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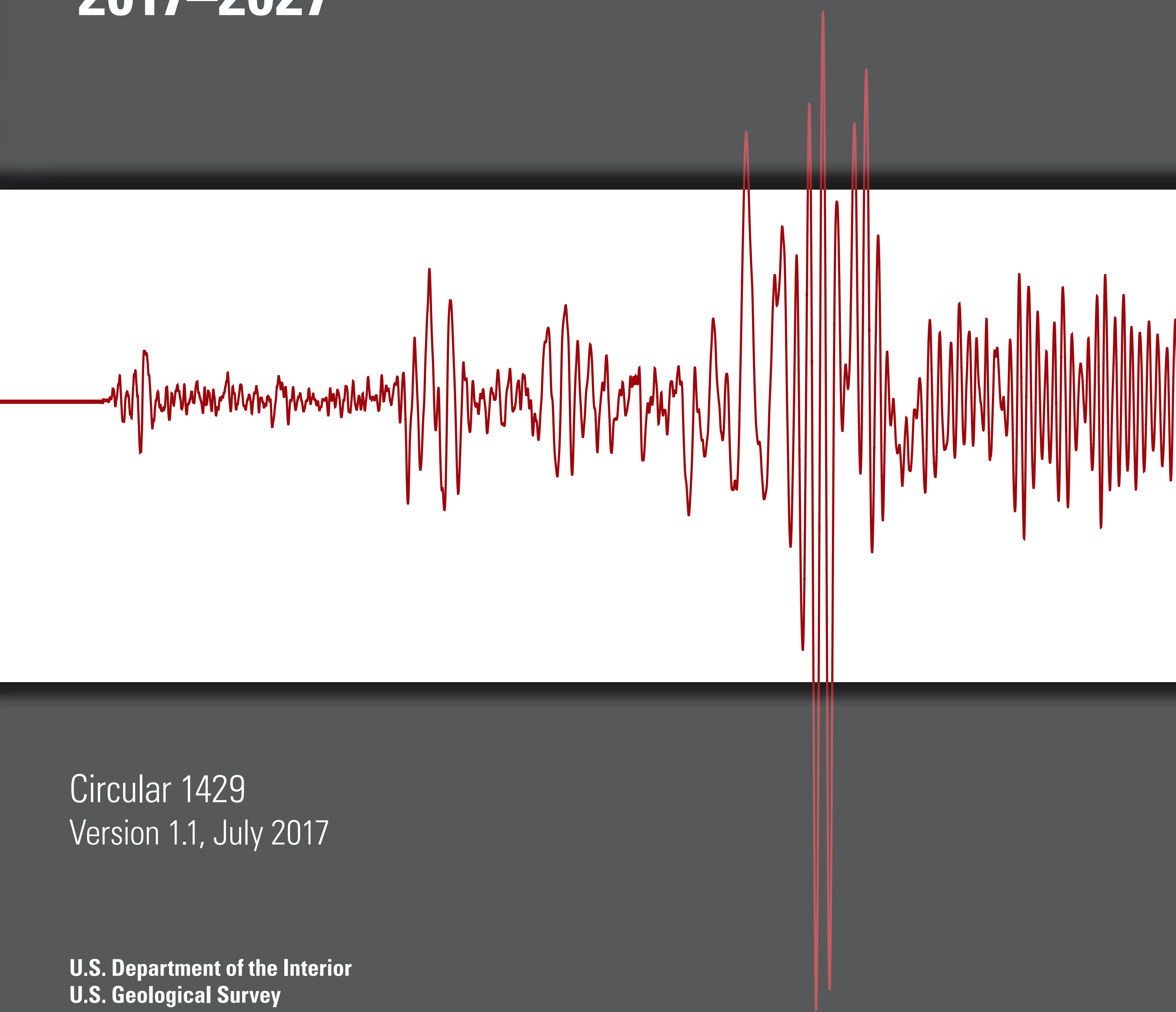
Advanced National Seismic System

