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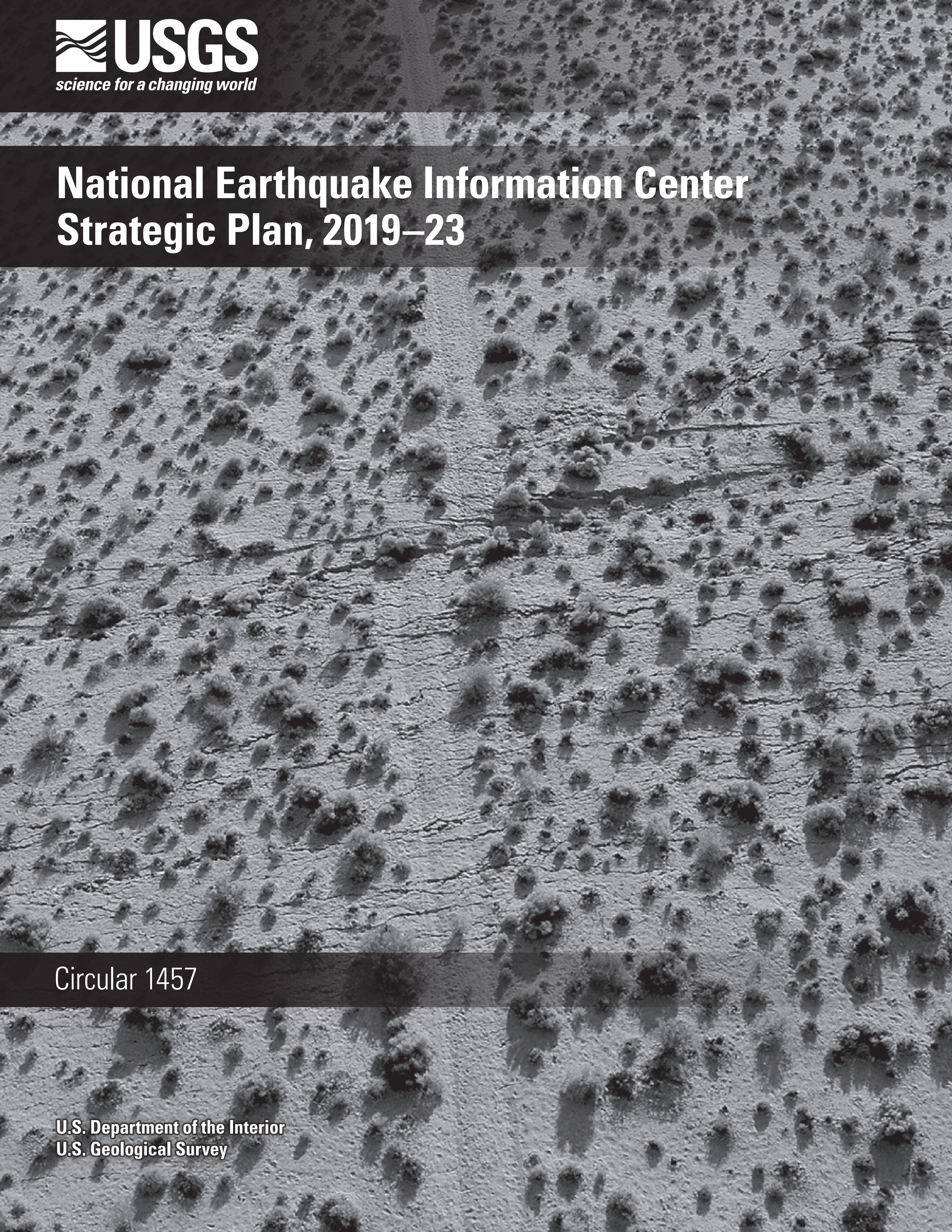

National Earthquake Information Center Strategic Plan, 2019–23

Circular 1457

U.S. Department of the Interior
U.S. Geological Survey

Cover. Surface faulting from the July 6, 2019, magnitude 7.1 Ridgecrest earthquake in California. View is from elevation, looking down, and approximately to the west. The dirt track (center) is right-laterally offset roughly 2.5 meters (approximately 8 feet).

National Earthquake Information Center Strategic Plan, 2019–23

By Gavin P. Hayes, Paul S. Earle, Harley M. Benz, David J. Wald, and William L. Yeck

Circular 1457

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
DAVID BERNHARDT, Secretary

U.S. Geological Survey
James F. Reilly II, Director

U.S. Geological Survey, Reston, Virginia: 2019

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Preface

This circular presents a strategic plan for the U.S. Geological Survey National Earthquake Information Center (NEIC). The report was written at the request of the USGS Earthquake Hazards Program, with input from all those who cooperate with the NEIC, including domestic earthquake monitoring agencies that are part of the Advanced National Seismic System (ANSS), international agencies with similar missions to the NEIC, and academic researchers focusing on earthquake monitoring.

Acknowledgments

This report benefitted from input from many members of the global earthquake monitoring community, many of whom gathered to be part of the U.S. Geological Survey Powell Center Working Group on Earthquake Monitoring at the Powell Center in Fort Collins, Colo., in September 2018. We thank Dr. Eric Bergman for his contributions to NEIC research and operations in the development of calibrated seismic source locations such as those shown in Figure 13 of this document. Additional thanks go to Jill McCarthy, Cecily Wolfe, and Bill Leith of the U.S. Geological Survey, and the National Steering Committee of the Advanced National Seismic System.

Contents

Figures

Abbreviations and Acronyms

AFTAC	Air Force Technical Applications Center
ANSS	Advanced National Seismic System
ComCat	ANSS Comprehensive Catalog
CTBTO	Comprehensive Test Ban Treaty Organization
DYFI?	Did-You-Feel-It?
EEW	earthquake early warning
EHP	USGS Earthquake Hazards Program
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GUI	Graphical User Interface
HAZUS	Hazards U.S.
InSAR	Interferometric Synthetic-Aperture Radar
M	magnitude
NEHRP	National Earthquake Hazards Reduction Program
NEIC	National Earthquake Information Center
NOAA/TWC	National Oceanographic and Atmospheric Administration, Tsunami Warning Center
NSHM	National Seismic Hazard Model
OAF	Operational Aftershock Forecasting
PAGER	Prompt Assessment of Global Earthquakes for Response
PCWGEM	Powell Center Working Group for Earthquake Monitoring
RSN	ANSS Regional Seismic Network
USGS	U.S. Geological Survey

National Earthquake Information Center Strategic Plan, 2019–23

By Gavin P. Hayes, Paul S. Earle, Harley M. Benz, David J. Wald, and William L. Yeck

Executive Summary

Damaging earthquakes occur regularly around the world; since the turn of the 20th century, hundreds of earthquakes have caused significant loss of life and (or) millions of dollars or more in economic losses. While most of these did not directly affect the United States and its Territories, by studying worldwide seismicity we can better understand how to mitigate the effects of earthquakes when they do occur within U.S. borders. Within the U.S. Government, this mandate falls on the U.S. Geological Survey (USGS) National Earthquake Information Center (NEIC), which has the statutory responsibility for monitoring and reporting on earthquakes domestically and globally.

The NEIC has been operating since 1966, and throughout its history has been recognized as a world leader for earthquake information. For much of this time, NEIC has been cooperating with a number of regional seismic networks (RSNs) which operate in areas of heightened seismicity in the United States. In 2000, the Advanced National Seismic System (ANSS) was founded as a cooperative umbrella for earthquake-related data collection, analysis, and dissemination in the United States, thereby promoting advanced interoperability between the NEIC and RSN partners. The NEIC also cooperates and coordinates with dozens of global seismic networks. At present (2019), NEIC acquires real-time waveform data from more than 2,000 seismic stations worldwide, contributed from more than 130 seismic networks.

Since 2006, the NEIC has operated on a 24-hour, 7-days per week (24/7) basis, and reports on about 30,000 earthquakes per year. Soon after the occurrence of a significant global earthquake, notifications are issued to government representatives, aid agencies, the press, and members of the general public by the Earthquake Notification Service (ENS), electronic feeds, and through the USGS Earthquake Hazards Program (EHP) website. Event-specific web pages provide detailed source parameter information outlining the location and magnitude of the earthquake, including more detailed source characteristics like moment magnitude and focal mechanisms and finite fault solutions. Further, NEIC produces a suite of real-time situational awareness products, including ShakeMap, ShakeCast, Did-You-Feel-It? (DYFI?), and Prompt Assessment of Global Earthquakes for Response (PAGER), to characterize the shaking resulting from the earthquake and the impact it is likely to have on nearby populations and infrastructure. All of these products are ultimately archived in the ANSS Comprehensive Catalog (ComCat), hosted and served by the NEIC.

The NEIC also pursues an active research program to improve its ability to characterize earthquakes and understand their hazards. These efforts are all aimed at mitigating the risks of earthquakes to humankind.

To maintain its prominent position in earthquake monitoring, the NEIC must continue to evolve, concurrently improving its operations and 24/7 robustness, streamlining services and infrastructure, and keeping pace with research and innovation in the field of seismology. This document outlines how the NEIC might best achieve such goals, by describing specific avenues and opportunities for development in the next five years (2019–23).

Several key areas of operational and research focus are identified in this plan as being of the highest importance. First, NEIC must finalize improvements to its regional monitoring capabilities, including the implementation of a variety of improved earthquake detection and association algorithms. One of the most exciting avenues of recent research expansion in earthquake monitoring has involved the use of machine learning; NEIC must explore the benefits of machine learning for improved earthquake detection and source characterization. NEIC also needs to address issues related to the timeliness of earthquake information, exploring the benefits of distributing information as it becomes available, rather than when certain quality criteria are met. To that end, the incorporation of real-time Global Positioning System (GPS) data into the NEIC operational workflow will help improve the speed and accuracy of information for moderate-to-large earthquakes. Finally, NEIC should explore how to further expand and improve the quality and content of the products served during earthquake response efforts, including the generation of new earthquake sequence-specific products, adding an evolutionary component to earthquake information, and continued improvements to earthquake impact products.

Introduction

In 1977, the U.S. Congress established the National Earthquake Hazards and Reduction Program (NEHRP), with the goal of reducing risks from future earthquakes in the United States by an effective Hazards Reduction Program. Within that act (formally the Earthquake Hazards Reduction Act of 1977; Public Law 95-124, 42 U.S.C. 7701 et. seq.), Congress set out the framework necessary to successfully work towards this goal. Within components charged to the U.S. Geological Survey (USGS), this included the operation of the National Earthquake Information Center (NEIC), labeled "a forum for the international exchange of earthquake information" (https://www.nehrp.gov/about/PL108-360.htm). The vision for the NEIC was a group which was the global face of USGS earthquake research and preparedness.

NEHRP guidelines (https://www.nehrp.gov/about/PL108-360.htm) also direct USGS to operate a National Seismic System. To that end, the subsequent reauthorization to NEHRP in 2000 (Public Law 108–360, 42 U.S.C. 7704 et. seq.) explicitly established the Advanced National Seismic System (ANSS). The vision of the ANSS is to provide the earthquake data and information needed to save lives and reduce earthquake losses, as a foundation for creating a more earthquake-resilient Nation. The NEIC is the national seismic network for ANSS, and coordinates monitoring efforts within the United States with other Regional Seismic Networks (RSNs). In addition to its global and domestic monitoring duties, the NEIC acts as a backup to those RSNs during the response to large domestic earthquakes in the various monitoring regions of each network.

