USGS Earthquake Hazards Program Research Priorities for FY2026

1. Introduction

The USGS Earthquake Hazards Program (EHP) Research Priorities presented here reflect its mission within the National Earthquake Hazards Reduction Program (NEHRP) to reduce loss of lives and property from earthquakes and improve public safety and community resilience in the Nation. The EHP has recently published a Decadal Science Strategy, available as USGS Circular 1544 (https://pubs.usgs.gov/publication/cir1544), which summarizes the program mission and both foundational and aspirational science priorities over the coming 10 years.

Applicants should review the four major program elements and common research priorities described in section 3, as well as priority research targets listed below that are specific to each region or topic. Proposed work should advance the science that underlies EHP products by posing and testing new hypotheses and/or developing novel data acquisition tools, analysis methods, and products. Proposed work can also improve information dissemination and make research results more effective in mitigating losses from earthquakes. While proposed projects may involve collection of data and/or application of existing analysis methods, such activities should be in support of clearly stated research goals. Proposals focused on development of new products must demonstrate strong collaboration with intended users. Research and other activities that leverage work of academic, governmental, and private partners also are encouraged. Proposals that address Department of the Interior (DOI) Secretarial Priorities are also encouraged.

The EHP produces data and information on earthquakes and related hazards, but the production of data and reports alone is not sufficient to reduce earthquake risk; the Program also engages with users in the application and interpretation of Program results. This engagement makes our products more useful, both through modifications to existing products and development of new ones. The EHP supports opportunities for engaging with users at the local, regional, national, and global level.

2. Regional and topical areas

Research priorities are distributed across ten Research Areas—five regional and five topical areas:

- Central and Eastern United States (CEUS): The United States east of the Rocky Mountains, including Puerto Rico and the U.S. Virgin Islands;
- Intermountain West (IMW): From the Cascade Range and eastern flank of the Sierra Nevada to the front ranges of the Rocky Mountains, including Idaho, Nevada, Utah, and Arizona, and portions of Washington, Oregon, California, Montana, Wyoming, Colorado, New Mexico, and Texas.
- Northern California (NC): From Cape Mendocino to the central creeping section of the San Andreas fault and the adjacent Coast Ranges, with particular emphasis on the greater San Francisco Bay Area;
- Pacific Northwest and Alaska (PNA): Washington and Oregon, California north of Cape Mendocino (Cascadia), and Alaska;
- Southern California (SC): From the Carrizo Plain south to the international border with Mexico.
- Earthquake Early Warning (EEW): Basic and applied research to improve the accuracy, reliability, and timeliness of earthquake early warning alerts generated by ShakeAlert as well as research to benefit ShakeAlert communication, education, and outreach needs;
- Earthquake Rupture Forecasting (ERF): Research that stands to have a more immediate impact on

earthquake rupture forecasts being deployed by the USGS, both with respect to time-independent and time-dependent models;

- Earthquake Source Processes (ESP): Basic and applied, geographically broad research to characterize natural and induced earthquakes and constrain their physics;
- Hazard, Impacts, and Risk (HIR): Basic and applied, geographically broad research on the effects of earthquakes (including ground failure) and their impacts to the built environment, research that is relevant for probabilistic and/or scenario seismic hazard and risk analysis (including the NSHM), and near-real-time earthquake response (including ShakeMap and PAGER).
- Ground Motion (GM): Basic and applied research to understand and model earthquake ground motions, including for use in EHP products.

REMAINDER OF PAGE INTENTIONALLY BLANK

3. Common Priority Topics and Data for all Research Areas (CEUS, ERF, ESP, EEW, GM, IMW, NC, PNA, SC, HIR)

This section summarizes relevant guidance from long-term science plans (section 3.1) and lists priorities for the EHP Program Elements common to multiple regional and topical areas (section 3.2). This guidance is not exhaustive; we encourage submission of proposals to accomplish other important tasks. Priorities for proposals tailored to specific topical or regional needs are noted in section 4. We welcome proposals relevant to multiple needs but require any proposal to be submitted to a single regional or topical panel. PIs are encouraged to reach out to Coordinators to discuss the most appropriate panel for submission, as well as the topic of their proposed research.

Applicants are encouraged to use seismic and geodetic monitoring data, including structural monitoring data, from the USGS Advanced National Seismic System (ANSS). Specific ANSS coordination priorities are included in several of the regional and topical priority areas.

3.1 USGS Science Plans

The EHP encourages applicants to consider priorities outlined in relevant USGS Science Plans, including Circular 1544, an EHP Decadal Science Strategy, discussed above. Other important plans include *Reducing Risk Where Tectonic Plates Collide – A Plan to Advance* ***Subduction Zone Science***. It emphasizes scientific and technological developments, improved hazard assessments, stakeholder needs, and maximizing capabilities through partnerships to reduce the risks posed by subduction zone hazards, including earthquakes. The Plan has three themes: (1) advancing observations and models of subduction zone processes, (2) quantifying natural hazards and risk and (3) hazard forecasting and situational awareness. For each of these themes, the Plan describes USGS accomplishments and current capabilities, specific key knowledge and capability gaps, scientific frontiers, needed research, required investments, and resulting products.

Science for a Risky World: a USGS Plan for Risk Research and Applications is a 2018 roadmap for delivering USGS hazards information through risk assessments and other products that can reduce losses of life and property. The Plan encouraged collaboration with users of hazards information, proceeding from research design and product development, through risk assessments, to evaluations that guide new research. We encourage submission of EHP proposals that address priorities and leverage resources noted in these Plans.

3.2 Program Elements and Common Priorities.

Element I. **National and regional earthquake hazards assessments.**
The EHP publishes national and regional assessments of the expected degree of ground deformation and shaking, and their impacts over various time periods. The EHP also prepares long-term forecasts of earthquake probabilities, as well as scenario ground motion maps of the expected shaking and ground deformation. These products, developed from EHP and partner research, support the development of cost-effective mitigation measures and practices in structure design, construction, and land use planning. They also provide the basis for the seismic safety elements of building codes affecting construction nationwide.

The USGS is particularly interested in research that improves the National Seismic Hazard Model (NSHM), including models of seismic source, recurrence, ground motions, and site effects, improved methodologies, and the assessment of earthquake hazards in metropolitan areas.

Common Priorities include:

- Develop and compare geologic and geodetic models of crustal deformation to improve regional seismic hazard maps and better constrain on- and off-fault slip/deformation rates.
- Improve estimates of the timing, size, and effects of prehistoric or early historic earthquakes.
- Conduct geologic, geomorphic, and paleoseismic studies to estimate the timing, recurrence, rupture lengths, and magnitudes of prehistoric earthquakes on Quaternary active faults.
- Use geologic data to quantify long-term (e.g., millennial scale) to short-term (e.g., earthquake-cycle scale) slip rates for Quaternary active faults and explore spatial and/or temporal slip rate variability.
- Characterize the factors that amplify or attenuate earthquake ground motions, such as in sedimentary basins, or near geologic structures and/or topography.
- Develop ground-motion models applicable to seismic hazard assessments, including regionalized, or non-ergodic, models.
- Improve existing 3D seismic velocity models of Earth structure onshore and offshore, particularly for sedimentary basins beneath or near urban areas, with application to earthquake source and ground motion characterization.
- Improve assessment of epistemic uncertainties in seismic hazard assessments.
- Consider time dependence in earthquake models to support improved seismic hazard and risk forecasts.

Element II. **Earthquake information, monitoring, and notification.**
The EHP supports efforts to improve the accuracy of algorithms and processes that provide information about earthquakes in near-real-time, including early warning, improved detection and location techniques, estimation of finite fault rupture extent, and refined seismic moment determinations. Routine seismic and geodetic monitoring activities are evaluated and funded under a separate solicitation.

Common priorities include:

- Develop and test new approaches to integrating seismic, geodetic, and other data, emerging technologies, and *a priori* information in monitoring operations, applicable to earthquake early warning, aftershock forecasting, routine earthquake monitoring, and slow slip detection and characterization.
- Advance machine learning/artificial intelligence methods for earthquake and deformation monitoring.

Element III. **Research on earthquake occurrence, physics, effects, impacts, and risks.**
Earthquake forecasts and assessments of hazard, impact and risks, help emergency managers, planners,

communities, and the public prepare for future earthquakes. With the goal of improving these forecasts and assessments, the EHP supports applied research on earthquake processes and effects. This work is focused on multi-disciplinary observations, theory, experiments, and development of testable models of earthquake and tectonic processes and of earthquake effects (e.g., macroseismic intensities, ground shaking, ground failure, and structural response).

