Attachment A

USGS Earthquake Hazards Program Research Priorities for FY2024

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.

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. Across all program elements, proposals focused on research targeting earthquake hazard mitigation and risk reduction in underserved communities, and in populations whose vulnerability may be directly related to socioeconomic factors, are strongly encouraged. Proposals that address Department of the Interior (DOI) and USGS goals to incorporate equity and environmental justice principles in associated research, where possible, 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 takes an active role with the user community in the application and interpretation of Program results. Active engagement with our user community provides opportunities for dialogues on modifications to our existing products and new products that make our work and results more relevant and applicable. The EHP supports opportunities for engaging the user community at both the national and regional levels.

2. Regional and topical areas

Research priorities are distributed across ten Research Areas—five regional and five topical areas. For FY2024, these topical research areas represent a change from previous years, wherein the previous topical panels (Earthquake Physics and Induced Seismicity, Engineering Seismology and Impacts, and National) have been migrated into four new panels, as included in the list below**:**

- 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.

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

Following are priority tasks and data for the EHP Program Elements common to multiple regional and topical areas. We emphasize that this is not an exhaustive list of all potential research topics, nor intended to discourage submission of proposals to accomplish other important tasks. Examples tailored to specific topical or regional needs are noted in respective sections. Common priorities for the EHP are included in section 3.2. Although these priorities are relevant to multiple research areas, related proposals must be submitted to a single regional or topical panel, and PIs are encouraged to reach out to Coordinators to discuss the most appropriate area for submission.

Applicants are encouraged to use seismic 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

Please note that the EHP encourages research proposals responsive to two USGS Science Plans in addition to priorities specified below. The first is a blueprint for advancing science and resilience from subduction zone hazards entitled *Reducing Risk Where Tectonic Plates Collide – A Plan to Advance* ***Subduction Zone Science***. This Subduction Zone Science plan emphasizes scientific and technological developments, improved hazard assessments, addressing stakeholder needs and maximizing capabilities through partnerships to reduce the risks posed by subduction zone events. The Plan focuses on 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, discusses specific knowledge and capability gaps, describes scientific frontiers, and summarizes key questions, needed research, required investments, and resulting products. The EHP encourages research proposals responsive to these themes.

Science for a Risky World: a USGS Plan for Risk Research and Applications (hereafter "**Risk Plan**") is a roadmap to ensure that USGS hazards information is delivered and incorporated into risk assessments and other products that can be used by decision makers to reduce loss. The Risk Plan includes 23 recommendations focused on building institutional capacity in partnerships, project funding, professional staff and capabilities, product delivery, and expanding information technology capabilities. Seventeen case studies highlight USGS risk work already underway. The Plan notes that collaboration with partners from the beginning of research and product development through to message delivery and continuing during product evaluation is necessary to provide partners with information that can support actionable decisions for risk reduction.

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. These products, developed from research on earthquake locations, magnitudes, recurrence, and ground motions, are the basis of the seismic safety elements of building codes affecting construction nationwide. 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 support the development of cost-effective mitigation measures and practices in structure design, construction, and land use planning.

The USGS is particularly interested in research that results in improvements to the National Seismic Hazard Model (NSHM), including models of seismic source, recurrence, ground motions, and site effects, and the assessment of earthquake hazards in large 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 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 result in amplification of earthquake ground motions, such as in sedimentary basins, or where geologic structures and/or topography modifies the ground motion amplitude.
- Develop ground-motion models applicable to hazards assessments.
- 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.

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.
However, routine monitoring activities are evaluated and funded under a separate solicitation for seismic and geodetic network operations.

Common priorities include:
- Develop and test new approaches to integrating seismic, geodetic, and other data 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 impact and risk assessments help emergency managers, planners, and the public prepare for future earthquakes. With the goal of improving hazard assessments, earthquake forecasts, and earthquake monitoring products, 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 address 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 the surface and subsurface rupture extent and displacement of earthquakes.
- Collect geological and geophysical data that will help characterize 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, or laboratory studies to improve our knowledge and modeling of induced seismicity.