National Earthquake Information Center and Global Earthquake Monitoring

The rapid and accurate production and communication of informational content related to a recent significant earthquake is an important step towards the ultimate mitigation of earthquake-related risk; to better prepare for and reduce the impact of future earthquakes, we must be able to understand the characteristics and effects of historical and ongoing seismicity. From 2010 to 2017 alone, the USGS Prompt Assessment of Global Earthquakes for Response (PAGER) system generated 18 red alerts (based on an estimated impact of at least 1,000 fatalities, or damage and economic loss exceeding 1 billion dollars), 40 orange alerts (at least 100 fatalities, or damage and economic loss exceeding 100 million dollars), and 175 yellow alerts (at least 1 fatality or damage, and economic loss exceeding 1 million dollars) from the roughly 5,000 magnitude (M) 5.5+ events NEIC reported during that time period (fig. 1). Since damaging earthquakes occur regularly on a global basis, monitoring and studying these events leads to increased preparedness for less frequent domestic earthquakes. The NEIC is the only earthquake monitoring group that is federally mandated to monitor and disseminate global and domestic earthquake information.

The NEIC operates a 24/7 service dedicated to the rapid determination of the location and size of all significant earthquakes worldwide and to the immediate dissemination of this information to concerned national and international agencies, scientists, critical facilities, and the general public. Within this operational framework, the NEIC is always staffed by at least 2 geophysicists responsible for reviewing and reporting all M5+ global earthquakes within 20 minutes of their origin time. For events of M~5.5 and larger, moment magnitude algorithms built into the NEIC processing system typically provide an accurate description of earthquake size when the event is first released. The distribution of this information triggers a broad range of other products generated to characterize the earthquake source (for example, moment tensors and finite fault solutions), its shaking and potential impact (for example, ShakeMap, ShakeCast, Did-You-Feel-It? (DYFI?), Prompt Assessment of Global Earthquakes for Response (PAGER), and Ground Failure characterizations).

This information is made available through the USGS Earthquake Hazards Program (EHP) website at https://earthquake.usgs.gov/, which receives millions of visits in the hours following major global earthquakes and is one of the most heavily trafficked sites in the Federal Government (for example, see https://analytics.usa.gov/). This content eventually became the foundation of the ANSS Comprehensive Catalog (ComCat), designed and maintained by the NEIC to be an extensive, global seismic database on earthquake source parameters that serves as a solid foundation for basic and applied earth science research, and for the communication and sharing of information products related to earthquake monitoring, response, and hazard reduction.

The NEIC also maintains its own active research program to improve our understanding of earthquake characteristics and their effects. Advances in earthquake monitoring practices and the enrichment of event-based informational content depend to a large extent on the research NEIC and its partners perform.

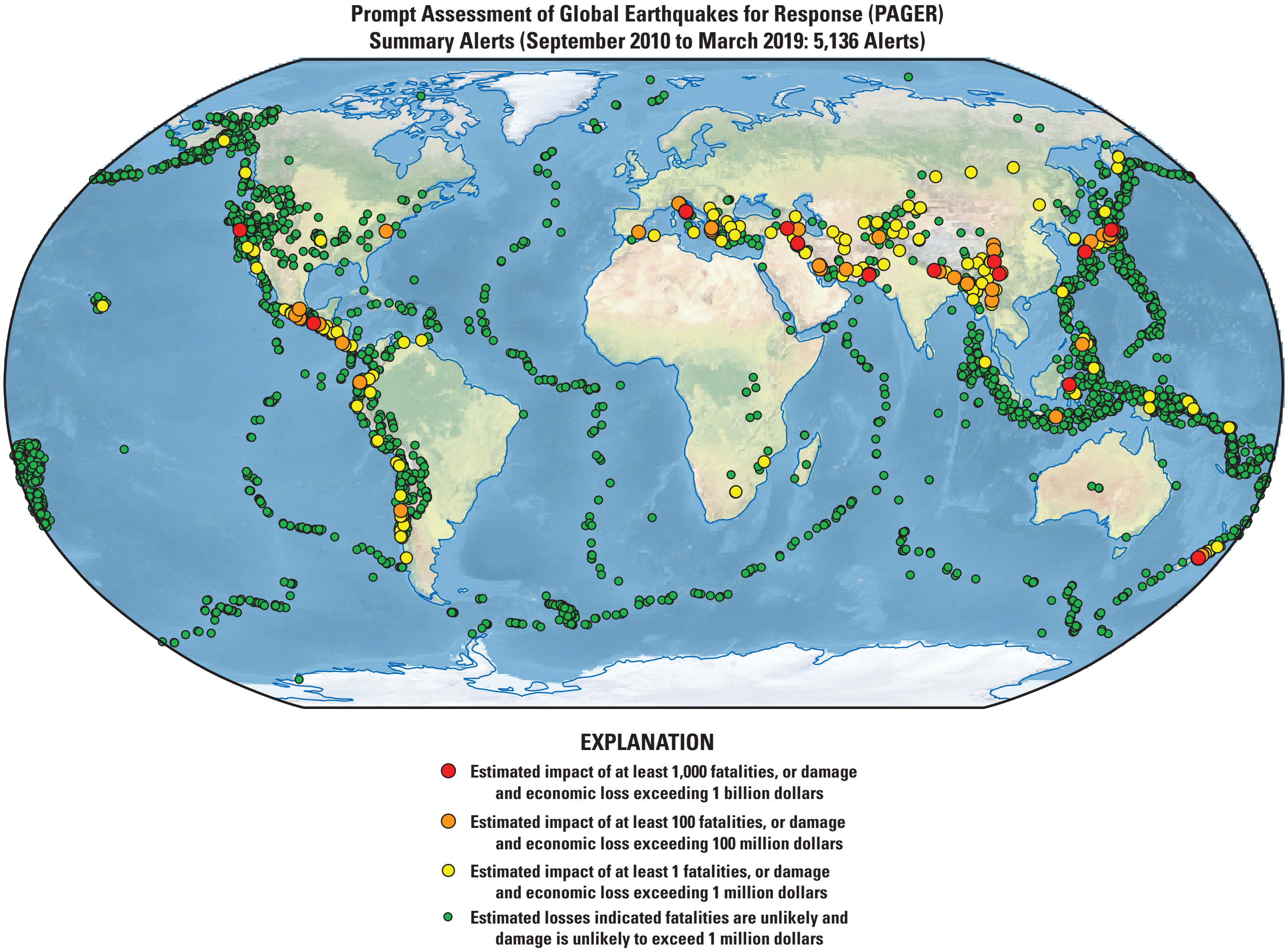


Figure 1. Color-coded U.S. Geological Survey Prompt Assessment of Global Earthquakes for Response alerts from September 2010 through April 2019. During this period there were 4,903 green-, 175 yellow-, 40 orange-, and 18 red-level alerts.

Goals of Report

In this five-year NEIC Strategic Plan we ask the question: Within our Mission, where should the USGS NEIC be five years from now (2024), and, how do we get there?

This plan focuses on the strengths and opportunities of the NEIC through USGS science and external collaborations. We leave limitations and threats to internal deliberation and documentation given their focus on IT security, budgetary limitations, and 24/7 personnel challenges and other internal issues.

The charge for this Plan was to assume flat funding but also explore the opportunities created by any budget increase. A second element of the charge was to identify shovel-ready projects—self-contained proposals achievable over relatively shorter timeframes—or resource needs that should be in place for any opportunities for additional funding. In response to the request for a strategic plan for the NEIC, the USGS Earthquake Hazards Program Office formed the NEIC Working Group 2017 (NEICWG17), charged with formulating a plan to meet the following operational and research goals:

1. Maintain and augment the NEIC position as the premier resource for national and global earthquake information.

USGS Powell Center Working Group for Earthquake Monitoring (PCWGEM)

In September 2018, the USGS NEIC led a USGS Powell Center meeting on the future of earthquake research and monitoring. The meeting brought together domestic and international researchers and network representatives interested in improving earthquake monitoring and characterization. The primary goals of assembling such a strong and diverse group of global seismological experts were to build a list of priorities, to begin outlining how these changes will be implemented, and to improve communication and coordination among regional and international earthquake monitoring agencies. The outcomes of the meeting were also intended to guide prioritizations in this 5-year NEIC Strategic Plan, and thus this workshop provided broad community input and support for NEIC planning efforts.

The group of 35 experts set the groundwork for achieving the workshop goals by identifying 6 key priorities for monitoring efforts, split into short-, medium-, and long-term targets:

1. Automatic sharing of parametric data between monitoring networks;
2. Using array azimuth and slowness information in network processing;
3. Machine learning for improving earthquake monitoring;
4. Improved exotic source characterization;
5. Rapid source characterization (10-year vision for full characterization in less than10 minutes); and
6. Setting criteria for assessing curated crowdsourced and social media-based data.

Focus groups were formed to coordinate continued efforts, and a smaller subgroup plan to reconvene in late 2019 or early 2020 to begin implementation of targeted priorities.

2. Leverage new and existing technologies that lead to improving monitoring capabilities, and thus, increase the timeliness and accuracy of earthquake information and products. Specifically, NEIC should approach or exceed current regional seismic network capabilities for detection, location, completeness, accuracy, and consistency, everywhere in the United States. Globally, NEIC should approach or exceed the detection capabilities of the Comprehensive Test Ban Treaty Organization (CTBTO) at M4.5+, and the National Oceanographic and Atmospheric Administration Tsunami Warning Centers (NOAA/TWC) in terms of timeliness of earthquake release. Ultimately NEIC should move towards the public release of high-quality automated solutions both domestically and globally.

3. In conjunction with (2), NEIC should target the automatic production of an authoritative, accurate, precise and complete (low-M) catalog of global seismicity, limited in timeliness only by the propagation speed of seismic waves, for use at all time scales from impact assessment, to rapid emergency response, to research-grade products such as seismic hazard maps, earthquake forecasting and sequence characterization, and source physics.

4. Expand the quality, content and usefulness of earthquake information products to enable more effective earthquake hazards assessment, information dissemination, communication, response, and mitigation.

Domestically, the NEIC plan aligns with the 2017 ANSS Strategic Plan (U.S. Geological Survey, 2017,Circular 1429) and priority goals and objectives of NEHRP. Circular 1429 describes a set of specific development opportunities that form ANSS priorities for the next decade to ensure ANSS readiness in an earthquake crisis, advance earthquake safety in urban areas, and expand the observational database for earthquake risk reduction.

Some of the key priorities outlined in Circular 1429 that pertain to the NEIC include the implementation of Earthquake Early Warning (EEW), Operational Aftershock Forecasting (OAF), and improved (higher resolution) Hazard and Impact Assessment products. The latter focus, in particular, will lead to improvements to the National Seismic Hazard Model (NSHM), which in turn helps to drive earthquake-resistant building construction in the United States. The NSHM Project (NSHMP) is ultimately an end user of NEIC data and products, and as such consistency between NEIC and NSHMP goals should also be a target of this plan. Each of these ANSS-focus topics is considered when prioritizing NEIC goals for the next 5 years.

Internationally, NEIC will continue to envision innovative seismological tools and impact assessment strategies as a forum for the international exchange of earthquake information. In terms of personnel and funding perspectives, NEIC needs the spare capacity to move beyond operational exhaustion to take advantage of rapidly changing technological, computational, and crowdsourcing (citizen-science) opportunities in the international arena to better our science, operations, and information systems.