Common priorities include:

- Conduct research on earthquake recurrence and interactions that underpin operational earthquake and aftershock forecasting, including improved approaches for characterizing earthquake swarms.
- Conduct geologic, geomorphic, seismological, geodetic, geophysical, and/or paleoseismic studies to constrain fault segmentation, multi-fault ruptures, long-term paleoseismic records, fault length and displacement scaling relations, empirical regressions on moment magnitude, and hazards resulting from near-surface and surface ground displacement.
- Improve our understanding of earthquake surface and subsurface rupture extent and displacement.
- Collect geological and geophysical data that constrain shear-wave and community velocity models as well as the effects of basin geometry, near-surface geology, and structure on strong ground motions and site amplification.
- Collect data and refine physical models of fragile geologic features to constrain past ground motions.
- Conduct observational, theoretical, computer modeling, or laboratory studies to improve our knowledge and modeling of induced seismicity.
- Conduct research to systematically collect information on earthquake disaster losses and to account for any disproportionate impacts to individuals or communities with shared geographic, demographic, or socio-economic characteristics.

REMAINDER OF PAGE INTENTIONALLY BLANK

Element IV. **Earthquake resilience, safety policy, communication, and user engagement**

The EHP t engages with the user community in the application and interpretation of Program results. This includes dialogues on modifications to our existing products and new products to make our work and results more relevant and applicable. The EHP supports opportunities for engaging the user community at the local, regional, national, and global levels.

- Provide collaborative engagement opportunities (workshops, focus groups, interviews, etc.) for specialists and practitioners that facilitate addressing important challenges, such as earthquake hazard mitigation, risk, response, preparedness, resilience; development of community velocity models; defining priority faults; fault setback planning, particularly within regional and local urban areas.
- Advance understanding of physical, social, and economic vulnerabilities to earthquake hazards; identify areas where vulnerable groups are disproportionately exposed to earthquake hazards, and best practices to make the populations most vulnerable to these hazards more resilient in the future.
- Advance coordination between Tribal, County, State, Territorial, and Federal Agencies, as well as boundary organizations and community groups, by examining resources for improved communication and dissemination of earthquake information through education, crowdsourcing, and emergency management tools, and other methods.
- Identify and engage a broad range of user communities to collaboratively assess the efficacy of existing earthquake products for actionable decision-making and consider the improvement of these products, or the development of new products to further advance actionable, data-driven decision making.
- Develop new tools and products for increasing awareness of seismic hazard, impacts, and risk, and with public and targeted user groups, such as emergency responders, public utilities, risk managers, decision makers, developers, engineers, community-based organizations, and policymakers, among others.
- Develop approaches to provide earthquake hazard information supporting risk assessments, and earthquake mitigation and response planning to decision makers, emergency responders, and the public, particularly that cross local, state, and national boundaries and various levels of government.
- Advance understanding of how earthquake hazard information supports risk reduction by analyzing communication efficacy and by identifying data and product gaps.
- Advance understanding of how best to share actionable information with a broad range of populations.

4. Proposal preparation guidance

Proposals submitted in response to this Program Announcement must indicate the Regional or Topical Research Area (CEUS, ERF, ESP, EEW, GM, IMW, HIR, NC, PNA, or SC) that the proposed research addresses. Only **one** Research Area may be selected per proposal. The specific priorities noted in this attachment and addressed in the proposal must also be indicated. We recommend developing proposals with members of those communities most vulnerable to earthquake effects. Although it is required to indicate the Regional or Topical Research Area when submitting a proposal, upon initial review, regional and topical coordinators may move proposals to another Regional or Topical Research Area deemed more suitable.

Proposals addressing earthquake ground-motion research that is national in scope and is in support of the National Seismic Hazard Model or NEIC real-time ground-motion products (ShakeMap), should be directed to the Ground Motion (GM) panel. Proposals for research on international earthquakes should be directed to the panel for the U.S. region or topic that will most benefit from the study's knowledge or to where new techniques would be most transferable. In all instances, **if uncertain about which panel is most appropriate, please contact one or more of the coordinators for guidance.** Coordinators may also assist applicants by describing related work being done internally within the USGS, identifying existing relevant data sets, and helping applicants establish contacts with USGS researchers working in similar areas. Coordinators are listed below in the descriptions of the priorities for each panel.

Examples of past or currently funded projects in each Research Area may be found at https://www.usgs.gov/programs/earthquake-hazards/science/external-grants-overview

Descriptions of some USGS internal projects can be found at: http://earthquake.usgs.gov/research. It is strongly recommended that the applicant contact the appropriate coordinator and other USGS points of contact to learn whether the proposed work duplicates work being done internally, and how their proposed work can complement and help support the goals and objectives of internal efforts. We particularly encourage discussions with the regional and topical coordinators before proposing work outside of goals and priorities noted in this document.

REMAINDER OF PAGE INTENTIONALLY BLANK

Priority Topics for Research in the Central and Eastern U.S. (CEUS) Coordinator: Thomas Pratt, tpratt@usgs.gov

Hazard assessments for the CEUS are based largely on the historical earthquake catalog and a small number of specific fault sources with a known history of prehistoric earthquakes. Identifying and characterizing potentially active faults and the frequency of large earthquakes on specific faults are priorities. A related topic is using geologic features to constrain minimum or maximum levels of past ground shaking, or timing of past ground shaking, especially in areas lacking known fault sources. Another major priority is improving and reducing uncertainties in estimates of strong ground motion for the National Seismic Hazard Model, in particular for areas with extensive sediment layers such as the Atlantic Coastal Plain, the Mississippi Embayment and Gulf Coast regions, and the large sedimentary basins elsewhere in the CEUS. Understanding the causes of seismicity in this intraplate setting is also a major priority. Across all of these topics priority will be given to studies that affect multi-state regions such as characterizing major seismic source zones, understanding and estimating ground motion effects from widespread geomorphic provinces, improving our understanding of processes causing CEUS earthquakes, or improving our knowledge about important large earthquakes in the region.

Contact the CEUS Coordinator to learn more about the status of internally supported projects that might overlap or complement proposed studies, or to discuss potential proposals. Studies of CEUS earthquakes resulting from human activities such as wastewater injection should be directed to the **ESP** panel (see Section 4).

In addition to the common priorities listed in section 3.2, the following priority tasks are identified under each element:

CEUS Element I. **National and regional earthquake hazards assessments.**

- Assess the seismic potential of earthquake source zones and active faults in the CEUS. Emphasis should be on areas where studies could have the greatest impact, either due to a lack of knowledge about a source fault or zone, because complementary data provide a high chance of a significant change in our assessment of the hazard, or due to proximity to major urban areas.
- Improve assessments of the earthquake potential of the U.S. Caribbean territories and surrounding offshore faults, the portion of the Antilles subduction zone that causes hazards in U.S. territories, ground motions in the region, and associated hazards (landslides, tsunamis, ground failure) to the U.S. Caribbean territories and Atlantic seaboard.
- Conduct reconnaissance, geologic, paleoseismic, or landform deformation (topographic evolution) studies of CEUS regions outside of known source zones to assess whether there is a history of strong ground shaking, or to determine the frequency and/or timing of strong ground shaking. Examples might include studies of fragile geologic structures (stalactites, balanced rocks), mapping and analyses of paleoliquefaction features, examination and analyses of scarps apparent in detailed topographic surveys (e.g., Light Detection and Ranging [Lidar]), or constraints from possible earthquake- or shaking-induced slope failures such as landslides, turbidites or rockfalls.
- Improve our understanding and estimates of site response and liquefaction potential using field experiments, seismic velocity models, existing instrumental recordings, or modeling studies, with an emphasis on geomorphic provinces that underlie large areas of the CEUS.

CEUS Element II: **Earthquake information, monitoring and notification.**

- Estimate earthquake source characteristics, calibrate seismic magnitude scales, and characterize wave propagation and attenuation in the CEUS.

- Systematically evaluate the temporal and spatial distributions of foreshocks and aftershocks of intraplate earthquakes to improve declustering of seismic catalogs, forecasting of aftershocks, and understanding of earthquake processes. Determine whether seismic activity in an area represents aftershocks of larger prehistoric earthquakes.
- Reduce earthquake location errors using improved regional velocity models or location methodologies.