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

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 takes an active role with the user community in the application and interpretation of Program results. Active engagement with our user community provides opportunities for dialogues on modifications to our existing products and new products that make our work and results more relevant and applicable. The EHP supports opportunities for engaging the user community at the national, regional, and local levels. As discussed above, proposals targeting earthquake hazard mitigation, risk reduction, response, and recovery to enhance the resilience of underserved and socially vulnerable populations are strongly encouraged.

- Provide collaborative engagement opportunities (workshops, focus groups, interviews, etc.) for specialists and practitioners that facilitate addressing important challenges in regional and local urban areas, such as: earthquake hazard mitigation, risk, response, preparedness, resilience; development of community velocity models; defining priority faults within a region for further study; fault setback planning, or similar.
- Advance better coordination between agencies by examining resources for improved communication and dissemination of earthquake information through education, crowdsourcing, and emergency management tools, and other methods.
- Engage user communities to assess the efficacy of existing earthquake products and elicit their suggestions for improvements and new products.
- 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.

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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. **Proposals applicable to a specific area in which an underserved community resides should be submitted to the relevant regional Research Area.** Although it is required to indicate the Regional or Topical Research Area when submitting a proposal, upon initial review, the regional and topical coordinators reserve the right to move proposals to the most suitable Regional or Topical Research Area.

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 encourage discussions with the regional and topical coordinators before proposing work outside of goals and priorities noted in this document.

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

A major priority for research in the CEUS is to refine seismic hazard estimates encapsulated in the National Seismic Hazard Model, which is used in the development of building codes and for emergency planning. 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 active faults and the frequency of large earthquakes on them are priorities. A second major priority is improving and reducing uncertainties in estimates of strong ground motion for the National Seismic Hazard Model, and 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. A third major priority is to understand the causes of seismicity in this intraplate setting. Priority for all these topics 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 geologic units, 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 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 3.3, 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 Puerto Rico and surrounding offshore faults, the Antilles subduction zone as pertains to 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, 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 of strong ground shaking. Examples might include studies of fragile geologic structures (stalactites, balanced rocks), mapping and analyses of paleoliquefaction features, 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, existing instrumental recordings, or modeling studies, with an emphasis on geologic units that underlie large areas of the CEUS. This might include construction of 3D seismic velocity models beneath, for example, the widespread Atlantic and Gulf Coastal Plains.

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 including basin effects.
- Systematically evaluate the temporal and spatial distributions of foreshocks and aftershocks of

intraplate earthquakes to improve declustering of seismic catalogs 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.
- Improve detection capabilities and reduce detection thresholds for current monitoring or enhancement of catalogs using machine learning/artificial intelligence.

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

- Develop physical 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 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.

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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 regional seismic hazard assessments such as the USGS National Seismic Hazard Model (NSHM). 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 3.3, the following priority tasks are identified under each element:

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

- Improve source models for IMW faults deemed priorities by each State (below). These studies could include investigations that determine late Quaternary fault geometry and length, slip rates, paleoseismic chronologies, earthquake recurrence, and segmentation of fault sources.
    - **Nevada:** A list of fault studies recommended by the Nevada Bureau of Mines and Geology is available at: http://www.nbmg.unr.edu/_docs/Earthquakes/NBMG_priorities_NEHRP.pdf
    - **Utah:** Priority faults deemed to need further study have been identified by the Utah Quaternary Fault Parameters Working Group (UQFPWG). An updated list of these priorities as defined by the UQFPWG is available at: https://geology.utah.gov/hazards/earthquakes-faults/utah-earthquake-working-groups/
    - **Elsewhere in the IMW:** Priority faults are summarized in a workshop report at http://ugspub.nr.utah.gov/publications/misc_pubs/mp-15-5/mp-15-5_workshop.pdf
- Compile and/or update regional information on Quaternary fault geometry and source parameters (e.g., paleoseismic history and fault slip rate) to support the USGS NSHM.