In the sections that follow, we outline NEIC-prioritized strategic goals, broken into two lists. These lists are ordered based on the NEIC current priorities; however, this ordering may change as a result of evolving external input, projects or opportunity, and required resources for the specific goals. The first (Foundational List A) describes existing operational efforts that must be continued over the next several years to achieve existing NEIC targets, and to provide a solid monitoring capability on which future work can be built. The second (Aspirational List B) outlines predominantly new directions seen as critical for NEIC advancement into the future of earthquake monitoring, and to maintain its position at the cutting-edge forefront of that field.

Foundational List: Existing Operational Considerations that Should Continue

A1. *Regional Monitoring and ANSS interactions.* As part of its mission, NEIC monitors domestic earthquakes across the United States, serving as the authoritative source in regions not covered by an ANSS RSN and as a backup in regions covered by an RSN. NEIC has placed additional emphasis on this domestic monitoring in recent years, particularly in the central and eastern United States, because of the increasing prevalence of induced seismicity, the loss of an RSN in the northeastern United States, and with the enhanced seismic station coverage of the recently formed 145-station N4 network (https://www.fdsn.org/networks/detail/N4/). This increased focus on regional monitoring motivates improved coordination with RSNs, as well as improvements to critical systems (for example, Foundational List item A2). With increased funding, these efforts can help reduce the NEIC magnitude of completeness for central and eastern United States regional monitoring from M 3.0 down to M 2.5.

A2. *Earthquake Detection and Association.* Earthquake monitoring efforts require sophisticated tools to analyze seismic data streams in order to detect and associate earthquakes. This element requires research into and implementation of algorithms to better detect and locate earthquakes at local, regional, and teleseismic distances. These efforts are underway and need to be continued and refined in the near term (for example, multiple frequency band picker, Kurtosis detection, subspace detection, correlation detection, Global Associator 3 [GLASS3; see figs. 2 and 3]).

A3. *Comprehensive Catalog (ComCat).* The goal of ComCat is to provide a comprehensive, reference database of earthquake source parameters, macroseismic observations, impact assessments, and related metadata and information. Further work is needed to achieve this goal, including the completion of the loading of regional seismic network historical catalogs; systematic catalog quality control, the incorporation of assigned macroseismic intensities, the integration of improved earthquake catalogs from special studies (for example, Aspirational List item B6, below); improvements to how individual events can be updated (for example, updating magnitudes for old earthquakes); and expansion of ComCat to include innovative new products (for example, sequence-based products; Aspirational List item B7, below). Importantly, ComCat is currently not the catalog of choice for NSHM products, because of issues related to earthquake location and particularly magnitude consistency (for example, Foundational List item A5). Efforts to improve ComCat should target an ancillary goal of making this the reference earthquake catalog for the NSHM. Increased funding will be necessary to propagate any improvements to the quality of future earthquake source parameters back through the historical catalog, to maintain its consistency through time. Significant work is also necessary on the development of tools to extract source parameter data from ComCat (fig. 4); such work is achievable with an increase to base funding.

A4. *Systems Infrastructure.* Significant effort has been made over the past approximately 10–15 years to overhaul NEIC processing systems, creating a more open, robust, modular, and scalable environment. This includes an effort currently (2019) in progress to migrate the Hydra database from Oracle to Postgres—an effort that will require ongoing support and improvements once the main thrust is complete. Other large-scale efforts include leveraging the cloud for access to high-performance computing and ease of operation, and a migration of Hydra Graphical User Interfaces (GUIs) from Windows to platform-independent, web-centric GUIs, which will integrate well with cloud-friendly approaches. These efforts would improve efficiencies while also reducing long-term operational costs.

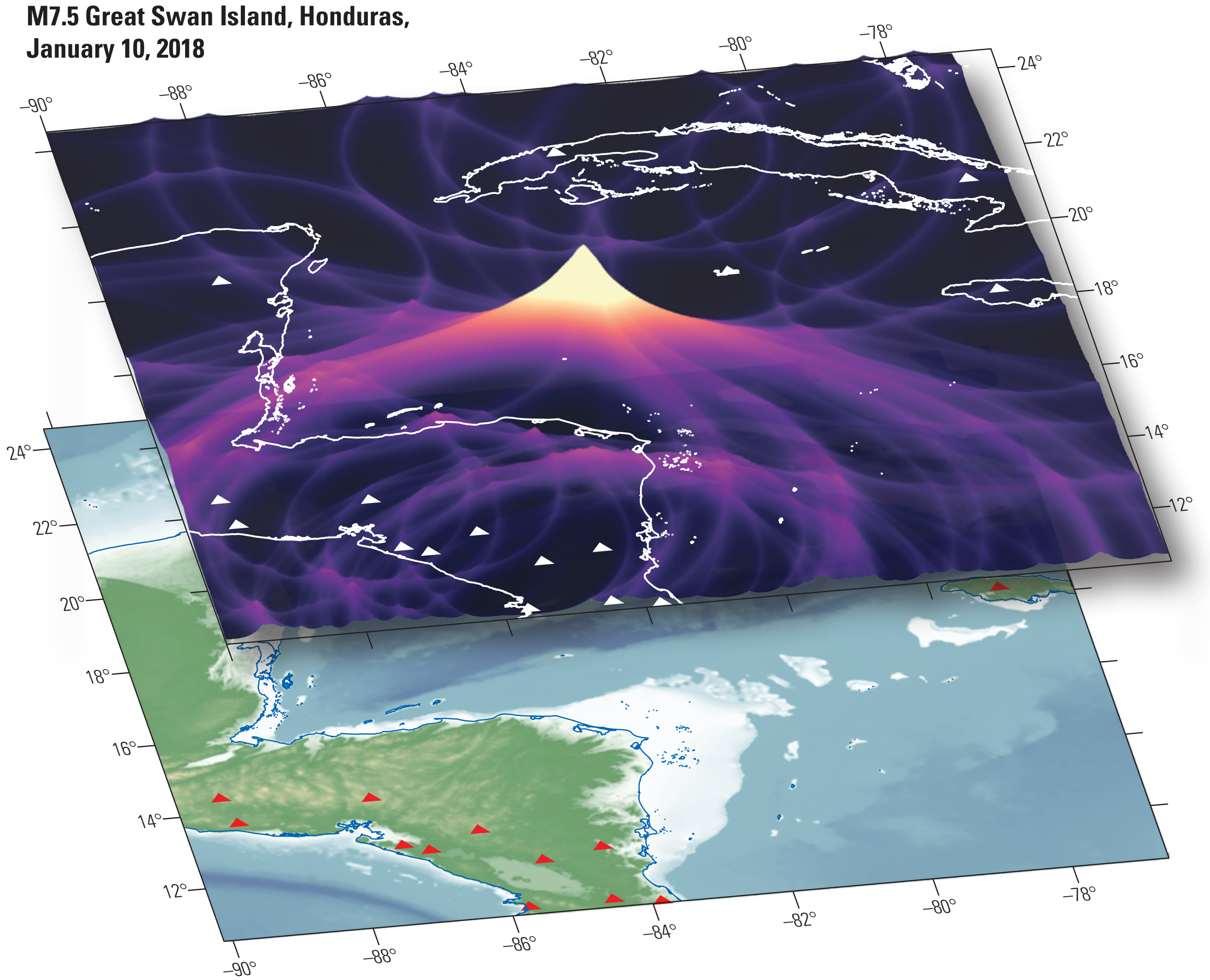


Figure 2. Nucleation stack for a large earthquake in the new GLASS3 associator (Foundational List items A1 and A2). Color and height in the top panel represent a summed probability density function for earthquake nucleation, based on contributions from regional seismic stations (gray triangles). The lower panel shows a shaded bathymetric map overlain with the station distribution (red triangles) in this region (M, magnitude).

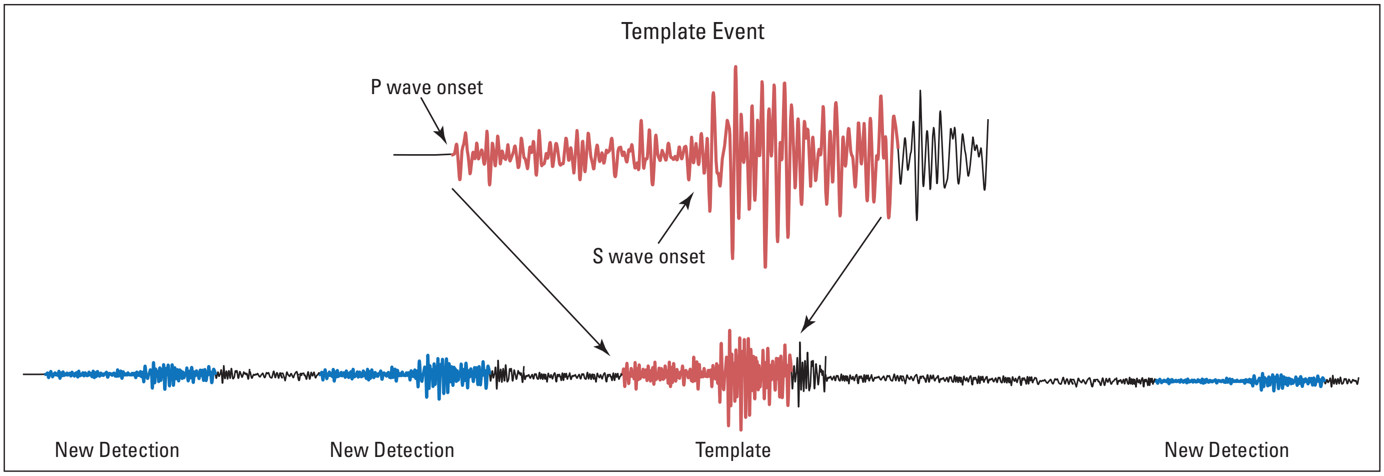


Figure 3. Earthquake-based correlation template (top, red) and subsequent detections (bottom, blue) in continuous waveform data (Foundational List items A1 and A2).

