failure, etc. These hazards should receive special attention in the Pacific Northwest, which has diverse terrain characterized by steep topography, significant relief, substantial tectonic uplift, numerous relict landslide features, and wet winter conditions that drive ground failure even in the absence of seismic forcing. This SIG will foster progress on the cascading hazard front by collaborating with federal (e.g., USGS, FEMA) and state agencies (CGS, DOGAMI, WA DNR, etc.), and industry partners (PG&E, BC Hydro), to better understand past and future ground failure events in Cascadia and generate knowledge relevant to mitigation and impact of coseismic ground failure.

Expanded compilation and analysis of a database consisting of potential paleoseismic proxies (landslide deposits, lacustrine/marine sediment records, paleo-liquefaction, precarious rocks, null events, etc.) will be a key priority for this SIG. This will help constrain past shaking intensity measures and overcome indeterminacy and non-uniqueness issues associated with geophysical inversions used to constrain metrics of past shaking. A particular focus will be the analysis of landscape and site responses to historical, shallow crustal earthquake events such as the Nisqually, Scotts Mills, and Klamath Falls events, quantifying where shaking was observed and the impacts it had and how those effects map to the greater Cascadia region. Long-term, this SIG aims to explore scenario-based analysis of cascading hazards from Cascadia and enable the advance of both basic and applied science as it relates to earthquakes as geomorphic agents and the potential impacts of strong shaking on communities in the region.

Toward a Community Fluids Model

The presence of fluids along the Cascadia subduction zone plate interface has long been noted. These fluids have been invoked to play a central role in controlling slip behaviors (e.g., slow slip, tremor, co-seismic slip, creep) through the central role of fluid pressure on stress and strength of faults, yet we do not have anything close to a comprehensive understanding of the volumes, sources, and magnitudes of these fluids nor fluid pressure. Nor do we understand the exact role

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of these fluids in controlling or influencing slip behaviors or chemical transformations. Accurately constraining the amounts, sources, and spatial and temporal correlations of these fluids to known slip behaviors in Cascadia will allow us to test hypotheses of the role of these fluids and fluid producing processes (e.g., metamorphism, pore collapse, diagenesis) and directly inform and contextualize the work of CVM, DET, and C3S. The goal of this SIG is to create a community fluids model which will aim to quantify fluids from the trench to the subarc along the Cascadia plate interface. We will engage with the broader community through a Fluids workshop aimed to take place Fall 2024 at UO.

Extensively veined blueschist facies rocks exhumed from deep slow slip conditions (Photo Credit: Amanda Thomas).

Diversifying and Training the Next Generation of Geoscientists

Building a diverse future geoscience workforce is of critical importance in the sciences. In no other discipline within the physical sciences is this more urgent than in the geosciences – creation of an inclusive discipline is at once a moral and social justice imperative. Through the Geoscience Education and Inclusion (GEI) pillar, CRESCENT will offer a tiered set of activities to engage students at secondary, undergraduate, and graduate levels in subduction zone science. Gaps in critical fields such as data science represent opportunities where the center can facilitate continuing education of the existing workforce. Central to the Center's effort are collaborations between the center and minority-serving institutions in the Pacific Northwest and national pedagogical institutions.

Engaging and empowering the next generation of geoscientists is at the core of the Geoscience Education and Inclusion pillar efforts (photos courtesy of Michael Hubenthal and Anna Ledeczi).

GEI activities include summer schools focused on integration of geologic observations with models, training workshops in state-of-the-art methods such as data science, artificial intelligence, fiber-optic sensing, and high-rate geodesy with specific applications to earthquake

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hazards, year-long research experiences for undergraduates, high school STEM experiences on college campuses, and professional development training for graduate students. The center's approach to GEI involves close interaction between scientists carrying out the research and the educational programs outlined below.

High school STEM pathways

We are developing a summer STEM experience for high-school students who identify as Indigenous and are from Indigenous communities throughout the Pacific Northwest. Summer students will visit one institution involved in CRESCENT for a three-day experience designed to expose students to higher education in a STEM-related discipline and active research in earthquake and tsunami science. In year 1, a program template will be developed for running the program. The central concept is for participants in the STEM pathways program to travel to a university campus with a paid chaperone, be housed in university dormitories, have meals in the university dining halls, and utilize university infrastructure—all mimicking the undergraduate experience. The STEM pathways organizers will then work with the leaders and graduate students to deliver (1) experiential learning activities in earthquake and tsunami science that are fun, social, and interactive and (2) culturally-relevant programming that connect participant experiences to their scientific activities on campus.