CEUS Element III. **Research on earthquake occurrence, physics, effects, impacts, and risks**.

- Develop models of long-term deformation in intraplate areas including both onshore and offshore areas of the CEUS. Proposals may address topics such as the causes of large earthquakes, regional migration of seismicity, and earthquake clustering.
- Investigate the tectonic, geodynamic and/or geophysical processes that lead to earthquakes in specific areas of the CEUS but not in adjacent, less seismically active areas.
- Reduce uncertainties in the interpretation of GNSS data in regions with low rates of seismic strain accumulation or use geodynamic modeling for assessment of earthquake-generation processes.

REMAINDER OF PAGE INTENTIONALLY BLANK

Priority Topics for Research in the Intermountain West (IMW) Coordinator: Christopher DuRoss, cduross@usgs.gov

Priorities for research in the IMW focus on the collection of data that directly contribute to (1) seismic hazard assessments such as the USGS National Seismic Hazard Model (NSHM) and (2) our knowledge of earthquake occurrence in the region. High priority issues to be addressed in proposed work are listed below for each EHP program element, although other proposal topics will be considered.

In addition to the common priorities listed in section 3.2, the following priority tasks are identified under each element:

IMW Element I. **National and regional earthquake hazards assessments.**

Conduct scientific studies to improve our understanding of seismic hazard and its uncertainty in the IMW region:

- Improve seismic source characterization for IMW faults included in local to regional seismic hazard assessments such as the NSHM. These studies could include investigations of Quaternary fault extent using high-resolution data (e.g., lidar), paleoseismic chronologies, earthquake recurrence, slip rates, prehistoric rupture length and magnitude, and fault segmentation. Priority faults, topics, and regions deemed to need further study can be found at:
    - **IMW region**: https://www.sciencebase.gov/catalog/item/67912c5ad34ea6a4002bf899
    - **Nevada** (Nevada Bureau of Mines and Geology): http://www.nbmg.unr.edu/_docs/Earthquakes/NBMG_priorities_NEHRP.pdf
    - **Utah** (Utah Quaternary Fault Parameters Working Group): https://geology.utah.gov/hazards/info/workshops/working-groups/q-faults/
- Compile, and/or update regional information on Quaternary fault geometry and length to support the USGS Quaternary Fault and Fold Database and NSHM.
- Conduct studies to develop or improve geologic, geodetic, seismotectonic, and/or numeric models of deformation across the IMW region. For example, explore on- and off-fault tectonic deformation, fault dip and connections between subsurface structures and surface faults, or normal-fault behavior using physics-based rupture simulations.
- Develop and refine seismic hazard analyses and earthquake rupture forecasts for regions of high hazard and risk such as the Wasatch Front and southwestern regions of Utah, the Reno-Carson City urban corridor, Las Vegas and surrounding urban areas of Nevada, and northern or southern Basin and Range cities.

IMW Element II. **Earthquake information, monitoring, and notification.**

- Use seismic data to improve determinations of IMW earthquake source characteristics, crustal structure, subsurface fault geometry, and fault rupture extent.

IMW Element III. **Research on earthquake occurrence, physics, effects, impacts, and risks.**

Address fundamental scientific questions regarding the occurrence, behavior, and effects of prehistoric and historic earthquake ruptures in the IMW region:

- Conduct studies that will improve our understanding of large historical earthquakes in the IMW.
- Develop long-term paleoseismic histories and evaluate temporal variability in earthquake recurrence.
- Determine the lengths of prehistoric surface ruptures and evaluate their possible termination at

along-fault structural complexities (fault segmentation).

- Evaluate surface displacement along fault strike, fault scaling relations (e.g., between fault length and displacement), distributed or off-fault deformation, and fault creep and afterslip.
- Improve understanding of the subsurface structure of normal faults (e.g., listric versus planar dip), behavior of opposing (e.g., primary–antithetic) or conjugate fault pairs, and relations between subsurface fault geometry and surface rupture.
- Use lacustrine paleoseismic data (e.g., geophysical data and sedimentary cores) to evaluate sediment response to strong shaking, improve prehistoric earthquake chronologies, and facilitate comparisons between lacustrine and terrestrial (e.g., trench) earthquake records.
- Explore spatial and temporal variability in fault slip rate and compare to geodetic deformation models and uncertainties.
- Conduct geological, geophysical, and/or geotechnical research to map subsurface faults and folds, develop joint analyses of multi-scale datasets, and develop or improve community velocity models for IMW urban areas.
- Develop geological, geophysical, and/or geotechnical models to characterize the effects of basin geometry, near-surface geology, and structure on strong ground motions and site amplification.

IMW Element IV. **Earthquake resilience, safety policy, communication, and user engagement.**

In addition to Section 1, IMW focused priorities are:

Collaboration (e.g., State or regional working groups) and community outreach on important problems in IMW urban areas.

REMAINDER OF PAGE INTENTIONALLY BLANK

Priority Topics for Research in Northern California (NC) Coordinator: Sarah Minson, sminson@usgs.gov

The Northern California component of the EHP is charged with characterizing seismic hazard throughout Northern California. One primary area of concern is the San Francisco Bay region, extending from Monterey to Willits, and from the Central Valley to the Pacific Coast: this region bears more than 25% of the nation's annualized seismic risk. The population of San Francisco Bay Area has evolved into a megaregion with a broad geographic distribution of critical infrastructure across which there is variability in hazard and risk, as well as variability in how well hazard and risk are characterized. Another high priority research area is the Mendocino Triple Junction which has high seismicity and high hazard, yet the regional faults, deformation rates, and seismic velocity structure are under-characterized. Improving our knowledge in these areas is vital to developing community models of fault geometry, seismic velocity, geology, etc. Research in Northern California outside these areas may also be supported, particularly to understand the plate boundary system, improve community models, and/or to evaluate hazards to critical infrastructure. Appropriate justification should be given for how proposed research could eventually help reduce earthquake impacts, which includes disseminating data and results so that they can be used in risk reduction activities. Please feel free to contact the NC Coordinator to learn more about coordination with internally supported projects and/or to discuss potential proposals.

In addition to the common priorities listed in section 3.2, the following priority tasks are identified under each element:

NC Element I. **National and regional earthquake hazards assessments.**

- Use crustal deformation measurements, geology, and/or seismic observations to estimate regional deformation rates, fault slip rates, fault creep, fault mechanics, strain transients, and stress evolution, as well as uncertainties on those estimates;
- Conduct geologic, geomorphic, geodetic, geophysical, paleoseismic, or similar investigations to estimate the timing, recurrence, rupture lengths, surface and subsurface slip, magnitude, and shaking in historical and prehistoric earthquakes in Northern California;
- Expand observations, improve models, and/or compile existing information in support of the USGS National Seismic Hazard Model;
- Develop methods to forecast coseismic and post-earthquake slip on faults that produce surface-rupturing and near-surface-rupturing earthquakes in Northern California;
- Validate and improve community regional 3D geologic, fault geometry, and seismic velocity models for the San Francisco Bay Area and Northern California, with emphasis on features that can affect seismic hazards such as basins;
- Characterize shallow shear wave velocity structure throughout Northern California, particularly at stations that have recorded strong ground motion.

NC Element II. **Earthquake information, monitoring, and notification.**

- Use seismic, geodetic, geologic, and/or geophysical data (both current and historical) to better quantify both seismic and aseismic slip potential, and improve understanding of subsurface geometry;
- Integrate and improve seismic and geodetic monitoring efforts in Northern California, in particular to enable recognition of anomalous, ephemeral, and/or precursory behavior;
- Assess creep rates and locations to identify fault coupling, frictional properties, and transient aseismic events, and also identify locations that do not creep;

- Measure crustal strain at a variety of scales from site to regional scale using creep meters, borehole strain meters, GNSS, InSAR, historical observations, etc.;
- Develop and utilize innovative observations or methodologies to improve hazard and risk quantification especially at locations in Northern California where hazard and risk are poorly characterized with conventional approaches;
- Identify and catalogue repeating earthquakes to understand fault frictional behavior and asperities.