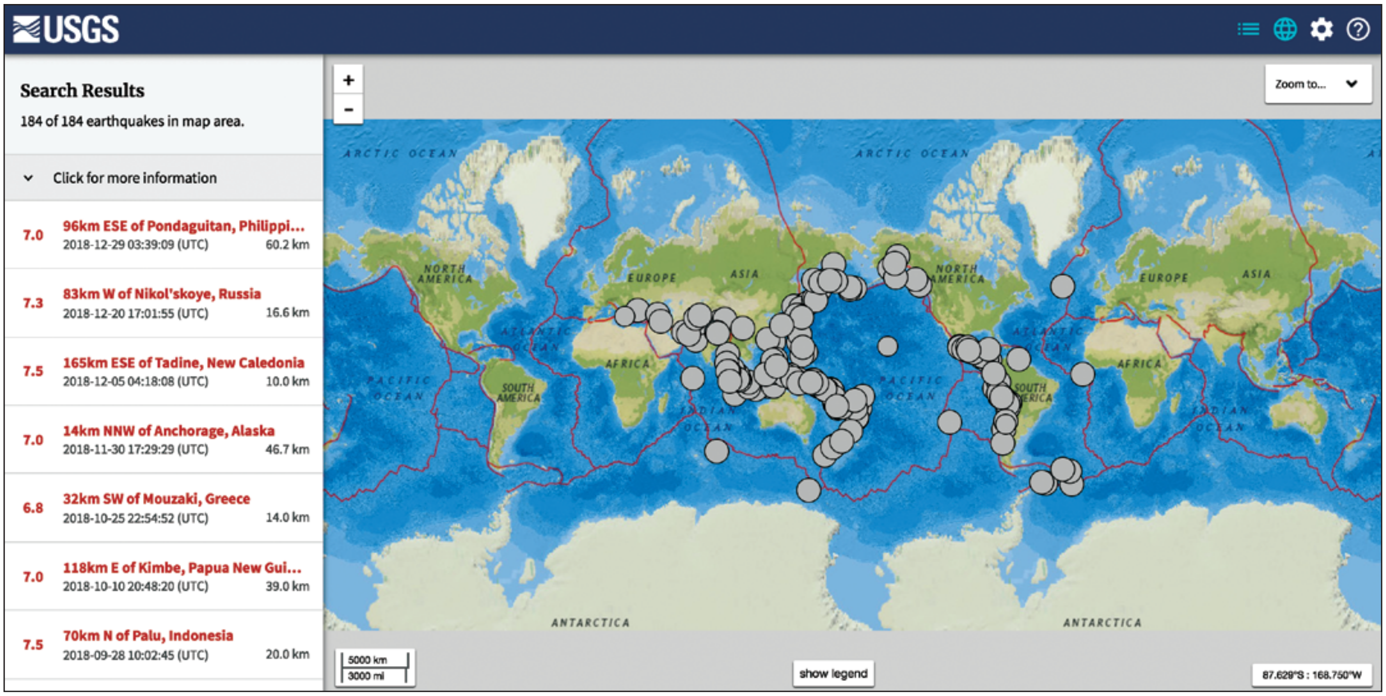


Figure 4. Comprehensive Catalog display of 168 magnitude 6.9–9.1 earthquakes with finite fault models published during the time period 1990–2017 (Foundational List item A3).

A5. *Calibration of Magnitude Scales at Small M.* Small magnitudes are characterized using a variety of methods and magnitude scales within the NEIC, across ANSS RSNs, and at other global seismic networks contributing to ComCat. These methods differ in important but poorly characterized ways (for example, fig. 5) and can thus lead to inconsistencies in ComCat. Efforts to resolve this issue are needed on at least three fronts: (1) improve documentation of existing methods; (2) calibrate and (or) adjust the methods employed to improve consistency; and (3) explore new methods for estimating more accurate moment magnitudes for small earthquakes. The latter issue is especially important for the production of an accurate and consistent earthquake catalog down to low magnitude—a key input to the NSHM. Exploratory research is underway on these issues—increased funding would allow more rapid implementation of improvements into operations.

A6. *Impact Products (ShakeMap, ShakeCast, DYFI?, and PAGER).* The NEIC produces a suite of situational awareness products following major earthquakes. Effort is needed to continue their development as well as to add new products that improve our understanding of earthquakes and their effects in the immediate aftermath of a significant event. A wholesale reengineering and migration of ShakeMap, ShakeCast, DYFI?, and PAGER codes to the platform-independent Python3 code base is in progress; such software harmonization should continue. Efforts are underway to include assessments of landslide and liquefaction likelihood in the evaluation of impacts within the ShakeCast and PAGER systems. Significant effort is also being made to design credible earthquake scenarios in areas of the globe of specific interest to the United States (for example, U.S. Agency for International Development [USAID], U.S. Africa Command [AFRICOM]) and for use by the international community to assess earthquake risk in regions of high risk (Himalayas and Middle East). Domestically, efforts are underway to improve the content of PAGER alerts for U.S. earthquakes, involving the integration of PAGER and the Federal Emergency Management Agency (FEMA) Hazards U.S. (HAZUS) software to model and communicate losses into a readily digestible two-page summary. An example of the prototype twoPAGER product is shown in figure 6. Additional resources to acquire new and integrate existing strong motion data from both regional and global seismic networks in order to densify the available strong motion recordings, with particular focus on high-risk urban regions, would significantly improve the quality and resolution of shaking and impact products for earthquakes in these areas, which in turn can be used for response, to reduce disruption, and to guide rebuilding efforts in and after earthquake disasters.

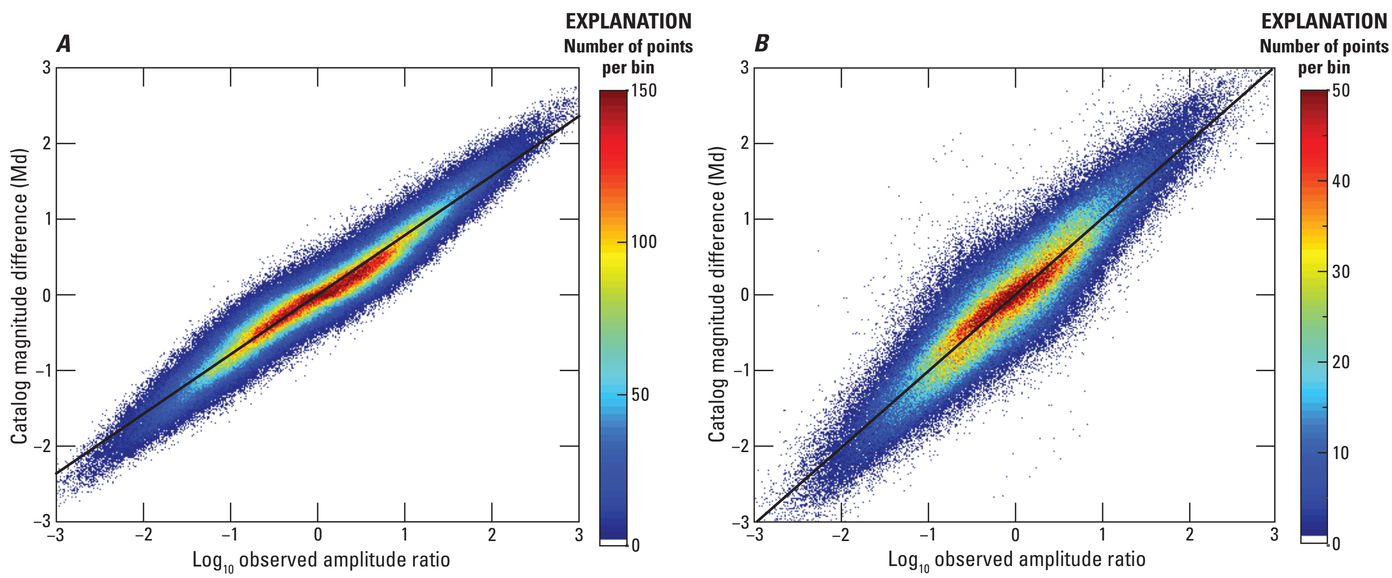
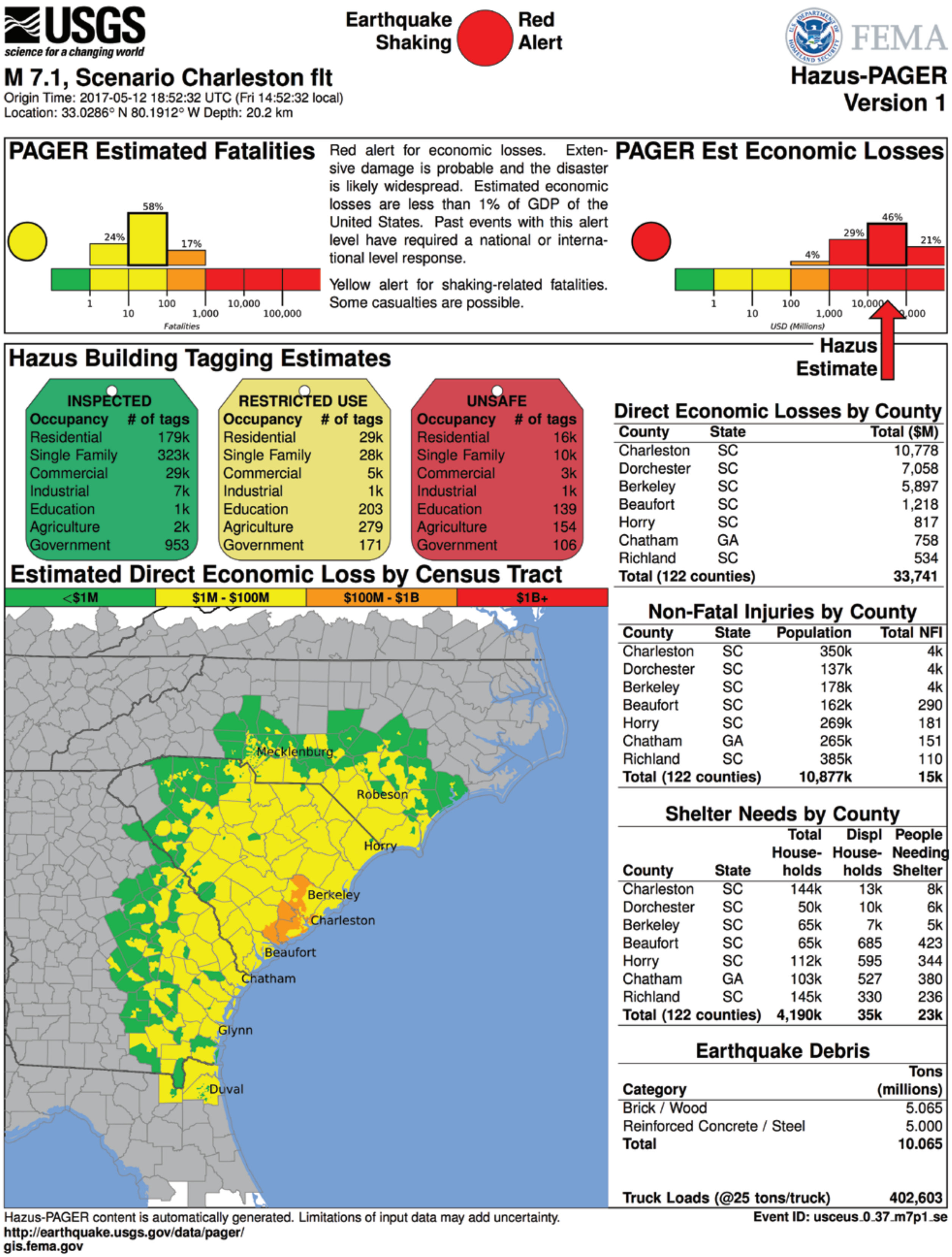


Figure 5. Catalog duration magnitude compared to station-specific amplitude (both taken as a ratio compared to a reference event) for *A*, the 2017 Yellowstone swarm, and *B*, the 2014 Long Valley swarm. Slope and scatter vary significantly between the two, illustrating that even though magnitude ranges are similar and relative amplitude measurements are the same, significant differences exist in magnitude computation between networks reporting to Comprehensive Catalog (Foundational List item A5).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Earthquake Shaking Red Alert

FEMA

M 7.1, Scenario Charleston flt

Origin Time: 2017-05-12 18:52:32 UTC (Fri 14:52:32 local)
Location: 33.0286° N 80.1912° W Depth: 20.2 km

Hazus-PAGER
Version 1

PAGER Estimated Fatalities

58%
24%
17%
1
10
100
1,000
10,000
100,000
Fatalities

Red alert for economic losses. Extensive damage is probable and the disaster is likely widespread. Estimated economic losses are less than 1% of GDP of the United States. Past events with this alert level have required a national or international level response.

Yellow alert for shaking-related fatalities. Some casualties are possible.