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 earthquake rupture behavior in the IMW, including: (1) prehistoric earthquake rupture timing, displacement, and recurrence; (2) rupture length and termination at structural complexities (fault segmentation); (3) long-term paleoseismic histories; (4) spatial and temporal variability in fault slip rate; (5) distributed or off-fault deformation; (6) behavior of opposing (e.g., primary–antithetic) or conjugate fault pairs; and (7) records of strong shaking from lacustrine paleoseismic data.
- Conduct scientific studies to improve our understanding of seismic hazard and its uncertainty in the IMW, including: (1) fault scaling relations (e.g., between fault length and displacement) and empirical regressions on moment magnitude, (2) subsurface structure of normal faults (e.g., listric versus planar) and relations between subsurface fault geometry and surface rupture, (3) limits on normal-fault rupture length and magnitude, (4) comparison of geologic and geodetic deformation models and uncertainties, and (5) assessment of fault creep and afterslip.
- Conduct studies that will improve our understanding of large historical earthquakes in the IMW, such as the M5.7 Magna, Utah, M6.5 Monte Cristo Range, Nevada, and M6.5 Stanley, Idaho earthquakes.
- Conduct geological, geophysical, and/or geotechnical research to develop and refine community velocity models in IMW urban areas, for example, by (1) collecting shear-wave velocity data and developing joint analyses of multi-scale datasets; (2) assessing basin geometry, structure, and

amplification; (3) developing and improving 3D velocity models, and (4) mapping subsurface faults and folds.

- 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.
- Conduct studies to develop or improve geologic, geodetic, and/or seismotectonic models of IMW deformation, for example, to characterize regions of on- and off-fault tectonic deformation and explore connections between subsurface structures and surface observations of faulting.
- Conduct numerical modeling studies using physics-based rupture simulations and/or other multi-cycle earthquake simulations on normal fault systems.
- Conduct earthquake hazards research and develop time-dependent earthquake probabilities for regions of high hazard and risk. Specific areas of interest include, but are not limited to, the Wasatch Front and southwestern (e.g., St. George) regions of Utah, the Reno-Carson City urban corridor, Las Vegas and surrounding urban areas of Nevada, northern Basin and Range cities (e.g., in Idaho, Montana, Wyoming, and Oregon), and lacustrine basins such as the Great Salt Lake and Lake Tahoe.

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 and risk reduction in underserved and/or vulnerable communities.

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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 is under-characterized. Research in Northern California outside these areas may also be supported, particularly to understand the plate boundary system 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. Attention to potential disparate impacts of earthquake hazards and risk is desirable. 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 3.3, 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 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 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, 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 after-slip.

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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.

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 GPS 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) GPS stations and tiltmeters; and 6) the Ocean Networks Canada and Oceans Observatory Initiative off-shore cabled networks. Research that leverages relevant activities sponsored by other agencies and institutions also is encouraged, such those that support development of the SZ4D Initiative (see https://www.sz4d.org). 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 3.3, the following priority tasks are identified under each element:

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

- Clarify the distribution and stationarity of locking along the plate-boundary (megathrust), particularly offshore.
- Develop numerical, observationally validated, ground motion models that include complex wave propagation effects for Cascadia M8-9 plate-interface earthquakes, in-slab and upper-plate earthquakes.
- Develop dynamic rupture simulations applicable to Cascadia, as well as computer models that simulate multiple earthquake cycles, and that link earthquake-related phenomena (e.g., tsunami, ground failure, turbidity current generation) to the earthquake source
- Characterize heterogeneities on the plate interface that may affect seismic radiation, particularly those likely to generate high-frequency strong ground motions.
- Develop approaches and observational inputs for temporal and spatial earthquake and aftershock forecasting, which account for potential differences among upper-plate, interplate and intraplate settings.
- Improve estimates of the sizes, recurrence intervals, and effects of past, late Quaternary earthquakes 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, improve estimates of its earthquake recurrence intervals, magnitudes, and rupture lengths, particularly that probe discordances between onshore and offshore evidence. Test potential links between megathrust and upper-plate faulting.

- 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.
- For plausible earthquake scenarios, model tsunami generation and inundation, collect data on and/or compare with paleo-tsunami deposits for model validation, and evaluate likely tsunami hazard variability.
- Quantify maximum magnitudes and occurrence probabilities of outer-rise and intraplate Cascadia earthquakes.
- Conduct lacustrine paleoseismic studies aimed at characterizing earthquake recurrence, particularly those that may distinguish initiating local, regional, and megathrust earthquake sources as well as 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.