Current Status, Development Opportunities, and Priorities for 2017–2027



Circular 1429
Version 1.1, July 2017

U.S. Department of the Interior
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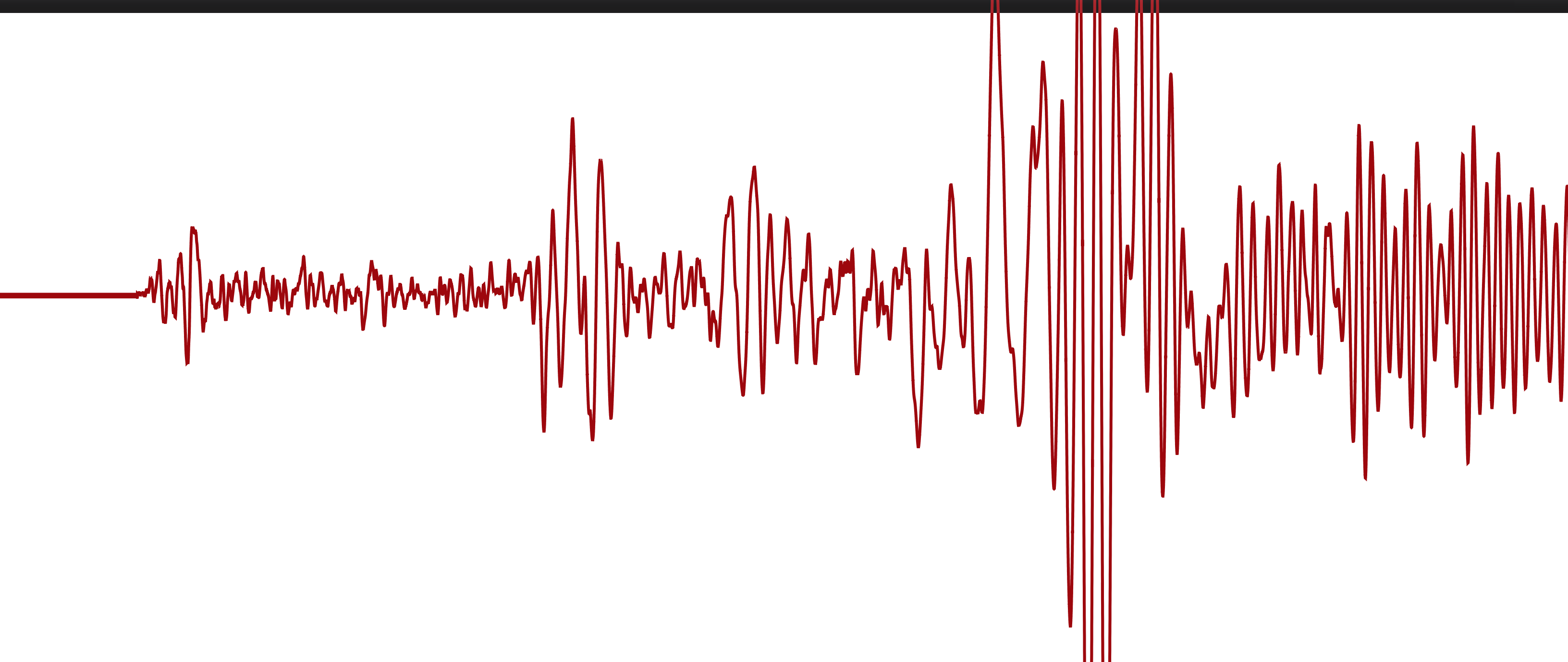

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U.S. Geological Survey

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

This Circular presents an updated strategic plan for the U.S. Geological Survey-led Advanced National Seismic System (ANSS). It was produced at the request of the ANSS National Steering Committee with input from all of those who cooperate in the ANSS. The ANSS is a cooperative effort that emphasizes regional implementation and national integration. Progress has been made possible by dedicated community, including the ANSS regions, organizations represented in the ANSS Steering Committee, and organizations participating in the ANSS, as highlighted below.

ANSS Regions

Alaska
California
Hawaii
Intermountain West
Central and eastern United States
Pacific Northwest
Puerto Rico and U.S. Territories

Organizations Represented in ANSS National Steering Committee

Association of American State Geologists
Consortium of Organizations for Strong Motion Observation Systems
Earthquake Engineering Research Institute
Incorporated Research Institutions for Seismology
National Emergency Management Association
Seismological Society of America
U.S. Geological Survey

Organizations Participating in ANSS in 2016

Alaska Earthquake Center, University of Alaska, Fairbanks
Center for Earthquake Research and Information, University of Memphis
Earthquake Center, Saint Louis University
Lamont-Doherty Cooperative Seismographic Network, Columbia University
Nevada Seismological Laboratory, University of Nevada, Reno
Pacific Northwest Seismic Network, University of Washington and University of Oregon
Puerto Rico Seismic Network, University of Puerto Rico, Mayagüez
Seismograph Stations, University of Utah
Seismological Laboratory, California Institute of Technology
Seismological Laboratory, University of California, Berkeley
South Carolina Seismic Network, University of South Carolina
U.S. Geological Survey (USGS) Earthquake Science Center, Menlo Park, Calif.
USGS Geologic Hazards Science Center, Golden, Colo.
USGS Hawaiian Volcano Observatory, Hawaii National Park, Hawaii

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This report was written by Cecily Wolfe and John Filson of the U.S. Geological Survey (USGS). This document benefitted from input from all of the Advanced National Seismic System (ANSS) community. Especially recognized for their contributions are the members of the ANSS National Steering Committee, the ANSS National Implementation Committee, and the Scientific Earthquake Studies Advisory Committee to the USGS Earthquake Hazards Program; and Greg Beroza of Stanford University; Bill Leith, David Applegate, Paul Earle, and Lind Gee of the USGS; and Walter Arabasz and Kris Pankow of the University of Utah.