PAGER Est Economic Losses

46%
29%
21%
4%
1
10
100
1,000
10,000
USD (Millions)

Hazus Estimate

Hazus Building Tagging Estimates

INSPECTED Occupancy	# of tags
Residential	179k
Single Family	323k
Commercial	29k
Industrial	7k
Education	1k
Agriculture	2k
Government	953

RESTRICTED USE Occupancy	# of tags
Residential	29k
Single Family	28k
Commercial	5k
Industrial	1k
Education	203
Agriculture	279
Government	171

UNSAFE Occupancy	# of tags
Residential	16k
Single Family	10k
Commercial	3k
Industrial	1k
Education	139
Agriculture	154
Government	106

Estimated Direct Economic Loss by Census Tract

<$1M | $1M - $100M | $100M - $1B | $1B+

Mecklenburg
Robeson
Horry
Berkeley
Charleston
Beaufort
Chatham
Glynn
Duval

Direct Economic Losses by County

County	State	Total ($M)
Charleston	SC	10,778
Dorchester	SC	7,058
Berkeley	SC	5,897
Beaufort	SC	1,218
Horry	SC	817
Chatham	GA	758
Richland	SC	534
Total (122 counties)		33,741

Non-Fatal Injuries by County

County	State	Population	Total NFI
Charleston	SC	350k	4k
Dorchester	SC	137k	4k
Berkeley	SC	178k	4k
Beaufort	SC	162k	290
Horry	SC	269k	181
Chatham	GA	265k	151
Richland	SC	385k	110
Total (122 counties)		10,877k	15k

Shelter Needs by County

County	State	Total House-holds	Displ House-holds	People Needing Shelter
Charleston	SC	144k	13k	8k
Dorchester	SC	50k	10k	6k
Berkeley	SC	65k	7k	5k
Beaufort	SC	65k	685	423
Horry	SC	112k	595	344
Chatham	GA	103k	527	380
Richland	SC	145k	330	236
Total (122 counties)		4,190k	35k	23k

Earthquake Debris

Category	Tons (millions)
Brick / Wood	5.065
Reinforced Concrete / Steel	5.000
Total	10.065
Truck Loads (@25 tons/truck)	402,603

Hazus-PAGER content is automatically generated. Limitations of input data may add uncertainty.
http://earthquake.usgs.gov/data/pager/
gis.fema.gov

Event ID: usceus_0_37_m7p1_se

Figure 6. Example of second page of twoPAGER for a magnitude 7.1 scenario modeled after the 1886 Charleston, South Carolina, earthquake. Top portion depicts PAGER loss model estimates; the lower portion presents Hazards U.S. (HAZUS) loss model estimates. The alert level, color-coded arrow connects the loss models, allowing PAGER and HAZUS economic loss model comparison (Foundational List item A6).

A7. *ANSS performance in crisis situations—RSN backup and response coordination.* ANSS is a system made up of many subcomponents, including the ANSS RSNs. One of the roles of the NEIC is to serve as an essential national core ANSS component that coordinates with RSNs and serves as their backup during times of crisis. Work is needed to improve NEIC coordination and backup planning with RSNs in the likelihood of reduced RSN response capacity after a significant domestic earthquake. Planning exercises by scenario drills and group analyses of network and operational resilience are fundamental. The complete loss of ANSS data flow from the Puerto Rico Seismic Network following Hurricane Maria in September 2017 illustrates how improvements are needed in this area.

A8. *International Network Collaborations.* In the backup and coordination role NEIC operates for the RSNs, there is mutual benefit through exchange of information, data, and skills. Similar benefits can be realized through direct interaction with other monitoring agencies worldwide, through the exchange of real-time waveform and parametric data, earthquake information and expertise (for example, fig. 7). Work to achieve similar goals has been conducted bilaterally in Chile (with the National Seismological Center of Chile [CSN]), Nicaragua, and Cuba in the past 5 years, and will continue in other regions of interest, such as New Zealand (with GNS Science, New Zealand [GNS]), Ecuador, and Peru. These efforts involve both knowledge transfer, and the cooperative (and coordinated) sharing of important real-time information and earthquake data. This work is directly supported by the Office of Foreign Disaster Assistance (OFDA), and directly parallels efforts initiated at the PCWGEM (Sidebar 1). In addition to existing efforts, coordination and collaboration should be increased with other global monitoring entities, such as the NEIC counterpart at the CTBTO, Federation of Digital Seismic Networks (FDSN),

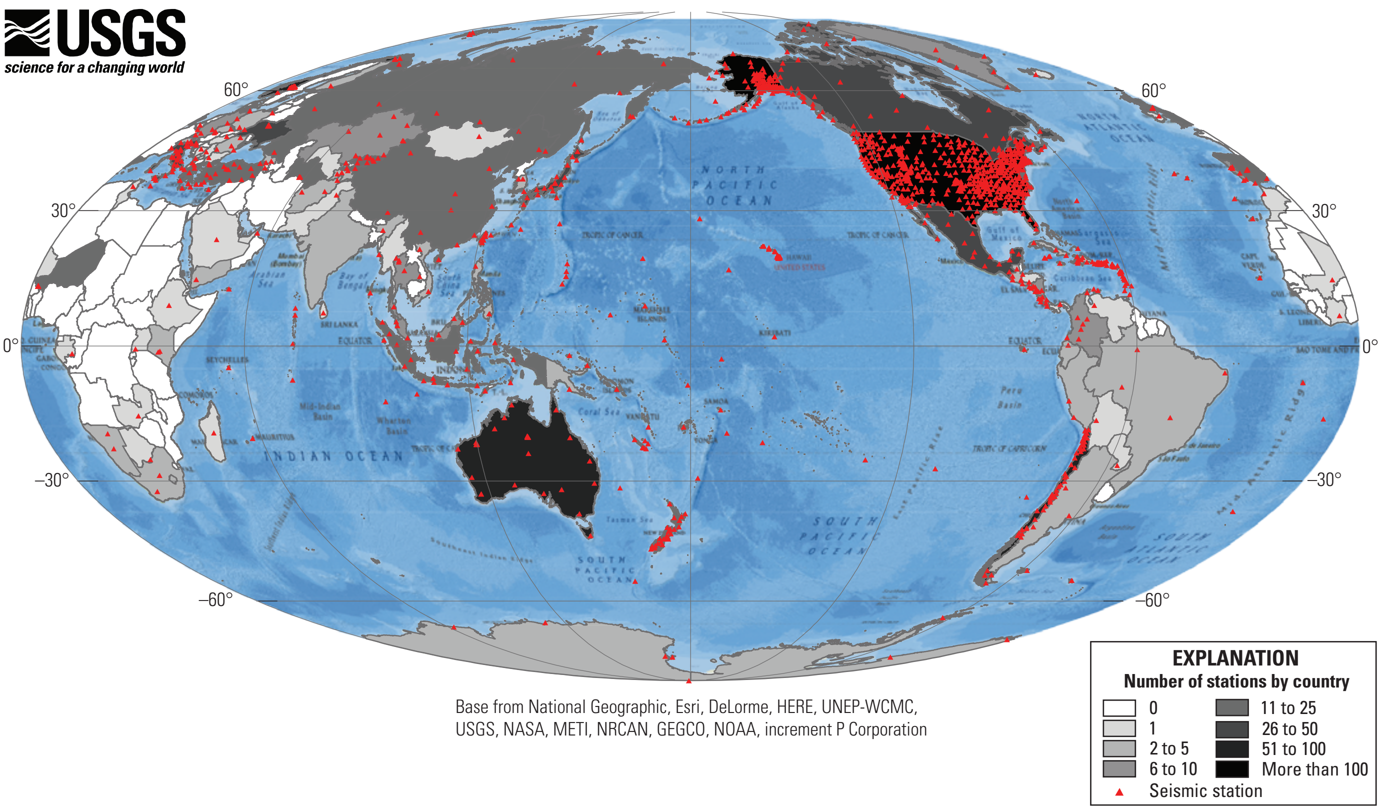


Figure 7. Global distribution of real-time seismic waveform data in use at the National Earthquake Information Center (NEIC) (Foundational List item A8). (Esri, Environmental Systems Research Institute; UNEP-WCMC,UN Environmental World Conservation Monitoring Centre; USGS, U.S. Geological Survey; NASA, National Aeronautics and Space Administration; METI, Ministry of Economy, Trade and Industry; NRCAN, Natural Resources Canada; GEGCO, Global Education Group; NOAA, National Oceanic and Atmospheric Administration.

Air Force Technical Applications Center (AFTAC), German Research Center (GFZ), the International Seismological Centre (ISC), the Euro-Med Seismic Center (EMSC), the National Institute of Geophysics and Volcanology in Italy (INGV), the Swiss Seismological Service (SED), the GEOSCOPE Observatory in France, the National Seismological Service of Mexico (SSN), Japan Meteorological Agency (JMA), and others.

A9. *Integrated Portable Deployments.* For domestic earthquakes of interest, NEIC scientists engage with the USGS Albuquerque Seismic Laboratory (ASL) and relevant RSNs to deploy temporary instruments in the region surrounding such events, to better record aftershocks, characterize ongoing seismicity and to record near-field strong motions. Additional funding would be required to expand these efforts (for example, to seamlessly include more instruments in any given deployment, and explore the use of smaller and (or) less costly sensors).

A10. *Pre-Positioned Earthquake Content.* Regionally specific, historical earthquake, seismotectonic, and impact content should be pre-positioned (databased) in order to facilitate improved links between events (context-based processing; see fig. 8). This and other information can be leveraged to expand NEIC's regional seismotectonic poster series to include areas of the western United States, for example, Intermountain West, Pacific Northwest, and California. Increased funding levels would allow NEIC to explore intelligent and automated reformatting of prepositioned information such that content related to a new event (or the region of a new event) is presented first.

Aspirational List: Opportunities for Operational and Research Innovation

B1. *Use of Machine Learning to Improve Monitoring Operations.* Because analyzing earthquakes requires human involvement, NEIC is staffed by a team of analysts, 24/7. Recent advances in the use of machine learning may in the near future make a variety of time-intensive processes more automated. When trained on a historical dataset of catalog picks, machine-learning algorithms have been shown to be capable of detecting earthquakes (and other similar signals; for example, Ross and others, 2018) and accurately picking phases from new seismic waveform data. This would be of great value to the NEIC analysts as a means of reducing their workload as magnitude thresholds are lowered, completeness improves, and monitoring networks are densified. Machine learning is also an ideal approach to discriminate between tectonic earthquake signals and other seismic sources, such as blasts, explosions, and volcano seismicity. Effort is needed to implement such tools in an operational framework over the next several years. Additional resources are necessary to more rapidly expand the use of machine learning into routine operations.

B2. *Earthquake Location Improvements.* Seismic arrays are systems of seismometers that are generally distributed over a relatively small geometrical footprint in a regular pattern to increase sensitivity to seismic signals. NEIC routinely receives seismic array data from organizations such as AFTAC and uses these data to aid earthquake processing by reducing signal-to-noise ratios in stacked signals. Such data can be better used in earthquake detection and association, for example, by making use of back azimuth and slowness information gathered when beamforming a given array. Additional resources are necessary to implement the use of higher-order seismic array processing in the NEIC detection and association workflow. Earthquake locations can also be improved by migration from the use of one-dimensional to three-dimensional velocity models. While it is not yet tractable to trace rays in three dimensions in real time, funding increases would facilitate research efforts to build a database of rays traced through a three-dimensional velocity model from node to node on a global grid, which can then be used rapidly in real time in a lookup framework.