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

- Improve estimates of fault-zone properties that may influence rupture area and fault slip. Quantify the relationship between slow slip events and earthquake potential.
- Evaluate potential interactions between interplate, intraplate, and upper-plate faults.
- Conduct studies of the transition from strike-slip to convergent boundaries (e.g., at the Mendocino Triple Junction).
- Develop computer models applicable to Cascadia that simulate multiple earthquake cycles, and that link earthquake-related phenomena (e.g., tsunami, ground failure, turbidity current generation).
- Develop dynamic rupture simulations applicable to Cascadia, as well as computer models that simulate multiple earthquake cycles, and that link earthquake-related phenomena (e.g., tsunami, ground failure, turbidity current generation) to the earthquake source.

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Priority Topics for Research in Alaska (PNA-Alaska) Alaska, Coordinator: Peter Haeussler, pheuslr@usgs.gov

USGS needs basic information to characterize the active earthquake sources in Alaska for use in updating the seismic hazard maps of Alaska and for informing the tsunami hazard of Alaska. The EHP encourages proposals for studies that take advantage of the Alaska Amphibious Community Seismic Experiment (AACSE) and EarthScope's Transportable Array deployment. High priority issues to be addressed in proposed work are listed below for each program element, although other proposal topics will be considered. Contact the Alaska Coordinator to learn more about internally supported projects or to discuss potential proposals.

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

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

- Improve the paleoseismic and paleogeodetic record of large to great earthquakes and tsunamis along the Alaska-Aleutian megathrust, including assessing the persistence, or non-persistence of rupture boundaries, recurrence intervals, and whether or not presently creeping sections of the megathrust have produced past great earthquakes.
- Perform lacustrine paleoseismology research to assess the record of strong ground motions along the subduction zone from megathrust, intraslab, and crustal earthquakes. Evaluate if lake sediments record historical earthquakes and events identified by other paleoseismology and paleotsunami records.
- Conduct geodetic field studies and/or modeling of geodetic data to resolve plate coupling and the role of aseismic slip on the potential for, and/or recurrence time of, large earthquakes along the Alaska-Aleutian megathrust, or the Queen Charlotte Fault and across southeastern Alaska.
- Examine large intraslab earthquakes, including the October 2020 Shumagin Islands, 2018 Anchorage and the 2016 Iniskin earthquakes, in order to better define the hazard, ground motions, and potential of these events along the subduction zone.
- Examine the Alaska Amphibious Community Seismic Experiment (AACSE) seismic data to better understand earthquake hazards along the megathrust in the region from Kodiak to Sanak Island.
- Evaluate the location, length, and nature of slow-slip events in Alaska, and particularly their relationship to down-dip and up-dip limits of co-seismic slip, or earthquake potential, along the Alaska- Aleutian megathrust.
- Develop methods and utilize geodetic data to estimate slip rates along faults or across regions that can be applied to seismic hazard analyses. Construct self-consistent models of crustal deformation that integrate seismic, geologic, and geodetic data from which hazard estimates can be derived.
- 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. In particular, increase knowledge of the Queen Charlotte-Fairweather fault system and its geologic structure and tsunami potential.
- Use high-precision hypocenter location methods and/or high-resolution topographic datasets and/or geodesy to identify the extent, geometry, and seismic hazards of faults in central Alaska seismic zones.
- Conduct studies to map active faults, define their earthquake history, and seismic potential on and near major crustal faults in Alaska – particularly those with no quantitative slip-rate information.
- 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 region-specific relationships for inferring seismic wave velocities from seismic or rock type data. 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, evaluating sedimentary basin ground motion amplification and the calculation of probabilistic hazard maps.
- Develop and test new approaches to integrating seismic, geodetic, and other data and *a priori* information in monitoring operations, applicable to earthquake early warning, routine earthquake monitoring, and slow slip detection and characterization.
- Advance machine learning/artificial intelligence methods for earthquake and deformation monitoring.