Undergraduate twinning program

An annual effort will fund 5-8 students per year to focus year-round on research, which is intended to foster participation of undergraduates from diverse backgrounds in subduction zone science and hazards research. Mentored research experiences are directly tied to increased retention of underserved students in the STEM pipeline. Our program requires that a student participate in a research project involving more than one institution (the "twinning" model). A research project is co-designed by a "home" and an "away" mentor and the student then spends the bulk of the school year working at their home institution with their home mentor before spending 8-12 weeks of the summer working at the away institution with the second mentor. The student thus works with two or more researchers in a mode of scientific collaboration that closely mimics real-world experiences. We anticipate this approach to be appealing because the students' research experience begins at or close to their home institution in a familiar setting without necessitating that they travel or live far away. Special emphasis will be focused on outreach to minority-serving institutions. Participants will attend the CRESCENT meeting or a related society meeting such as the SSA or GSA, carry out research during the academic year and up to 8 weeks during the summer, and other cohort-building activities. Critical to this effort is also to provide training for the mentors who will have different degrees of familiarity with issues faced by students from minoritized backgrounds in the geosciences. Year 1 goals include application development, cohort recruitment and launching the first cohort for the 2024/25 academic year.

Cores2Code

The interdisciplinary Cores2Code program creates the opportunity for undergraduate students to conduct coastal geological studies in data-poor areas, and/or legacy sites that could benefit from re-analysis using updated techniques. The earthquake geology workforce is depleted, limiting new data collection and analyses and inhibiting advances in our understanding of the subduction zone. The Cores2Code Summer School is underpinned by experiential learning that combines field, laboratory, and modeling techniques to provide the type of interdisciplinary investigation typified by science of the present and future. Students will both collect geological samples and then spend time in the lab learning to process them before turning their attention to learning computational techniques to model earthquakes and their hazards using modern approaches in Jupyter notebooks. The program thus envisions an "end to end" scientific experience combining geological and geophysical work. It will be based in years 2 and 4 out of Cal Poly Humboldt, a minority-serving university. Summer school organizers and Center staff intend to proactively attract underrepresented students from Cal Poly Humboldt and other regional minority-serving institutions. Two onsite instructors and two graduate student co-instructors will deliver 4 weeks of instruction to 10 undergraduate attendees, comprised of 3 weeks of field-based experience and ~1 week of quantitative and laboratory-based experience. Year 1 activities include development of curricula, site selection, logistical planning at Cal Poly Humboldt and application development and cohort recruitment for course delivery in Year 2.

Students hiking in Mt. Rainier National Park as part of a seismometer deployment (Photo Credit: Amanda Thomas).

Graduate Student Professional Development Fellowships

CRESCENT offers fellowships for participation in professional development workshops hosted by a professional society. This effort seeks to help candidates strengthen the presentation of their skills and accomplishments in anticipation of entering the workforce. The National Association of Geoscience Teachers (NAGT), for example offers "Preparing for an Academic Career" workshops that focus on strategies for becoming both a successful teacher and researcher as a candidate for academic positions and to succeed in academic jobs. Participation in professional development events hosted by societies such as the Society for the Advancement of Chicanos and Native Americans in Science (SACNAS), the National Association of Black Geoscientists, the Association for Women Geoscientists or other organizations are appropriate. Year 1 activities include application development and recruitment for participation during 2024 events.

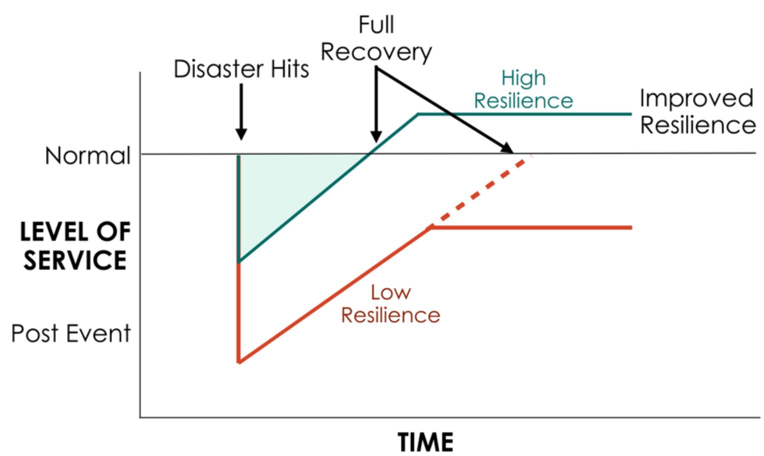
Technical short courses

Technical short courses (TSCs) are planned for delivery by community scientists who are experts in the subjects and who are participating in the Working Groups and Special Interest Groups.

The courses are intended for any subduction zone hazards scientist at any career stage, but preference will be given to graduate students and early career researchers. CRESCENT GEI committee members will work with the instructors to ensure high quality pedagogical practices. The senior personnel will provide guidance on short course pedagogical design during year 1 planning. EarthScope personnel supported by the Center have extensive experience running both technical and educational short courses via any combination of in-person, virtual, and hybrid delivery modes. Year 1 activities focused on planning for the “Machine learning for geophysical signal detection” short course to be hosted by C3S in Year 2.