NC Element III. **Research on earthquake occurrence, physics, effects, impacts, and risks.**

- Develop, refine, and test models (particularly probabilistic models) for earthquake rupture, shaking hazard, and displacement hazard in Northern California, in coordination with USGS efforts;
- Evaluate models for strain transfer along fault systems, especially in the San Francisco Bay Area megaregion and San Andreas fault/Mendocino Triple Junction focus areas;
- Quantify uncertainty and identify ways to reduce uncertainty in all aspects of earthquake risk assessment in Northern California from understanding earthquake occurrence, rupture physics, and fault rheology; through modeling potential earthquake shaking, surface displacement, and other earthquake effects; to estimating earthquake risk;
- Develop, refine, and test models for other earthquake impacts in Northern California such as landslides, liquefaction, and afterslip;
- Update effects, impacts, and risks estimates to reflect seasonal variability in earthquake impacts as well as the probability of an earthquake happening during an extreme weather event and the impacts that would have on liquefaction, fire following earthquake, and other hazards associated with earthquakes.

REMAINDER OF PAGE INTENTIONALLY BLANK

Priority Topics for Research in the Pacific Northwest and Alaska (PNA)

Research priorities for the Pacific Northwest and Alaska are considered by a combined panel, but priorities specific to each region are listed separately below. PI's are encouraged to contact the coordinators listed below, for coordination with internally supported projects and/or to discuss potential proposals.

9.1 Priority Topics for Research in the Pacific Northwest (PNA-Pacific Northwest)

Pacific Northwest Coordinator for External Research: Joan Gomberg, gomberg@usgs.gov

Research proposed should advance understanding of earthquake-related processes by stating and testing new hypotheses and/or developing and employing novel data sets and analyses. Multi-disciplinary projects that leverage already-vetted methods and datasets are encouraged, with examples of the latter from: 1) the Advanced National Seismic System and Canadian National Seismographic Network and strong motion networks in Cascadia; 2) the 2011-2017 Cascadia Initiative and Cascadia Seismic Imaging Experiment 2021 onshore-offshore deployments; 3) Network of the Americas GNSS sites, strainmeters, tiltmeters, and strong motion sensors; 4) high-resolution LiDAR, InSAR, potential field, and other remote sensing data; 5) the Pacific Northwest Geodetic Array (PANGA) GNSS stations and tiltmeters; and 6) the Ocean Networks Canada and Oceans Observatory Initiative off-shore cabled networks. Research that partners with and leverages relevant activities sponsored by other agencies and institutions also is encouraged, such as those that support development of the NSF-supported SZ4D Initiative (https://www.sz4d.org) , CRESCENT (https://cascadiaquakes.org/), Near Trench Community Geodetic Experiment (https://www.seafloorgeodesy.org/commexp), and Cascadia CoPes Hub (https://cascadiacopeshub.or). Topics noted below should focus on the Cascadia subduction zone region, although research elsewhere with clear relevance may also be proposed. Product development activities should demonstrate user involvement in product conception, implementation, and evaluation.

In addition to the common priorities listed in section 3.2, the following priority tasks are identified under each element:

PNA-Pacific Northwest Element I. **National and regional earthquake hazards assessments.**

- Clarify the distribution and time-dependence of locking along the plate-boundary (megathrust), particularly offshore.
- Develop observationally validated ground motion simulations that include complex wave propagation effects for Cascadia M8-9 megathrust and intraplate earthquakes.
- Characterize plate interface heterogeneity that may affect seismic radiation and ground motions.
- Develop approaches and observational inputs for temporal and spatial earthquake and aftershock forecasting, which account for potential differences among interplate and intraplate settings.
- Improve estimates of the sizes, recurrence intervals, and effects of late Quaternary earthquakes on crustal faults in the regions of the Puget Sound, Olympic Mountains, Yakima fold and thrust belt, the Columbia Plateau, and Portland and Tualatin basins and vicinity. Augment seismic intensity data for historical earthquakes.
- For the Cascadia megathrust, clarify estimates of its earthquake recurrence intervals, magnitudes, rupture lengths, and coseismic deformation. Seek stratigraphic evidence that distinguishes between a long rupture and a swift series of shorter ruptures.
- Evaluate earthquake-induced ground failure potential (*i.e.*, landslides and liquefaction), particularly in populated areas, transit corridors, and near bodies of water where landslides could generate hazardous local tsunamis or form hazardous temporary dams.

- Apply tsunami deposit surveys and geological estimates of coseismic vertical deformation to numerical modeling of tsunami generation and inundation to investigate ranges of likely tsunami hazards.
- Quantify maximum magnitudes and occurrence probabilities of outer-rise and other intraplate Cascadia earthquakes.
- Reconstruct long Holocene earthquake histories from lacustrine deposits. Distinguish among turbidite records of intraplate earthquakes, and megathrust earthquakes, and non-seismic triggers.

PNA-Pacific Northwest Element II. **Earthquake information, monitoring, and notification.**

- Develop and apply new approaches and technologies for measuring seismic and aseismic geodetic deformation offshore and onshore.
- Improve the detection and characterization of tremor and other slow earthquakes.

PNA-Pacific Northwest Element III. **Research on earthquake occurrence, physics, effects, impacts, and risks.**

- Improve estimates of fault-zone properties that may influence rupture mode, area, and fault slip.
- Quantify the relation between slow slip events and earthquake potential.
- Characterize segmentation based on geologic and/or geophysical properties.
- Evaluate potential interactions between interplate, intraplate, and upper-plate faults.
- Study the transition from strike-slip to convergence at the Mendocino Triple Junction.
- Develop Cascadia-specific dynamic rupture and cycle models that improve characterization of the earthquake source and link earthquake-related phenomena (e.g., tsunami, ground failure, turbidity current generation) to earthquake sources.

REMAINDER OF PAGE INTENTIONALLY BLANK

Priority Topics for Research in Alaska (PNA-Alaska) Alaska Coordinator: Rob Witter, rwitter@usgs.gov

The USGS invites research proposals that present and test hypotheses and/or develop new tools, methods, and products aimed at improving the National Seismic Hazard Model for Alaska. Anticipated products should advance understanding of the earthquake rupture processes, the radiation of seismic waves, and ground-deformation effects, including tsunamis, landslides and liquefaction to enhance earthquake-resilience in Alaska communities. We seek multidisciplinary research proposals that analyze data acquired by 1) the Advanced National Seismic System; 2) the 2018-2019 Alaska Amphibious Community Seismic Experiment (AACSE); 3) the Near-Trench Community Geodetic Experiment (NTCGE); 4) Network of the Americas GNSS sites; 5) high-resolution LiDAR, InSAR, potential field, and other remote sensing data; and 6) multibeam, seismic reflection, and sediment coring data collected in lake and fjord environments. Contact the Alaska Coordinator to learn more about internally supported projects and to discuss potential proposals.

In addition to the common priorities listed in section 3.2, the following priority tasks are identified under each element:

PNA-Alaska Element I. **National and regional earthquake hazards assessments.**

- Develop and compare geologic earthquake rates and geodetic slip-deficit models across Alaska to improve seismic hazard models, with particular focus on the Alaska-Aleutian megathrust, the Queen Charlotte-Fairweather fault system, and the Denali fault system.
- Perform subaqueous investigations of Alaskan lakes and fjords to assess the sedimentary record of strong ground motions emanating from Alaska-Aleutian megathrust, intraslab, and crustal earthquakes. Evaluate and compare the subaqueous paleoseismic record to paleoseismology records in coastal and terrestrial environments.
- Examine the Alaska Amphibious Community Seismic Experiment and Near-Trench Community Geodetic Experiment data to better characterize earthquake hazards along the Alaska megathrust.
- Evaluate the location and duration of slow-slip events in Alaska, and their relationship to up- and down-dip limits of co-seismic rupture along the Alaska-Aleutian megathrust.
- Improve the understanding of active faulting, historical seismicity, and the paleoseismic record of large earthquakes on major crustal faults in Alaska, including the Denali, Totschunda, Fairweather, Queen Charlotte, Castle Mountain, Tintina, and Kaltag faults, and on subsidiary and related faults such as the Northern Alaska Range Thrust System.
- Use high-precision hypocenter location methods and/or geodesy to identify the extent, geometry, and seismic hazards of cryptic faults in central Alaska seismic zones.
- Investigate megathrust splay faults in the accretionary prism of the Alaska-Aleutian subduction zone to better define where they occur, their slip histories, and potential implications to tsunami hazard.