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

- Evaluate the potential interactions among subduction-zone faults, intraslab faults, splay faults, and crustal faults and the impacts of such interactions on seismic hazard.
- Develop physical and statistical models that may be used in earthquake hazard and risk assessments for the range of source types and seismicity patterns in Alaska.
- Develop empirical or simulation-based ground motion models that incorporate three-dimensional seismic structure and consider a range of earthquake source scenarios and complexity.
- Improve ground motion models for subduction interface and deep intra-slab earthquakes for use in the Alaska update of the National Seismic Hazard Model (see NAT priorities).
- 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.
- Improve understanding of co-seismic ground failure by better accounting for ground displacements that were neither classic liquefaction nor proper landslides. Advance models for estimates of liquefaction and landslides, which are currently rather crude both in terms of the underlying empirical framework and input data. Assess the potential for large volume/high mobility co-seismic rock avalanches in Alaska.

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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 3.3, 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.
- Develop, refine, and test probabilistic models for earthquake rupture using or advancing the approach provided by the Uniform California Earthquake Rupture Forecast-3 (UCERF3) Report.

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.

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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 in order to mitigate losses. The USGS operates the ShakeAlert Earthquake Early Warning System for the United States West Coast (https://earthquake.usgs.gov/research/earlywarning). 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 Program Announcement.

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 3.3, 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 used to issue earthquake early warning alerts. Examples include algorithms that identify the finite fault extent, improve early magnitude or location estimates, improve estimates of parameter uncertainty, estimate expected ground motions directly from observed ground motions, methods that incorporate directivity into predicted ground motions, or real-time methods to estimate the probability that a fault rupture will continue or terminate.
- Improve methods used to combine source and/or ground motion information from multiple algorithms in order to generate a single, high-quality alert stream.
- Improve methods for using seismic algorithm output as prior information for geodetic algorithms or for algorithms that combine seismic and geodetic data to improve source parameter or predicted ground motion estimates.
- Identify and assess novel instrumentation for use in earthquake early warning systems, 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.
- Proposals to 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 are encouraged, particularly from geographic areas covered by ShakeAlert and time intervals that are long enough to include earthquakes of sufficient shaking intensity to issue alerts as well as a representative sampling of possible noise sources.
- Investigate if ShakeAlert's use of the internet for data telemetry and alert delivery is sufficiently resilient to be effective during large earthquakes including quantification of likely telemetry delays and/or outages in such events.
- Evaluation and prototyping the use of artificial intelligence, machine learning, edge computing and

cloud computing to improve the ShakeAlert system.

- Evaluation of near-fault arrays for resolving rupture propagation and improved ground motion forecasts.
- Evaluation of the algorithms, data streams, and telemetry methods that would allow efficient use of offshore instrumentation in Cascadia to improve ShakeAlert warnings for large offshore earthquakes, particularly the evaluation of distributed acoustic sensing systems utilizing submarine cables and also telemetered buoys.
- Improve performance evaluation metrics used 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.
- Holistic comparative assessment of earthquake early warning algorithm performance, in a theoretical or empirical framework.
- Improve the identification and classification of seismic phases in real-time to better discriminate earthquake signals versus noise, P-wave versus S-wave phases, local versus teleseismic earthquakes.
- Improved EEW algorithms for forecasting shaking in tall buildings and evaluation of user experiences in tall buildings to determine appropriate alerting criteria.
- Investigation of ShakeAlert technical partner alerting needs (e.g., assessing who needs alerts at high MMI values).

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

- Reduce uncertainties in ground motion predictions that demonstrates improved accuracy of earthquake early warning alerts, particularly in high-risk urban areas. This could 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 broadband synthetics for use in testing EEW systems, or develop new synthetics if appropriate ones do not exist. Synthetics of particular interest are scenarios for which there are no available ground motion recordings along the west coast of the US, including: isolated, large-magnitude scenario events, especially at close distances to population centers; and complex sequences of events including doublets, mainshock-aftershock sequences, and/or swarms.
- 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 a true earthquake.
- Evaluation of user experiences in tall buildings, including the identification of useful alert metrics and strategies.

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

In addition to Section 1, ShakeAlert focused priorities are:

- 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.
- 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.