Creating a Collaborative Pipeline from Science to Society

Science products resulting from major activities are immediately applicable for advancing science but are not immediately useful to society without additional work and collaboration. The Partnerships and Applications (P&A) pillar ensures CRESCENT activities lead to impact and greater societal resilience and that community input simultaneously steers the center efforts. Our collaborative partners will include federal and local agencies, regional utilities, organizations, and individual communities. We aim to collaborate with these groups in a variety of ways to establish substantive relationships, recognizing that an adaptable and bi-directional plan best serves our objective to be responsive to stakeholders’ needs. The concept of the “Resilience Triangle’ illustrates the goals of the P&A pillar. When a disaster strikes, a society with low resilience and a large triangle suffers larger impacts, bounces back slowly, and often never recovers the level of services it had before the event. This is most likely the potential situation across the Pacific Northwest today. Meanwhile a resilient society with a small triangle (such as Japan), suffers fewer impacts, recovers quickly and to an improved level of services. Effectively translating Center science is important to enable partners to carry out the necessary work to make Cascadia’s resilience triangle smaller.



A well prepared and more resilient society not only recovers faster from a devastating event, but learns from the experience, adapts, and becomes more resilient afterwards. A low resilience society never fully recovers and is less resilient in the aftermath. An essential mission of CRESCENT is to create a highly resilient Pacific Northwest society.

Community engagement strategies

Annual 1-day community meetings, with agendas and activities created and/or led by facilitators, will convene CRESCENT scientists with community partners and agencies. Through a series of talks and activities, we will work towards our goal of building (and in Years 2-5, maintaining) collaborations among partners and CRESCENT working groups. One actionable outcome of these meetings will be to develop structured plans for collaboration among interested partners and CRESCENT working groups or programs. For example, we will convene quarterly meetings for working groups that include and update partners on science products and advances.

Practitioner-focused webinars

Partnering with the Cascadia Lifelines Program (CLiP), we will collaborate to produce a series of webinars intended for the practicing engineering community. These webinars will serve as free professional development opportunities and will showcase state-of-the-art research, including CRESCENT's emerging science outcomes, that will impact long term policy and building code changes. Within the 5 yr timeframe of CRESCENT, we also envisage making incremental research advances that can be immediately incorporated into applications such as CLiP's geospatial hazards platform, O-HELP, which is used widely by the practicing engineering community in Oregon.

Communications and outreach

Combining efforts with GEI and the Science pillars, a unified communications strategy will guide dissemination of new and pertinent science results and the release of updates on CRESCENT major activities. Engagement will be accomplished through social media platforms, email newsletters, website updates, publications, media-releases, and in-person outreach efforts (e,g. conference participation and visits to communities and partner institutions).

Connections with existing community efforts

Many existing research programs are addressing parallel science questions and resilience efforts and are foundational for many of CRESCENT's science goals and objectives. For example, federal and state agencies such as the U.S. Geological Survey (USGS), National Oceanic and Atmospheric Administration (NOAA), Federal Emergency Management Agency (FEMA), Oregon Department of Geology and Mining Industries (DOGAMI), the WA Department of Natural Resources (DNR), the California Geological Survey CGS, WA Office of Emergency Management (OEM) have all devoted significant time and resources to addressing earthquake and cascading hazards and risks in the region. We will maintain close relationships with these key agencies as the center evolves. We will also collaborate with other related NSF/federally and state-funded research initiatives (such as the Cascadia Coastline and Peoples Hazards Research Hub (CoPes), Subduction Zones in 4 Dimensions (SZ4D), WA and OR Sea Grant, and the Southern California Earthquake Center (SCEC)) and Cascadia hazard focused groups (e.g. UO's Oregon Hazards Lab (OHAZ), the Pacific Northwest Seismic Network (PNSN) and Cascadia Lifelines Program (CLiP)).

Through these connections, CRESCENT aims to help unify Cascadia earthquake research efforts, aspiring to increase institutional knowledge co-production, avoid duplication of work, and minimize "science fatigue" in the broader community of partners that we collectively engage with.

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Expanding the Circle: Future Growth, Partnerships, and Connections

The strategic plan as outlined above focuses on clear, present needs to push the envelope on subduction zone earthquake hazards. However, the structures, connections, and expertise obtained through the lifetime of CRESCENT will lend themselves well to growth beyond earthquake science only. Our long-term view is that, over time, CRESCENT should embrace an Earth systems approach and transform into a center that takes a holistic view of all subduction zone hazards. The Pacific Northwest, with its basins containing population centers, topography and steep wet slopes, onshore-offshore tectonic duality, and associated ever-present earthquake, volcanic, and cascading hazards, is uniquely poised for such a long-term focused center and, in fact, progress on mitigating geohazard is stymied without it.

Greater understanding in earthquake science will only come through concerted effort focused on convergent margins and Cascadia is the ideal natural laboratory. At the same time, the geosciences have a poor track record of attracting and retaining students from underrepresented minorities and this dire situation can only be improved through strategies focusing on all levels of education, from K-12 to graduate school and beyond. Finally, the Pacific Northwest lacks a well-developed "earthquake culture" and is low in resilience. Improvements in these domains will come from steady and trustworthy bi-directional communication and collaboration between scientists, engineers, practitioners and the Pacific Northwest community at large. The CRESCENT community, building on the pillars of science, education and partnerships will take on these critical tasks.

As the nation's first subduction zone earthquake hazards center, CRESCENT will establish a new paradigm of collaborative Earth science research for the societal good.

For more information, contact us at cascadiaquakes@uoregon.edu.
Visit us at https://cascadiaquakes.org/.