PNA-Alaska Element II. **Earthquake information, monitoring, and notification.**

- Develop 3-D community seismic velocity models for Alaska that are validated against earthquake catalog data to support improving earthquake locations, simulating ground motions, determining source mechanisms, and evaluating sedimentary basin ground motion amplification.

PNA-Alaska Element III. **Research on earthquake occurrence, physics, effects, impacts, and risks.**

- Improve ground motion models for subduction interface and intraslab earthquakes. Develop new empirical or simulation-based ground motion models that incorporate three-dimensional seismic structure and consider a range of earthquake source scenarios and complexity.
- Characterize site conditions at Advanced National Seismic System (ANSS) National Strong Motion Network stations outside of the Anchorage bowl for developing statewide ground motion prediction equations.
- Better quantifying earthquake-triggered landslide hazard & risk and resulting tsunamigenesis.

PNA-Alaska Element IV. **Research resilience, safety policy, communication, and user engagement.**

- Promote coordination between Tribal, State, and Federal partners, by improving communication of earthquake-early warning information through education, and emergency management tools.
- Advance understanding of how best to share actionable information with a broad range of populations.

REMAINDER OF PAGE INTENTIONALLY BLANK

Priority Topics for Research in Southern California (SC), Coordinator: Katherine Scharer, kscharer@usgs.gov

Southern California is a region of complex geology containing large mountain ranges, deep sedimentary basins, and numerous active faults. To better quantify the hazard from future earthquakes in this region, it is necessary to improve our understanding of fault characterization, earthquake rupture properties, and seismic wave propagation at local and regional distances using a combination of field observations, analysis of monitoring data, and modeling approaches. Contact the SC Coordinator to learn more about internally supported projects or to discuss potential proposals.

In addition to the common priorities listed in section 3.2, the following priority tasks are identified under each element:

SC Element I. **National and regional earthquake hazards assessments.**

- Refine models of relative or absolute activity of offshore faults system using geophysical data and chronostratigraphic constraints from sediment cores.
- Investigate the surface deformation field from past buried or distributed faulting, and model potential future effects on the built environment.
- Develop methods or facilitate use of machine learning techniques in investigations of large spatial and/or temporal datasets in seismology, geodesy and earthquake geology.
- Refine estimates of the interseismic deformation field including vertical deformation and post-seismic transients from historic ruptures.
- Improve information on basin structure and methods to integrate basin models of varying resolution.
- Develop and test ground motion simulation models with application to addressing seismic hazards in Southern California.
- Advance the use of ground motion records (natural or synthetic) to constrain ground motion simulation models.
- Develop new, improved, or alternative models of 3D fault, seismic velocity, and seismic attenuation structures. Integration of these models within the existing SCEC Community Fault and Velocity Models is strongly encouraged.
- Develop methods to improve the treatment of site and path effects into existing models, including ergodic and non-ergodic models, and linear and non-linear site effects.

SC Element II. **Earthquake information, monitoring, and notification.**

- Use seismic data to determine earthquake source parameters, fault and crustal structure and the state of stress in the crust, including further development and testing of 3-D structural models. Integration of results with the existing SCEC Community Fault and Stress Models is strongly encouraged.
- Develop methodology to improve the characterization of instrumentally recorded notable earthquakes and earthquake sequences, including interactions between events.

SC Element III. **Research on earthquake occurrence, physics, effects, impacts, and risks.**

- Test earthquake recurrence models and address contemporaneity of ruptures along major faults through development of long or spatially targeted paleoseismic records.
- Develop methods to distinguish or characterize rates of past earthquakes vs. creep events.

- Develop methods to assess rupture directivity and speed from past earthquakes.
- Improve characterization of the processes that drive earthquake occurrence, including tectonic loading, short-term static and dynamic stresses, fluids, and aseismic slip.
- Investigate characteristics, causal mechanisms, and interactions between fluid-driven and tectonic swarms.
- Develop methods to estimate variations in expected ground motions, accounting for local geological structure, topography, and soil-structure interaction.
- Develop methodologies to characterize earthquake ruptures for use in ground motion simulations. Approaches including multi-segment ruptures and/or complex fault geometries are encouraged.
- Use ground motion simulations and/or recordings of past earthquakes to quantify the expected level and distribution of shaking over a broad frequency range (e.g., 0-20 Hz) for future large earthquakes.

REMAINDER OF PAGE INTENTIONALLY BLANK

Priority Topics for Research on Earthquake Early Warning (EEW) Coordinator: Jeffrey McGuire, jmcguire@usgs.gov

Earthquake early warning (EEW) systems aim to provide advance warning of specified earthquake ground motion levels to populations to mitigate losses. The USGS operates the ShakeAlert Earthquake Early Warning System for the United States West Coast (https://www.usgs.gov/programs/earthquake-hazards/science/early-warning). The EHP encourages proposals for studies that clearly demonstrate how the proposed research can be applied to improve the accuracy, reliability, and timeliness of ShakeAlert Messages issued by the USGS which in turn are used by distribution providers (e.g., apps, transportation agencies, etc.) for the development and delivery of alerts to people and automated systems.

The EHP supports efforts focused on scientific research on the topics identified below. However, all other monitoring and notification activities are evaluated and funded under a separate solicitation for seismic and geodetic network operations. Furthermore, operationalization, testing and upkeep of current ShakeAlert algorithms are not supported under this Notice of Funding Opportunity.

Proposers are strongly encouraged to contact the EEW Research Coordinator to learn more about internally supported projects or to discuss potential proposals.

In addition to the common priorities listed in section 3.2, the following priority tasks are identified under each element:

EEW Element II. **Earthquake information, monitoring and notification.**

- Advance existing algorithms and processes, or develop novel techniques, to improve the timeliness and accuracy of predicted ground motions. . Examples include improved identification and classification of seismic phases, finite fault extent identification, early magnitude or location estimates, parameter uncertainties, estimation of expected ground motions directly from observed ground motions, incorporation of directivity into predicted ground motions, and methods to estimate the probability of a fault rupture continuation or arrest.
- Improve existing or develop new methods for incorporating geodetic data. Examples include using seismic algorithm output as prior information for geodetic algorithms, algorithms that combine seismic and geodetic data, incorporation of real-time GNSS-based ground velocities, and characterization and quantification of quality of real-time GNSS data for noise mitigation.
- Improve methods for combining source and/or ground motion information from multiple algorithms to generate a single alert stream.
- Identify and assess novel instrumentation, including lower-cost sensors and fiber-optic based methods. Any proposal to use new instrumentation should clearly demonstrate its value in terms of improved (e.g., faster, more reliable) alerts, augmentation of existing network-based systems, or other considerations relative to existing real-time data streams used by ShakeAlert.
- Develop continuous, open test datasets of either seismic waveforms or derived parametric data from low-cost sensors and/or Internet of Things and/or fiber-optic based methods, particularly from geographic areas covered by ShakeAlert that include earthquakes of sufficient shaking intensity to issue alerts as well as a representative sampling of possible noise sources.
- Investigate resiliency of ShakeAlert's data telemetry and alert delivery, especially during large earthquakes, including quantification of likely telemetry delays and/or outages in such events.
- Evaluate and prototype the use of artificial intelligence, machine learning, edge computing and cloud computing to improve the ShakeAlert system.
- Evaluate use of near-fault arrays for resolving rupture propagation and improved ground motion

forecasts.

- Evaluate algorithms, data streams, and telemetry methods that would allow efficient use of offshore instrumentation in Cascadia to improve ShakeAlert warnings for large offshore earthquakes.
- Develop performance evaluation metrics to assess the accuracy and timeliness of predicted ground motions issued by earthquake early warning systems and assess the cost benefit for end-users in threshold-based applications.
- Develop uncertainty measures that are consistent across EEW algorithms. Develop methods that consider both the uncertainty in parameter estimates (shaking intensity) and the likelihood that an alert is associated with a true earthquake.
- Develop assessment metrics of earthquake early warning algorithm performance that quantitatively and accurately portray the performance of the overall system.