- Explore new and emergent communication technologies to increase the reach of ShakeAlert to diverse audiences.
- Advance ShakeAlert education and training in multiple languages while accounting for linguistic, social, and cultural differences and/or limited written or oral proficiency.
- Explore how to improve ShakeAlert to be inclusive and accessible to diverse populations including those with access and functional needs.
- Research channels to provide access to ShakeAlert for people without access to technologies due to disabilities, socioeconomic variances, and/or other factors.
- Analyze education materials (e.g. text books, curriculum guides, videos, posters, brochures, and other ephemera), to determine key themes and gaps about EEW systems, protective actions, and earthquake behavior.
- Explore potential iconography, images, sounds, or other cognitive tools that can improve various communities understanding and use of ShakeAlert and protective actions.
- Analyze human behavior and responses to people receiving a ShakeAlert-powered alert.
- Compare and contrast ShakeAlert public performance to other EEW systems.
- Advance understanding of how ShakeAlert can catalyze discourse about retrofitting and improving building codes.
- 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.
- Exploring counter narratives of technical partners regarding ShakeAlert responses.
- 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.
- Examine issues of trust in channel providers for warnings e.g., app providers, IPAWS, and others.
- Social media analysis of how people responded online to various alerts sent by ShakeAlert alert providers, as well as better understand sentiment and discourse online about the system.
- Assess the limits of over-alerting from a social science perspective (e.g., What forms of over alerting will cause users to not act when they receive future ShakeAlert-powered alerts?).
- Research on how ShakeAlert education can be incorporated into supporting school programs like afterschool programs, museum experiences, displays, curriculum units, either by schools or through not-for-profit organizations.
- Examine potential risks of over-alerting with the addition of ShakeAlert to the Integrated Public Alerts and Warning Systems (IPAWS) portal, which is being used for multiple purposes, e.g., to distribute Wireless Emergency Alerts (WEAs), including AMBER alerts, Blue and Silver alerts, Weather warnings, and other types of alerts.

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Priority Topics for Research on Earthquake Rupture Forecasting (ERF), Coordinator: Ned Field, field@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 flagship products, including operational earthquake forecasting, risk analyses, and earthquake early warning. ERF development is a system-level problem in terms of needing to incorporate information from a broad range of disciplines, including seismology, geology, geodesy, earthquake physics, and even engineering in terms of ensuring usefulness. The slow rate of large earthquake data collection has two important manifestations: 1) a need for adequate quantification of epistemic uncertainties; and 2) a need for more physics-based approaches. Two overarching goals for future models are a better representation of multi-fault ruptures and spatiotemporal clustering (because aftershocks can be damaging). We also intend to support a living "research" model that would embody more continual updates than has traditionally been achieved.

This panel is aimed at supporting external research that stands 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 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, but we emphasize that other ideas are welcome as well.

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

- Explore improved representations of explicitly modeled fault networks, such as quantifying uncertainties with respect to the nature of fault surfaces at depth, connectivity with neighboring faults, or quantifying the probability of an active fault existing where none has yet been identified.
- Improve quantifications of the probability of missed or over-interpreted events in paleoseismic recurrence-interval studies, particularly with respect site-specific analyses (given unique deformational environments and fault styles at each site).
- Improve slip-rates and their uncertainties derived along faults that lack explicit geologic data constraints (categorical values).
- Improve the general fidelity and uncertainty estimates of average slip-per-event constraints.
- Improve uncertainty of three-dimensional fault geometry, include lower seismogenic depth and fault dips, as well as uncertainty of fault rakes. Characterize the potential spatial correlations of these values and their uncertainties.
- 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 deformation models (as a possible substitute for smoothed-seismicity in ERF models). What fraction of this off-fault deformation is aseismic?
- Further refine "ghost transient" corrections in deformation models (viscoelastic effects).
- Improve the treatment of creep processes in deformation models and/or earthquake rate calculations.
- Develop algorithms for inferring long-term magnitude frequency distributions, including uncertainties,

from observed seismicity and at various regional 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.
- Improve scaling relationships used to infer magnitude and average slip from rupture area or length.
- Define the spatial distribution of focal-mechanism probability distributions (e.g., for gridded seismicity).
- Improve constraints on segmentation and multi-fault ruptures with respect to jump distance, fault geometry and/or rake changes, or any other quantifiable characteristics.
- 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?).
- 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.
- Help reduce overall model complexities.
- Develop ERF-applicable physics-based or statistical models for forecasting rates of induced earthquakes from wastewater injection or other manmade activities.
- Develop aftershock and swarm forecasting algorithms that go beyond ETAS to provide better 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.