B3. *Systems Infrastructure Expansion*. As discussed in Foundational List item A4, much effort has been expended at the NEIC to create and maintain a reliable system of earthquake monitoring operations. To continue to meet NEIC 24/7 demands while keeping pace with technological and scientific advances, additional resources are necessary to explore how NEIC can best leverage infrastructure resources in the cloud. Such work will be vital as NEIC moves toward more rapid and accurate solutions through the use of machine learning (Aspirational List item B1) requiring graphics processing units (GPUs) and state-of-the-art detectors and associators that in turn also require High Performance Computing (HPC). Cloud resources are also readily scalable, to accommodate on-demand processing needs as earthquakes are occurring.

B4. *Timeliness of Public Release of Earthquake Information*. At present, NEIC earthquake solutions for global earthquakes are released within approximately 20 minutes of the event occurring. This time allows a more accurate characterization of the earthquake location and magnitude than is afforded by more rapid analyses; since

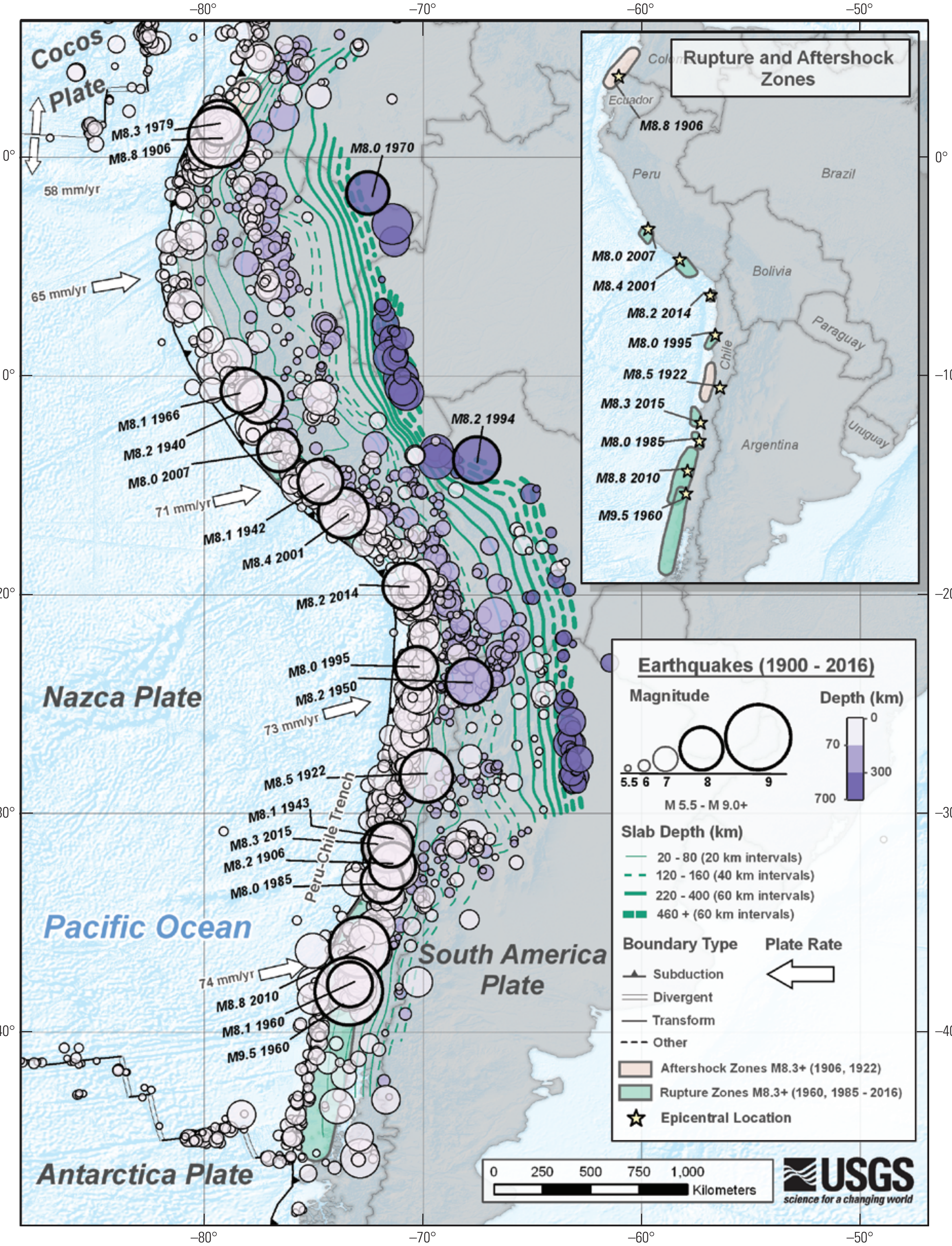


Figure 8. Seismotectonic map of South America describing the history of large earthquakes in the region and the broad tectonic controls on those events. This and other similar maps for other regions, accompanied by a regional tectonic summary, populate earthquake event pages automatically when new solutions are published (M, magnitude; km, kilometer; mm/yr; millimeter per year) (Foundational List item A10).

location accuracy is particularly critical for NEIC flagship products like ShakeMap and PAGER, the NEIC has generally resisted calls to provide more rapid earthquake solutions. However, as data coverage expands and our processing capabilities improve, the ability of NEIC to provide accurate information on quicker timescales should be reassessed. Two issues—speed and early information content—should be addressed regarding the release of earthquake information. First, NEIC should explore challenging the speed of other agencies (for example, NOAA TWCs), with the ultimate goal of making NEIC earthquake response operations faster. Concurrently, with the same goal in mind, NEIC should explore the viability of releasing automatic earthquake solutions, prior to more detailed human review. A comprehensive assessment of the quality and completeness of automatic solutions compared to more detailed reviewed solutions must be conducted before any decision can be made regarding whether future changes are possible. It is important to balance accuracy with speed; the former cannot be significantly diminished to achieve the latter. A second issue to consider is that information content of an earthquake release can evolve, and the first release does not necessarily have to include a magnitude. For example, NEIC could migrate to a system in which the first information that is released about an event notifies users of an earthquake occurring in a broad region, without assigning a magnitude (for example, major earthquake in Montana). Subsequent information can be layered onto previous versions in this emergent solution framework. This approach could eventually help bridge the gap between traditional solutions and EEW; *earthquake alerts* may sometimes occur prior to shaking in a given region, and sometimes soon after; either way, they can be rapid. Likewise, downstream products could await authoritative solutions with differing criteria depending on the application. For example, the ShakeMap and PAGER systems may stand down until stable magnitude and depth determinations are achieved.

B5. *Geodetic data (real-time Global Positioning System (GPS), optical, Interferometric Synthetic-Aperture Radar (InSAR) geodesy; rupture modeling).* While standard seismic instrumentation typically used by monitoring networks for earthquake detection and characterization can suffer from tilting, rotation, and clipping in the near field of large earthquakes, geodetic observations, specifically high-rate Global Navigation Satellite Systems (GNSS) displacements, provide direct measurements of the associated large static and dynamic ground displacements of such events. Other types of geodetic data (InSAR, optical imagery) can be used to directly study properties of an earthquake rupture and have been shown to complement, and in some cases to improve upon, similar analyses that use only seismic data. As the use of geodetic data in studies of earthquakes expands, and becomes closer to real time, so does our need to incorporate such data into routine earthquake processing and analyses. Optical imagery, GPS, and InSAR data can be systematically incorporated into post-event characterization work such as damage detection, fault displacement, and rupture modeling (for example, fig. 9); these efforts are underway and should be enhanced. Real-time GPS (GNSS) data can also be used for event detection and magnitude characterization, at potentially faster speeds than globally distributed broadband seismic data in some densely instrumented locations (for example, Melgar and others, 2015; Goldberg and others, 2018). As such, and with increased funding, the NEIC should begin the incorporation of available domestic and international real-time GPS data into routine earthquake processing, as additional time series that can be used for event detection, location, and magnitude characterization.

B6. *Seismotectonic studies of aftershock sequences (earthquake sequence characterization).* Studies of active earthquake sequences or those of special interest (for example, in subduction zones; fig. 10) which integrate all monitoring improvements (detection, association, and location) and earthquake characterization products (earthquake relocation, sequence characterization, fault modeling, and stress modeling), create a conduit of these operational efforts to the community, and in turn facilitate further improvements to operations. These studies also have direct applications for operational aftershock forecasting (OAF), with statistical or stress change models that, for example, forecast aftershock distributions from estimates of mainshock slip distribution (finite-fault models). With increased funding levels, the viability of producing and providing new informational products related to aftershock sequence monitoring and aftershock forecasting can be assessed and communicated to users.

B7. *Event-Based Products.* For a given moderate-to-large earthquake, the NEIC generates a suite of products to describe the events' source characteristics and potential impact. Effort is necessary to maintain the level of service and excellence achieved by the NEIC in recent years, and to sustain the timely reporting of earthquake response products. Additional resources are necessary to expand these products, to more effectively communicate earthquake hazard analyses and research, and to promote corresponding mitigation efforts. For example, linking to Aspirational List items B4 and B6 above, the development of earthquake-sequence-specific products (linking foreshocks, mainshocks,

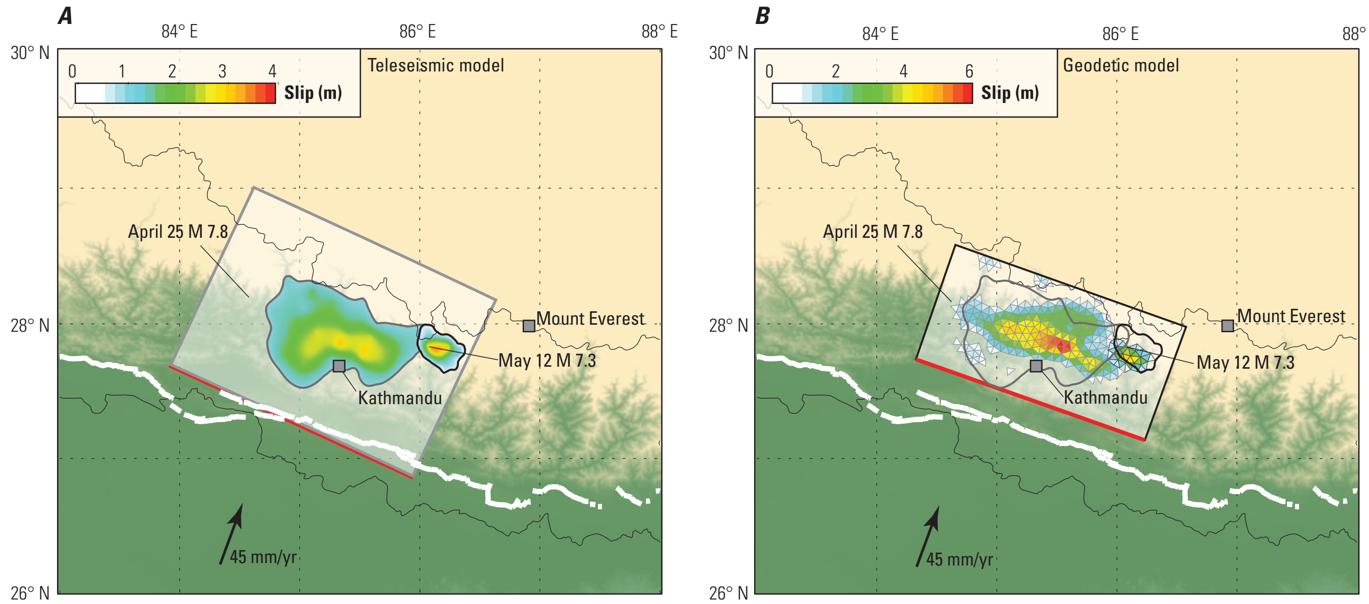


Figure 9. Teleseismic (*A*) and geodetic (*B*) finite fault models for the 2015 magnitude 7.8 Gorkha, Nepal earthquake, produced by National Earthquake Information Center in the days following the earthquake (m, meters; M, magnitude; mm/yr, millimeters per year) (Aspirational List item B5).

and aftershocks; generating sequence-specific statistics; generating sequence-specific visualizations; for example, fig. 11) would facilitate NEIC moving away from a single-event mindset, to a more integrative, dynamic, and context-based framework where users can easily understand the relations between nearby events in space and time.