EEW Element III. **Research on earthquake occurrence, physics, effects, impacts, and risks.**

- Reduce uncertainties in ground motion predictions, particularly in high-risk urban areas. Examples include incorporation of real-time site response at ShakeAlert seismic stations, rapid source characterization (including stress drop), calibration of seismic magnitude scales, new approaches to using finite fault information to predict ground motions, and characterization of wave propagation and attenuation, including basin effects.
- Evaluate suitability of existing or develop new broadband (including GNSS) synthetics for use in testing EEW systems. This priority is particularly important in scenarios for which there are no available ground motion recordings along the west coast of the US, such as for isolated, large-magnitude events, especially at close distances to population centers; and complex sequences of events including doublets, mainshock-aftershock sequences, and/or swarms.
- Improve EEW algorithms for forecasting shaking in tall buildings and evaluation of user experiences in tall buildings to determine appropriate alerting criteria.

EEW Element IV. **Earthquake resilience, safety policy, communication, and user engagement.**

- Advance messaging, communication, and education strategies for critical ShakeAlert topics such as use of countdowns for alert delivery to wireless devices like cell phones, the late alert zone, complex earthquake sequences, and other topics that communicate appropriate expectations from and the limitations of the ShakeAlert System.
- Conduct communication, education, and outreach projects specific to ShakeAlert including but not limited to building awareness, education and training, and the integration of earthquake early warning with other tools for earthquake risk reduction.
- Support the implementation of drills and exercises via social science research to determine ideal formats, timing, drill cues (e.g., sounds, messages, accommodation(s) for those with access and functional needs), as well as the evaluation of these activities.
- Analyze education materials (e.g., textbooks, curriculum guides, videos, posters, brochures, and other ephemera), to determine key themes and gaps about EEW systems, protective actions, and earthquake behavior.
- Study integration of ShakeAlert into educational environments (e.g., K-12 schools, daycare and early childhood learning environments, libraries, museums, etc.,) and how they are utilizing this technology for the benefit of learners, educators, and staff.
- Research how ShakeAlert education can be incorporated into supporting school programs like afterschool programs, museum experiences, displays, and curriculum units, either by schools or through not-for-profit organizations.

- Investigate ShakeAlert technical partner alerting needs (e.g., assessing who needs alerts at high MMI values).
- Use social science to analyze human behavior and responses to ShakeAlert-powered alerts and examine issues of trust in channel providers for warnings, e.g., app providers, IPAWS, and other.
- Explore how to improve ShakeAlert availability for a broad range of populations, including use of new and emergent communication technologies, iconography, images, sounds, or other cognitive tools.
- Assess potential risks of over-alerting from a social science perspective, especially with the addition of ShakeAlert to the Integrated Public Alerts and Warning Systems (IPAWS) portal, which is being used for multiple alerting purposes.
- Advance understanding of how ShakeAlert can catalyze discourse about retrofitting and improving building codes.

REMAINDER OF PAGE INTENTIONALLY BLANK

Priority Topics for Research on Earthquake Rupture Forecasting (ERF) Coordinator:

Alex Hatem, ahatem@usgs.gov

Earthquake Rupture Forecasts (ERFs) are one of two main modeling components used in seismic hazard and risk assessments (the other component being a ground-motion model). An ERF, also referred to as a seismic source characterization in some time-independent analyses, gives the probability of every possible earthquake rupture in a region and over a specified timespan (or a suite of synthetic catalogs of such events, especially in the case of fully time-dependent or physics-based approaches). ERFs have traditionally been developed for the time-independent National Seismic Hazard Model, but we are also interested in their development for other products or potential products, including operational earthquake forecasting, risk analyses, and earthquake early warning. ERF development is a system-level problem that relies on four major disciplines: earthquake geology, tectonic geodesy, seismology, and earthquake physics. Combined, results and insights from these disciplines determine a possible set of rupture rates that goes beyond our observational bounds. We seek to constantly improve the input data, epistemic uncertainties, and philosophies used in these four modules. Two overarching goals for future models are a better representation of multi-fault ruptures and spatiotemporal clustering. We also intend to support a living "research" model that would facilitate the development and testing of hazard model components and enable more continual updates than have traditionally been possible. Collectively, we aim to move towards more physics-based approaches, which will require more independent constraints to verify model results.

This panel is aimed at supporting external research that proposes to make a direct contribution to ongoing ERF developments at the USGS. Site-specific or local data gathering efforts (e.g., individual paleoseismic studies; nodal arrays) should be submitted to an appropriate regional panel, whereas studies submitted here should be aimed at improving specific components used in current ERFs or developing more novel capabilities that could be of use in the future. The following lists some ERF priority tasks associated with each element outlined above, and we also welcome other novel research ideas.

ERF Element I. **National and regional earthquake hazards assessments.**

Earthquake geology:

- Explore improved representations of fault networks, such as quantifying uncertainties of fault surfaces at depth, fault rake, fault dip, and lower seismogenic depth.
- Definitions of geologic connectivity with neighboring faults.
- Improve quantifications of uncertainties in geologic constraints, including paleoseismic recurrence, geologic slip rates, prescribed geologic slip rates (including slip rate "bins"), and slip-per-event.
- Use of geologic or geophysical observations to constrain multi-fault ruptures with respect to jump distance, fault geometry and/or rake changes, or any other quantifiable characteristics.
- Observations that help define and constrain regions of distributed faulting for implementation as areal or discrete fault sources.

Tectonic geodesy:

- Develop regional deformation models, which apply both geologic and geodetic constraints to solve for slip rates throughout a fault system. Improve these models with respect to quantifying slip-rate correlations and a more complete exploration of null spaces (alternative models that fit data equally well). Apply these models to subduction zones.
- Improve the reliability of off-fault deformation estimates derived from geodetic deformation models (as a possible complement to smoothed-seismicity in ERF models). Define fractions of off-fault deformation as potentially coseismic vs. aseismic.

Seismicity:

- Develop algorithms for inferring long-term magnitude frequency distributions, including uncertainties, from observed seismicity and at various regional and temporal scales.
- Further refine declustering algorithms, which are needed to properly infer the spatial distributions of long-term seismicity rates.
- Improved smoothed seismicity estimates of long-term rates, including optimizations for different forecast durations.
- Define a spatial distribution of focal-mechanism probability distributions (e.g., for gridded seismicity).
- Develop aftershock and swarm forecasting algorithms that go beyond ETAS to provide improved forecasting of large aftershocks, to rapidly estimate the spatial pattern of aftershocks, and to characterize both short and long-term spatiotemporal variations in background rates.
- Investigate improvements in the utilization of earthquake catalogs against seismic hazard assessment metrics, potentially through improved characterization of catalog uncertainties, consideration of sampling error (how representative is our observed seismicity catalog of future earthquakes), or the use of high-resolution catalogs.

Earthquake physics:

- Improve scaling relationships used to infer magnitude and average slip from rupture area or length.
- Evaluation of stress models to constrain plausibility of multi-fault ruptures using dynamic rupture modeling.

Computation/Modeling:

- Explore alternatives to simulated annealing with respect to inversion-based fault-system solutions (are other algorithms more efficient, better at sampling null spaces, or an improvement with respect to exploring a range of models that match overall uncertainties?). There is clear method dependency in solving for the magnitude-rate distributions on faults that may imply hidden uncertainty associated with using only one approach.
- Pursue ideas on how to relax the artificial distinction between on-fault and gridded-seismicity events in current ERF models.
- Develop more objective ways of setting logic-tree branch weights, especially where there are either known or suspected correlations between branches.
- Develop ERF-applicable physics-based or statistical models for forecasting rates of induced earthquakes from wastewater injection or other manmade activities.
- Formulation of sensitivity tests across all modules of ERF development to understand relative importance of choices within modeling framework before rupture rates are combined with ground motion models for probabilistic seismic hazard analyses.

ERF Element II. **Earthquake information, monitoring and notification.**

Seismicity:

- Improve the maintenance and curation of earthquake catalogs, particularly with respect to representing uncertainties, real-time updates/additions with respect to ongoing seismicity, and quantification of magnitude-completeness thresholds (or probability of missed events as a function of space, time, and magnitude).

ERF Element III. **Research on earthquake occurrence, physics, effects, impacts, and risks.**

Earthquake geology:

- Improve elastic-rebound-motivated conditional probability estimates for fault systems where multi-fault rupture assumptions have been relaxed, including the extent to which recurrence-interval coefficients-of-variation are magnitude or slip-rate dependent.

Tectonic geodesy:

- Further refine "ghost transient" post-seismic viscoelastic corrections in deformation models. Expand the current set of applied "ghost transients" throughout the U.S.
- Provide a better understanding of creep behavior in deformation models and/or earthquake rate calculations.