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

- 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.**

- Improve elastic-rebound-motivated conditional probability estimates for fault systems where segmentation assumptions have been relaxed, including the extent to which recurrence-interval coefficients-of-variation are magnitude or slip-rate dependent.
- Address the so-called paleo-hiatus observation in which the collective lack of recent ruptures at California paleoseismic trenches appears at odds with model predictions (Biasi and Scharer, 2019; https://doi.org/10.1785/0220180244).
- 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.
- 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.

- 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.
- 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.
- Develop and/or maintain multi-cycle physics-based earthquake simulators, which are perhaps our most promising approach for addressing many of the bullet items here (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 (to represent alternative hypotheses and to better quantify epistemic uncertainties). 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 test (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.**

- Address how aftershocks and other time dependencies should be handled in various hazard and risk applications (e.g., building codes)?
- 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?
- Are the probability gains afforded by operational earthquake forecasts, or the quantification of hazard and risk during seismically quiet times, value added compared to operational aftershock forecasts?
- More generally, 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).

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Priority Topics for Research on Earthquake Source Processes (ESP), Coordinator: Justin Rubinstein, jrubinstein@usgs.gov

Earthquake Source Processes encompasses basic research on the occurrence 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 3.3, the following priority tasks are identified:

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

- 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 in near real time, including the estimation of location, depth, magnitude, directivity, and rupture extent.
- Develop finite-fault modeling algorithms with a focus on the inclusion of multiple geophysical observations, rapid processing, and uncertainty estimation.
- Develop or improve novel techniques for earthquake detection, phase association, location, 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.
- Use geodetic, geologic, and seismic observations to quantify slip rates for Quaternary active faults over a range of time scales. Reconcile deformation rates inferred from different types of observations, and differences between apparent locking depth.
- 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.
- Determine, refine, and test fault constitutive laws for the earthquake cycle, through laboratory, field, geodetic, and seismic observations, heat flow studies, and numerical modeling. Develop theory, models, and 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 free surface in determining coseismic motion on the shallow extent of faults, and distributed shallow deformation.
- Develop, improve, and apply improved methods for determining stress drop. Quantify stress drop uncertainty and evaluate the level of agreement between different methods.
- Conduct field and laboratory studies on mechanisms responsible for episodic tremor and slip (ETS). Determine the mechanical relation between ETS and other transient deformations and the occurrence of earthquakes or provide information that constrains time-dependent earthquake probabilities.
- Develop, improve, and apply computational models of earthquake rupture, including earthquake nucleation, dynamic rupture propagation, arrest, and aseismic processes including afterslip.
- Develop and test methods for evaluating the degree to which human activities induce earthquakes. Of particular interest are analyses of new data or analyses methods (including the use of machine learning) of case histories that yield novel insights regarding the relationships between the fluid injection or production activity and the resulting induced earthquakes.
- Conduct seismological, geodetic, numerical modeling, and integrated studies of the ongoing seismicity

in the Delaware Basin in Texas and New Mexico. Studies rapidly characterizing the seismicity are particularly desirable.

- 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 strong motion.
- Use numerical models, scalable experiments, or theory to test whether earthquake occurrence and energy release induced by industrial activities can be controlled to limit the seismic hazards posed by that operation.
- Determine the role of pore fluid pressure in initiation and during fault slip, including how moment release may be partitioned between aseismic versus seismic slip.
- 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.
- 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.

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

The EHP supports 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, 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:

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

Ground shaking hazard:

- Development of 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.
- Assess the relative importance/value of alternative ground motion metrics for risk/loss models.
- Quantification of epistemic uncertainties in forecasted ground shaking hazard (i.e., the National Seismic Hazard Model), with due consideration of the correlations of these uncertainties across earthquake sources.
- Testing of the National Seismic Hazard Model.