B8. *Event Page and Product Evolution.* Effort is required to add an evolutionary component to NEIC event pages and products, such that as we learn more about a given earthquake, and as the communities we serve desire to know more detail, our public-facing information for that event also updates and evolves. This information should evolve on several time scales: frequently in the days immediately following an event of interest, up to a week after the event, and then again after a month when more detailed event characterization is complete. This work naturally links to Aspirational List items B6 and B7 above. However, to execute this well, consistently for all relevant events, and with an appropriate level of detail, additional resources will likely be required.

B9. *Impact Product Evolution.* A potential breakthrough in terms of the accuracy and use of post-earthquake, response-oriented products would be the direct integration of ground truth information into shaking and impact modeled estimates. Similar to the way strong motion recordings and macroseismic data can ground truth ShakeMap, impact assessments can be better calibrated if a more consistent effort were made to gather post-event impact related data (for example, fig. 12). This could involve establishing in-country contacts around the world who can help guide information collection efforts, crowdsourced damage inventory collection, and (or) the incorporation of remotely sensed imagery of regions damaged by shaking and secondary effects.

B10. *Characterization of exotic events (for example, landslides, nuclear explosions, mine blasts, sonics; fig. 13).* Non-earthquake seismic events are currently characterized by the NEIC on an ad hoc basis, and often with a variable level of detail from event to event (dependent on interest). With existing funding, event-page templates that could be used for communicating our knowledge and understanding of non-earthquake events could be pre-positioned in order to be of timely use after such events. An increased level of funding would allow NEIC to improve our automatic characterization of such events, for example by leveraging improvements in machine-learning algorithms in concurrent development, leading to automated classification and cataloging of such events.

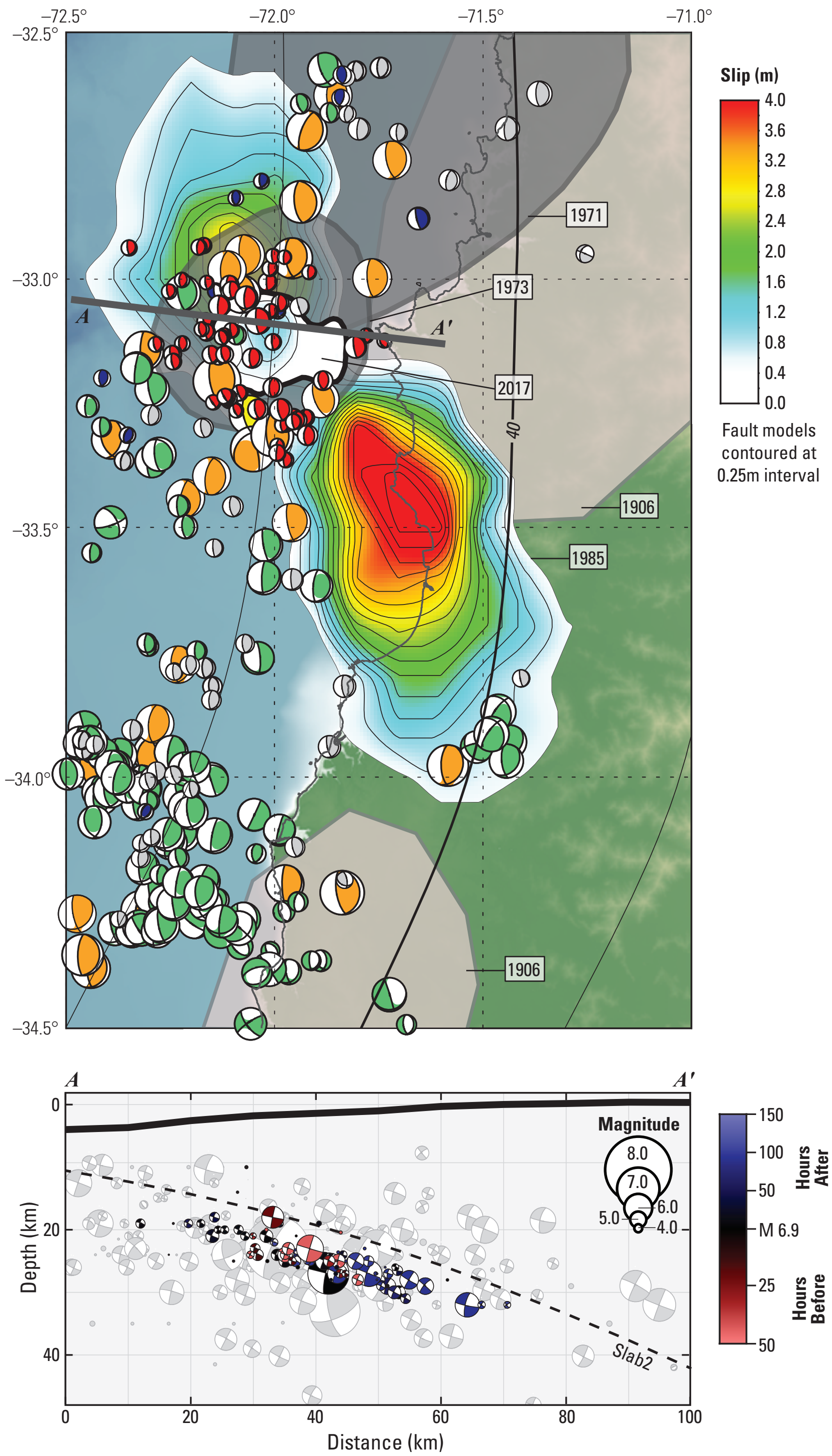


Figure 10. Finite fault models for the 1985 and 2017 Valparaíso, Chile earthquakes. The two-lobed model in the background is the slip model for the 1985 event. The smaller model between the two lobes of the 1985 model, outlined with a thick black line, is for the 2017 Valparaíso earthquake. The dark gray polygons show the aftershock areas of the 1971 magnitude 7.8 and 1973 magnitude 6.5 earthquakes. Orange focal mechanisms correspond to aftershocks of the 1985 Valparaíso earthquake; yellow are 1985 foreshocks; green are 2010 Maule aftershocks; blue relate to the 2015 Illapel event; red are the 2017 sequence; gray are background seismicity. The cross section (black line on the map) shows the depths of the 2017 Valparaíso sequence compared to the regional slab model. Valparaíso events with focal mechanisms are shown colored by time in relation to the mainshock. Comprehensive Catalog events with focal mechanisms up until April 20, 2017, are shown in gray (from Nealy and others, 2017). This illustrates the improved level of tectonic understanding facilitated by National Earthquake Information Center seismotectonic studies (m, meters; km, kilometers; M, magnitude) (Aspirational List item B6).

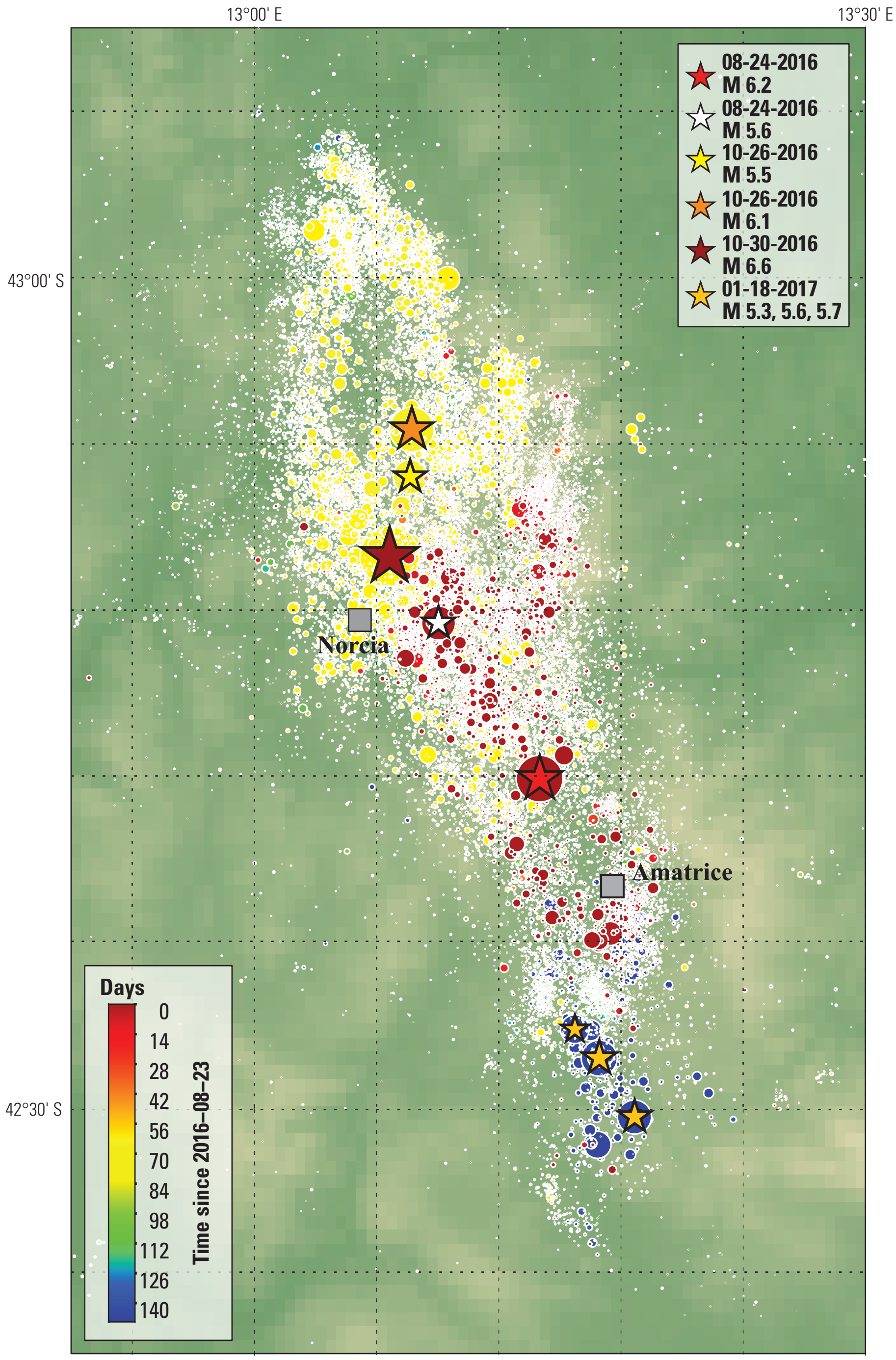
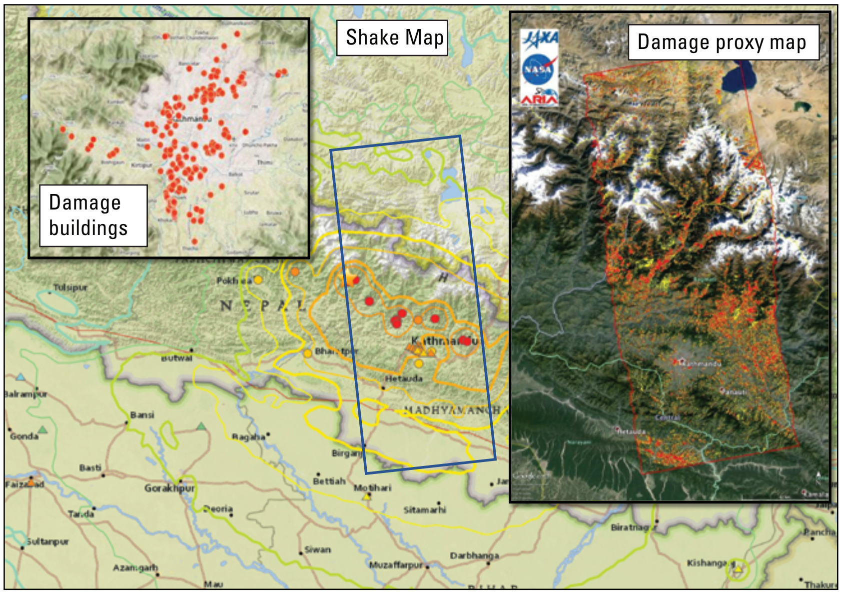