Seismicity:

- Improve spatiotemporal clustering models (e.g., ETAS), especially in the context of explicitly modeled finite-fault surfaces and/or with respect to regionally variable or sequence-specific triggering parameters.
- Constrain the long-term magnitude frequency distribution near faults, and how this transitions spatially into the surrounding region.
- Develop model components that can be used to represent induced seismicity, seismic swarms, or other time dependencies such as super cycles, mode switching, or stress shadows.
- Constrain the extent to which large aftershocks can spatially overlap with mainshock rupture surfaces, from where such aftershocks can nucleate, and how this behavior evolves with time.

Earthquake Physics & Computation/Modeling:

- Develop alternative forecasting models to ETAS, particularly machine learning models. Of particular interest is quantifying the improvement over ETAS, making use of alternative real-time data (e.g., earthquakes below the magnitude of completeness, strain, finite-source information), and developing methods to make suites of long-term, realistic stochastic event sets to span the range of future earthquake scenarios that could occur.
- Develop or utilize multi-cycle physics-based earthquake simulators (e.g., see Field, 2019, https://doi.org/10.1785/0220180299). Priority improvements include incorporating off-fault seismicity, dynamic weakening, off-fault viscoelasticity, elastic heterogeneity, ductile deformation in the lower crust and upper mantle and alternative loading schemes. Of particular interest is establishing a single platform that could support a wide range of modeling options. Development of open-source, community tools is a priority as well.
- Develop machine learning or other approaches for inferring time-dependent predictability from multi-cycle, physics-based earthquake simulators.
- Help bridge the gap between current multi-cycle physics-based earthquake simulators and dynamic rupture models, including the development of benchmark verification test cases.
- Develop ways to formally validate ERF models.
- Determine whether ERFs would be useful in earthquake early warning (e.g., as a Bayesian prior).

ERF Element IV. **Earthquake resilience, safety policy, communication, and user engagement.**

ERF implications for hazard & risk:

- Address how aftershocks and other time dependencies should be handled in various hazard and risk applications (e.g., building codes), and in hazard communication.
- Help define a necessary and sufficient set of hazard and risk evaluation metrics, which are needed to inform ERF development (e.g., in quantification of which epistemic uncertainties are most influential and, therefore, in need of further scientific scrutiny).
- Explore the potential usefulness of operational earthquake forecasting, particularly with respect to tradeoffs between model complexity (realistic-ness) and usefulness. For example, are sequence-specific parameters value added if there is significant latency in their determination (at which time the

risk will have decayed)? Likewise, is the inclusion of explicitly modeled faults value-added?

- Quantify the probability gains afforded by operational earthquake forecasts, and determine the value added, focusing on hazard and risk metrics.
- Add model valuation to our verification and validation protocols (because simpler, less-realistic models can be more useful in some situations). This will also help answer the question of whether the value of a model "improvement" outweighs the deployment and maintenance costs.
- Develop more-objective and consequence-based algorithms for extracting meaningful scenario earthquakes from ERF models (and for different types of applications).

REMAINDER OF PAGE INTENTIONALLY BLANK

Priority Topics for Research on Earthquake Source Processes (ESP)

Coordinator: Justin Rubinstein, jrubinstein@usgs.gov

Earthquake Source Processes encompasses basic research on the occurrence, characterization, and physical processes of natural and induced earthquakes. We encourage applicants to consult with USGS staff to coordinate proposed work with ongoing USGS activities.

In addition to the common priorities listed in section 3.2, the following priority tasks are identified:

ESP Element III. **Research on earthquake occurrence, physics, effects, impacts, and risks.**

Research on earthquake source properties & simulation:

- Develop, improve, and apply techniques to characterize the spatiotemporal characteristics of earthquake rupture in high-resolution. Develop and apply techniques to use seismic data, geodetic data, aftershock locations, and/or other observations to image the 3D rupture geometry, spatial slip distribution, and time history of slip for significant earthquakes.
- Develop algorithms to provide information about source characteristics of earthquakes, including the estimation of location, depth, magnitude, directivity, and rupture extent. Methods that include uncertainties would be particularly valuable.
- Develop finite-fault modeling algorithms with a focus on the inclusion of multiple geophysical observations, rapid processing, and uncertainty estimation.
- Develop, improve, and apply improved methods for determining earthquake stress drop. Quantify stress drop uncertainty and evaluate the level of agreement between different methods. Develop a synthetic or simulated dataset of waveforms that could be used for stress drop estimation and validation.
- Develop, improve, and apply computational models of earthquake rupture, including earthquake nucleation, dynamic rupture propagation, arrest, and aseismic processes including afterslip. Consider components that affect the generation and scaling of earthquake ground motion.

Research on earthquake sequence characterization:

- Develop or improve novel techniques for earthquake detection, phase association, location, magnitude determination, and/or focal mechanism estimation, with associated uncertainties. Apply these techniques to produce enhanced earthquake catalogs with lower magnitude of completeness and/or higher accuracy than traditional network catalogs. Techniques leveraging machine learning, native cloud-based processing, and automation are encouraged, as are methods that can be applied in near-real time.
- Conduct studies to characterize, model, and describe the mechanisms underlying earthquake sequence behavior and earthquake interaction in all forms: aftershocks, earthquake triggering, earthquake swarms, and background seismicity.

Research on Slow slip:

- Better determine the origin, mechanisms, and duration of post-earthquake deformation, including afterslip and viscoelastic and poroelastic relaxation. Determine the relation of aftershocks and other triggered seismicity to post-earthquake deformation and pore fluid pressure evolution, as well as coseismic static and dynamic stress changes.
- Conduct field and laboratory studies on mechanisms responsible for episodic tremor and slip (ETS).
- Determine the influence of ETS and other transient deformations on the occurrence of earthquakes and the time-dependent earthquake probabilities following transient deformations.
- Better understand the interaction between aseismic and seismic slip in areas where both behaviors are present, e.g., repeating earthquakes and areas where faults transition from aseismic to seismic behavior.
- Better characterize the spatial distribution of fault creep along known major creeping faults.
- Develop new techniques for detecting and locating tremor, low-frequency earthquakes, or very-low-

frequency earthquakes (seismically) or small slip events (geodetically), to improve spatial and/or temporal resolution of slip on faults.

Research on Fault System Behavior:

- Use geodetic, geologic, and seismic observations to quantify slip rates for Quaternary active faults over time scales ranging from an individual earthquake sequence to the length of the Quaternary. Reconcile deformation rates inferred from different types of observations, and differences between apparent locking depth.
- Determine, refine, and test fault constitutive laws for the earthquake cycle, through laboratory, field, geodetic, and seismic observations, heat flow studies, and numerical modeling. Make field and laboratory measurements of fault zone properties, their evolution with accumulated offset and shear strain, and their changes following an earthquake rupture.
- Through observation, modeling, and experimentation, improve understanding of the interactions among rheology, material properties, fault geometry and the Earth's free surface in determining coseismic motion on the shallow extent of faults, and distributed shallow deformation.
- Better understand regions of distributed deformation, where strain release occurs either on multiple major faults or is distributed across a broad region.

Research on induced seismicity:

- Conduct seismological, geodetic, numerical modeling, and integrated studies of seismicity induced by any cause including wastewater disposal, hydraulic fracturing, geothermal energy production, carbon sequestration, etc. Studies of the Permian Basin in Texas and New Mexico are encouraged.
- Develop and test methods for evaluating the degree to which human activities induce earthquakes. Of particular interest are analyses of new data or implementing new methods (including machine learning) with the end goal of novel insights into the relationships between the fluid injection or production activity and the resulting induced earthquakes.
- Develop methods (statistical or otherwise) that can be used to distinguish induced earthquake sequences from natural earthquake sequences.
- Develop methods of anticipating the magnitude distribution of induced earthquakes and their contribution to seismic hazard, on the basis of anthropogenic activities (e.g., injection or production rate, pressure, total volume), presence of nearby seismogenic faults, stress state, and formation properties (e.g., rheology, pore pressure). Determine whether maximum magnitude for induced seismicity differs from that of natural seismicity.
- Improve seismic hazard analyses for induced earthquakes. Examples may include earthquake rupture forecasts that employ earthquake statistics (e.g., foreshock/aftershock, clustering) and ground motion models from analysis of induced earthquakes.
- Develop methods to make short-term forecasts of induced seismicity and its hazard using seismicity and/or industrial operation data. Where possible consider integration and coordinating with existing Operational Earthquake/Aftershock Forecasting Efforts. Forecasts should be evaluated using rigorous statistical methods, e.g., those employed by CSEP.
- Use numerical models, scalable experiments, or theory to test whether earthquake occurrence and energy release induced by industrial activities can be controlled so as to limit the seismic hazard posed by that operation.
- Determine the role of pore fluid pressure in all aspects of fault slip including: earthquake nucleation, earthquake rupture, and the partitioning of slip between aseismic and seismic modes.
- Apply results from studies of earthquakes induced by anthropogenic activities to improve our understanding of natural earthquakes.
- Conduct observational, theoretical, or laboratory studies to constrain the involvement of poroelasticity in induced seismicity, including but not limited to contributions from anisotropy, the influence of the ambient stress state, and long-range stress interactions.