Ground failure hazards:

- Estimation of the occurrence of ground failure (liquefaction, landslides, lateral spreading, surface fault rupture) as well as resulting displacements. Methods that are applicable at regional scales are the highest priority. Both empirical and mechanistic approaches are encouraged.
- Development of methodologies for combining site-specific and geospatial data to improve on uncertainties in regional-scale ground failure hazard assessments
- Advancements in the characterization of ground failure uncertainty, including methods for fully capturing epistemic and aleatory sources of uncertainty.
- Development of methodologies for rapidly identifying the occurrence of ground failure after an earthquake.
- Development of new curated digital inventories of ground failure including consistent and thorough metadata. Both historic and modern events are priorities.

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

Near real-time, scenario, and forecasted impacts:

- Develop or contribute to national or international databases and methods to help quantitatively estimate losses from ground shaking and ground failure.
- Development of open-source inventories, engineering exposure models, and

fragility/vulnerability models for use in ShakeCast and/or with the National Seismic Hazard Model; fragilities for critical facilities and geo-spatially distributed lifelines are of particular interest to USGS.
- Develop new products and procedures that will allow the USGS to deliver more rapid and/or more accurate post-earthquake loss and risk information.
- Develop new tools to analyze (and database) traditional and/or social media content to inform NEIC of earthquake casualties, damage to structures, and characterize occurrences of ground failure in the immediate aftermath of earthquakes.
- Develop tools for use in near-real-time to predict and/or monitor structural health, assess damage levels, and investigate failure mechanisms. We encourage the use of data from ANSS instrumented structures (http://strongmotioncenter.org).
- Develop probabilistic methods and open-source models or tools to describe building performance in response to strong shaking. We encourage the use of data from ANSS instrumented structures (http://strongmotioncenter.org).
- Develop rigorous methods for efficiently propagating uncertainties in ground motion estimation in risk assessments, including effects from various forms of correlations.
- Develop open-source data, methods, and methods to demonstrate impacts of hazard uncertainties on loss/risk estimates with the goal of identifying the most influential components of hazard modeling.
- Develop approaches for efficiently and accurately generating hazard-consistent stochastic event sets for the purpose of estimating seismic risk. These event sets could also be used to inform 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.
- Quantify the impact/importance of epistemic vs aleatory uncertainty, correlation among sources of epistemic uncertainties, spatial correlation, and inter-metric correlation structure on distributed losses.
- In coordination with USGS personnel, 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).

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, communication, or ability to support underserved and socially vulnerable populations to earthquakes.

- Evaluate the effectiveness of information and metrics in current products devoted towards earthquake hazards, impacts, and risk (such as the National Seismic Hazard Model, ShakeMap, PAGER, ground failure, or others) through engagement with targeted users.
- Develop improved methods for communication of current hazard, impacts, and risk information that increases earthquake awareness with targeted users and communities, such as web platforms, posters, messaging, etc.
- 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.

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Priority Topics for Research on Ground Motion (GM), Coordinator: Morgan Moschetti mmoschetti@usgs.gov

The EHP supports basic and applied research on the modeling and analysis of earthquake ground motions across EHP's portfolio of products (NSHM, ShakeMap, 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 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 and/or combining ground-motion models in a consistent manner, appropriate to ShakeAlert, near-real-time response, and 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 are of particular interest;
- Advance the characterization of ground motion uncertainty, including methods for capturing 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;
- Update or develop new ground-motion models for seismic intensity (modified Mercalli intensity MMI) for either direct intensity prediction equations (IPEs) or conversion equations (GMICE) that are relevant to needs for ShakeAlert or ShakeMap;

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

- Fundamental investigations into the physical processes that control the character (e.g., frequency content) of ground motions, especially high frequency (>1 Hz) energy;
- Improve understanding of regional variations in basin-amplification effects;
- Research that identifies trends in single-station standard deviations, including regional variations and variations with source parameters;
- Development of 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;
- Quantifying the epistemic uncertainty of physics-based simulations;
- Deterministic simulations across broad regions to explain observed patterns in seismic waveforms (for example, regional differences in geometric 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 into ground-motion models.

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