Figure 11. Example of how earthquakes could be associated in the Comprehensive Catalog to better characterize and display information related to earthquake sequences (Aspirational List items B6–8). Seismicity in central Italy during a series of moderate-to-large magnitude (M) earthquakes in August 2016–January 2017. Earthquakes are colored by time from the beginning of the sequence. Key events are labeled with stars and colored according to the inset. Earthquake data from National Institute of Geophysics and Volcanology in Italy earthquake catalog between August 24, 2016, and January 20, 2017 (Aspirational List item B7).



SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
DAMAGE	None	None	None	Very light	Light	Moderate	Moderate/heavy	Heavy	Very heavy
PGA (%g)	<0.05	0.3	2.76	6.2	11.5	21.5	40.1	74.7	>139
PGV (cm/s)	<0.02	0.13	1.41	4.65	9.64	20	41.4	85.8	>178
INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Scale based on Worden et al. (2012)

△ Seismic Instrument ○ Reported Intensity ★ Epicenter

Figure 12. Example illustrating the potential for combining reported building collapses around Kathmandu (left) for the 2015 magnitude 7.8 Gorkha, Nepal earthquake, with the U.S. Geological Survey Did-You-Feel-It? and ShakeMap (basemap), and National Aeronautics and Space Administration damage proxy map (right, from S. Yun, National Aeronautics and Space Administration, Jet Propulsion Laboratory) (Aspirational List item B9).

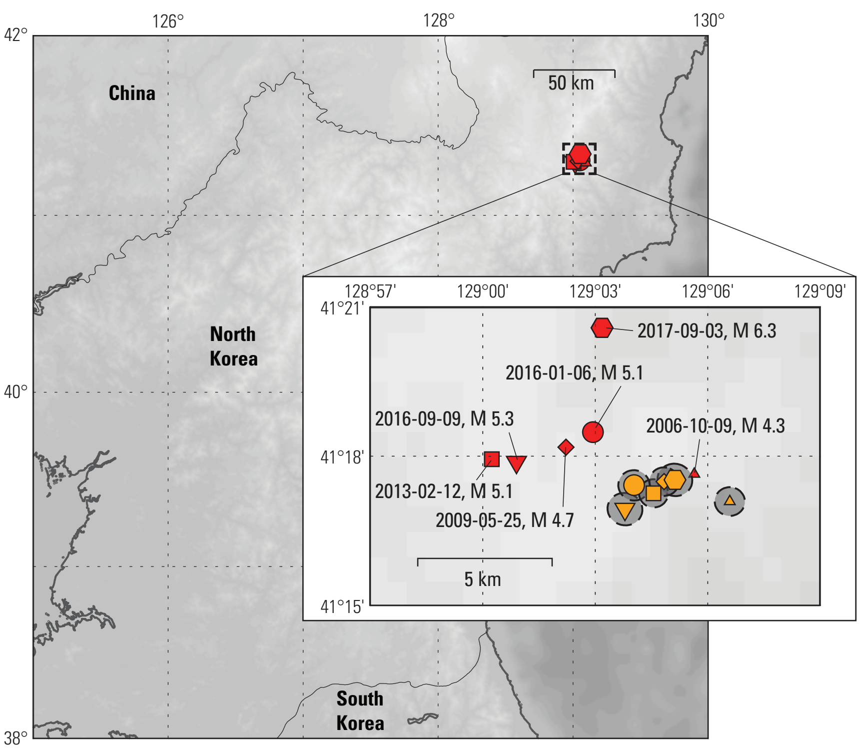


Figure 13. Single-event locations (red) and improved multiple-event relocations (orange) for North Korea nuclear tests (km, kilometers; M, magnitude; dates given as year, month, day). (Aspirational List item B10).

B11. *Subduction Zone Science.* Subduction zones produce the largest earthquakes globally and are home to a number of other important and costly hazards, such as volcanoes, landslides, and tsunamis. These can have significant economic and environmental impact and directly affect U.S. interests in Cascadia, Alaska, Caribbean, Guam, and American Samoa (see Circular 1428, Gomberg and others, 2017). Improving our knowledge of subduction zones and associated hazards ties into many of the key issues identified in both the Foundational and Aspirational Lists, and may further reduce risk. An example of recent efforts is NEIC research into the three-dimensional geometry of subduction zones (Slab1.0, Hayes and others, 2012; and Slab2, Hayes and others, 2018), which can help hazard characterization by improving our knowledge of the location and frequency of major earthquakes and by discriminating between different types of seismicity in these environments (for example, interface or intraplate earthquakes, which have different implications for potential ground motion). Additional work is needed from both monitoring and research perspectives and should include partnerships with other scientists and stakeholders. Increased funding levels would facilitate such work, leveraging improvements in technology and scientific understanding of subduction zone systems (fig. 14) to advance our monitoring and research efforts in these regions.

B12. *Real-time earthquake relocation (calibrated reference catalog, aftershock sequences).* Recent NEIC efforts in global monitoring have focused on enhancing event characterization by the improved definition of aftershock sequences and their relation to mainshock slip. The improved location (calibrated relocation) methods motivates a goal of the incorporation of relocation analyses into routine event processing that would rapidly improve the accuracy of real-time earthquake locations, with consequent improvements to downstream products as well. Such real-time relocation can take advantage of the catalogs of reference events, for example, calibrated locations that past studies have produced for global earthquakes in regions of interest (for example, Jordan and Sverdrup, 1981; Walker and others, 2011). A collection of calibrated relocations can be found at https://www.sciencebase.gov/catalog/item/59fb91fde4b0531197b16ac7. Improved earthquake location can also be achieved by the use of three-dimensional velocity models (Aspirational List item B2).

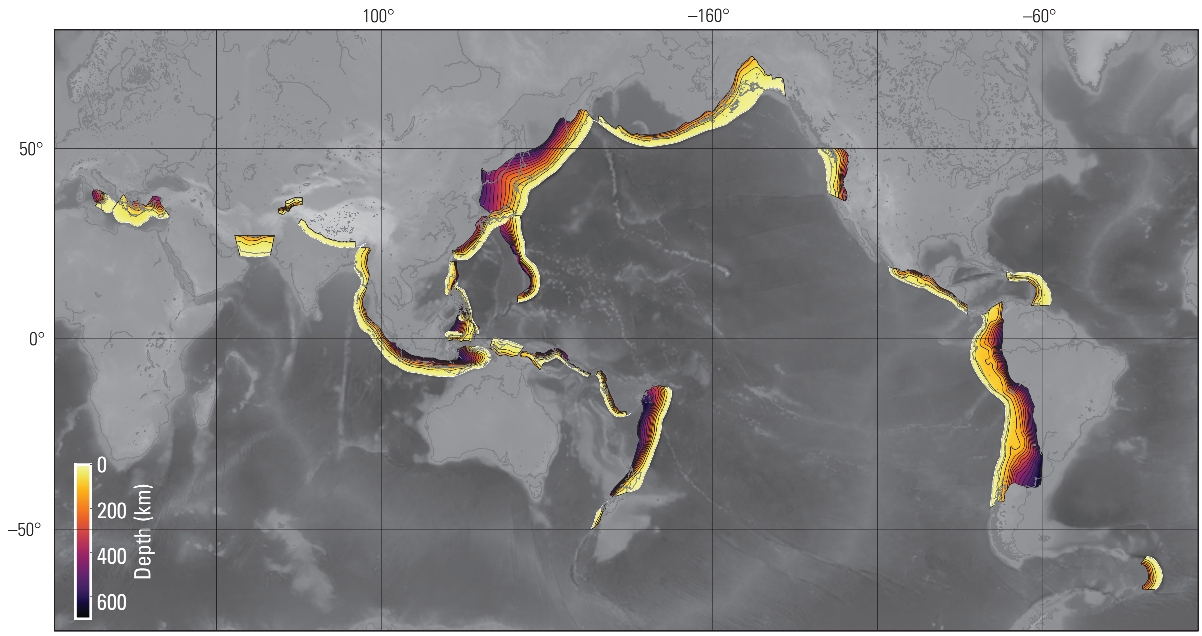


Figure 14. Subduction zone geometry models forming part of Slab2 (Hayes and others, 2018). Slab2 expands and improves on Slab1.0, a broadly used collection of models of global subduction zone geometries (km, kilometers) (Aspirational List item B11).

Conclusions

This plan outlines prioritized strategic goals for operations and research at the U.S. Geological Survey National Earthquake Information Center (NEIC) during the next five years (2019–23). Two targeted lists are provided: A Foundational List discusses existing critical efforts that should be continued in the near future to provide a solid foundation on which further work can be built. An Aspirational List describes new and innovative work that will move NEIC forward into the future of earthquake monitoring.

Several focused themes stand out as being especially important to NEIC monitoring goals:

- NEIC should finalize focused improvements in regional monitoring capabilities, while investigating and implementing cutting-edge earthquake detection and association algorithms (Foundational List items A1 and A2).

- NEIC anticipates major advances in earthquake monitoring through exploration of the use of machine learning to improve earthquake detection and source characterization. Earthquake locations can also be improved by taking better advantage of information provided by seismic arrays (Aspirational List items B1–3).

- When confronting a society that requires accurate information on rapid timescales, timeliness of earthquake information is becoming an increasingly important issue for NEIC to address. To further our efforts to that end, the incorporation of real-time Global Positioning System data into the NEIC operational workflow is necessary (Aspirational List items B4 and B5).

- NEIC can also significantly improve the information content and quality of the products we serve in a post-earthquake response framework, for example, by the production of sequence-specific earthquake products, evolution of earthquake content during the days and weeks following an important event, and further expansion of and improvements to our earthquake impact products (Aspirational List items B6–9).

Implementing these and other items described in both prioritized lists will allow NEIC to remain the leading resource for domestic and global earthquake information, and will further improve the timeliness, accuracy and efficacy of NEIC earthquake products to meet the evolving needs of the communities we serve.

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