- Develop, utilize, and test theory, numerical tools, and experimental techniques, such as coupled geomechanical and dynamic rupture models, to determine the physics of induced seismicity.
- Conduct research into the spatiotemporal evolution of induced earthquake sequences to determine whether induced earthquake sequences evolve differently than natural sequences.

REMAINDER OF PAGE INTENTIONALLY BLANK

Priority Topics for Research on Hazards, Impact, and Risk (HIR) Coordinator: Eric Thompson, emthompson@usgs.gov

The EHP supports both basic and applied, geographically broad research on the effects of earthquakes (including ground failure) and their impacts on the built environment, research that is relevant for probabilistic and/or scenario seismic hazard and risk analysis (including the NSHM), and near-real-time earthquake response (including ShakeMap, ShakeCast, the Ground Failure (GF) product, and PAGER). The USGS priorities on these topics are described below and we encourage applicants to consult with USGS staff to coordinate the proposed work with USGS activities when possible.

In addition to the common priorities listed in section 3.3, the following priority tasks are identified under each element. The most important priorities are marked with the text "Top priority" at the beginning of the description.

HIR Element I. **National and regional earthquake hazards assessments.**

Ground shaking hazard:

- Top priority: Assess the relative importance/value of alternative ground motion metrics for risk/loss models.
- Develop models for a broad range of ground motion characteristics, including inelastic response spectra, coherence and variability, spatial correlation structure, ground motion duration, energy-related parameters, and the spatial cross correlation between different ground motion parameters as needed for engineering and loss analyses.
- Quantify the epistemic uncertainties in the forecasted ground shaking hazard (i.e., the National Seismic Hazard Model), considering the correlations of these uncertainties across earthquake sources.
- Evaluate the National Seismic Hazard Model, focusing on identifying and enhancing aspects that need improvements.

Ground failure hazards:

- Top priority: Estimate the occurrence of ground failure (liquefaction, landslides, lateral spreading, surface fault rupture) and the resulting displacements. Methods that are applicable at regional scales are the highest priority. Both empirical and mechanistic approaches are encouraged.
- Top priority: Develop new curated digital inventories of ground failure including consistent and thorough metadata. Both historic and modern events are priorities.
- Develop methodologies for combining site-specific and geospatial data to improve on uncertainties in regional-scale ground failure hazard assessments.
- Develop methodologies for rapidly identifying the occurrence of ground failure after an earthquake.

HIR Element III. **Research on earthquake occurrence, physics, effects, impacts, and risks**.

Near real-time, scenario, and forecasted impacts:

- Top priority: Develop or contribute to national or international databases and methods to help quantitatively estimate losses from ground shaking and ground failure.

- Top priority: Develop open-source inventories, engineering exposure models, and fragility/vulnerability models for use in ShakeCast and/or the National Seismic Hazard Model; fragilities for critical facilities and geospatially distributed lifelines are of particular interest to USGS.
- Top priority: Investigate the effects/impacts of multiple ground-motion occurrences (e.g., from aftershocks) on the natural/built environment, and the implications for the modeling of earthquake occurrences (e.g., declustering and aftershock forecasting), physics (e.g., in simulations), ground motions (e.g., durations), and/or consequent risks (e.g., monetary losses, both total and proportionate).
- Develop rigorous methods for efficiently propagating uncertainties in ground motion estimation in risk assessments, including effects from various forms of conversion equations or intensity measure correlations.
- Develop approaches for efficiently and accurately generating hazard-consistent stochastic event sets to estimate seismic risk. These event sets could also contribute to the development of both hazard- and consequence-driven scenarios for emergency management planning.
- Develop a probabilistic framework that uses USGS earthquake science and products to assess system-level risk for geo-spatially distributed lifeline infrastructure and to assess aggregate losses for portfolios of assets.

HIR Element IV. **Earthquake resilience, safety policy, communication, and user engagement.**

Across all below items, effectiveness can be evaluated in multiple ways, including improved usability, accessibility, and communication.

- Develop new methods, datasets, or computational frameworks that support improvements to various seismic design guidelines and building code provisions.
- Assess the effectiveness of information and metrics in current products related to earthquake hazards, impacts, and risks (including the National Seismic Hazard Model, ShakeMap, PAGER, ground failure, and others) by engaging with a broad range of targeted users.
- Identify user needs and develop hazards, impacts, and risk tools to support earthquake preparedness, mitigation, response, and recovery decisions and policies at local, state, or national scales.

REMAINDER OF PAGE INTENTIONALLY BLANK

Priority Topics for Research on Ground Motion (GM) Coordinator: Grace Parker (gparker@usgs.gov)

The EHP supports basic and applied research on the modeling and analysis of earthquake ground motions across the EHP portfolio of products (NSHM, ShakeMap, ShakeAlert, etc.), and harmonization of those efforts between products. We especially encourage proposals towards implementation of partially nonergodic GMMs for seismic hazards assessments. We encourage applicants to consult with USGS staff to coordinate proposed work with ongoing USGS activities.

In addition to the common priorities listed in section 3.3, the following priority tasks are identified under each element:

GM Element I. **National and regional earthquake hazards assessments.**

- Develop new ground-motion models or regional adjustments for the conterminous U.S., Hawaii, Alaska, Puerto Rico and the U.S. Virgin Islands, Guam and the Northern Mariana Islands, and American Samoa to improve accuracy and precision of ground motion estimates;
- Develop procedures for selecting or combining ground-motion models and their uncertainties in a consistent manner, appropriate to ShakeAlert, near-real-time earthquake response, and the NSHM;
- Develop regional-scale nonergodic ground-motion models that include adjustments to GMM medians, aleatory variabilities, and epistemic uncertainties;
- Develop improved site response models, regional-scale maps of site parameters, or empirical site terms: parameters that capture basin and deep-structure effects and nonlinear site response models are of particular interest;
- Advance the characterization of ground motion uncertainty, including methods for modeling epistemic uncertainty and aleatory variability;
- Develop seismic directivity models for implementation into PSHA (e.g., adjusting median and variability of ground motions). Models must be applicable to NSHM, which requires consideration of complex fault geometries and a generalized coordinate system;
- Develop GMMs for the vertical component for use in the NSHM, with models for the CEUS and subduction zones being of particular interest;
- Update or develop new ground-motion models for seismic intensity (modified Mercalli intensity, MMI) for either direct intensity prediction (IPEs) or conversions (GMICE) that are relevant to needs for ShakeAlert or ShakeMap;

GM Element II. **Research on earthquake occurrence, physics, effects, impacts, and risks.**

- Investigate the physical processes that control the character (e.g., frequency content) of ground motions, especially high frequency (>1 Hz) energy or near-fault motions;
- Improve understanding of regional variations in basin-amplification effects;
- Identify trends in partitioned standard deviations (e.g., single-station sigma), including regional variations and variations with source parameters;
- Develop new methods or algorithms for automated waveform processing protocols including quality control. Examples could include the presence of multiple events, outlier detection, and nonlinear instrument response;
- Quantify the epistemic uncertainty of physics-based simulations;
- Perform deterministic simulations across broad regions to explain observed patterns in seismic waveforms (for example, regional differences in attenuation);
- Improve understanding of earthquake source effects (such as stress drop, slip

distributions, directivity, radiation pattern, asperity locations) on ground motion, and improve our ability to include them in ground-motion models;

- Improve understanding of physical processes controlling path effects (such as Q attenuation, geology, or seismic velocity properties), and improve our ability to include them in ground-motion models.

REMAINDER OF PAGE INTENTIONALLY BLANK