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Abbreviations

ANSS	Advanced National Seismic System
ASL	Albuquerque Seismological Laboratory
Caltech	California Institute of Technology
CESMD	Center for Engineering Strong Motion Data
CEUSN	Central and Eastern United States Network
CGS	California Geological Survey
CISN	California Integrated Seismic Network
ComCat	ANSS Comprehensive Catalog
DOT	Department of Transportation
DYFI	Did-You-Feel-It?
EEW	earthquake early warning
ENS	Earthquake Notification Service
FEMA	Federal Emergency Management Agency
FY	fiscal year
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
IRIS	Incorporated Research Institutions for Seismology
M	magnitude
MEMS	micro-electro-mechanical system
NEHRP	National Earthquake Hazards Reduction Program
NEIC	National Earthquake Information Center
NOAA	National Oceanographic and Atmospheric Administration
NRC	U.S. Nuclear Regulatory Commission
NSF	National Science Foundation
NSHM	National Seismic Hazard Model
PAGER	Prompt Assessment of Global Earthquakes for Response
PBO	Plate Boundary Observatory
SESAC	Scientific Earthquake Studies Advisory Committee
USAID/OFDA	U.S. Agency for International Development, Office of Foreign Disaster Assistance
USGS	U.S. Geological Survey
VA	U.S. Department of Veterans Affairs

Advanced National Seismic System

Current Status, Development Opportunities, and Priorities for 2017–2027

By U.S. Geological Survey

Executive Summary

Earthquakes pose a threat to the safety of over 143 million people living in the United States. Earthquake impacts can be significantly reduced if communities understand their risk and take proactive steps to mitigate that risk. The Advanced National Seismic System (ANSS) is a cooperative effort to collect and analyze seismic and geodetic data on earthquakes, issue timely and reliable notifications of their occurrence and impacts, and provide data for earthquake research and the hazard and risk assessments that are the foundation for creating an earthquake-resilient nation.

As a result of investments made in the ANSS, any earthquake of significance in the United States or anywhere in the world can now be rapidly characterized by a suite of products, providing situational awareness during times of crisis. ANSS monitoring serves scientific research and earthquake engineering needs, including advancing the understanding of how buildings and other structures perform in an earthquake.

As one of four Federal agencies participating in the National Earthquake Hazards Reduction Program (NEHRP), the U.S. Geological Survey provides management and financial support for the ANSS. Congress established the ANSS as a NEHRP facility in the 2000 reauthorization of the NEHRP (Public Law 106–503).

The ANSS is a collaboration of Federal, State, and academic partners. Recognizing that earthquake hazard and risk varies from region to region, the ANSS management structure emphasizes regional implementation and national integration. Its organization allows collaboration with other Federal and State agencies and with the earth science and engineering communities with interests in seismic monitoring.

The ANSS promotes partnerships among those working at local, regional, and national levels committed to reducing earthquake losses. These partnerships are necessary in order for the ANSS to be coordinated nationally, designed and implemented regionally, and supported locally. Moreover, host academic institutions, some State agencies, other Federal agencies, private foundations, and scientific organizations have contributed support to ANSS growth and (or) operations.

The ANSS requirements were originally described in a U.S. Geological Survey (1999) publication entitled "An Assessment of Seismic Monitoring in the United States—Requirement for an Advanced National Seismic System"; these needs included strengthening coordination among the nation's monitoring networks, developing new earthquake information products, and expanding monitoring infrastructure nationwide. Since 2000, the ANSS has strengthened infrastructure and partnerships, and developed new earthquake information products and services. Although the funding to fully implement the ANSS vision has not been realized, at the end of fiscal year 2016 the ANSS achieved 42 percent of the goal set in 1999 for the installation of 7,100 modern seismic stations in the free field and in buildings, bridges, and other structures. The timeliness and usefulness of ANSS products have increased the expectations of its capabilities within government agencies, emergency responders, the public, and the engineering and scientific communities.

The reporting of earthquakes has been revolutionized as a result of ANSS investments. Notable ANSS products and services include immediate earthquake notifications to governments and emergency managers, rapid notification by email or text via the Earthquake Notification Service, earthquake source characteristics, ANSS websites with real-time earthquake information, a suite of real-time situational awareness products (ShakeMap, ShakeCast, Prompt Assessment of Global Earthquakes for Response [PAGER], Did-You-Feel-It?), a catalog of information (the ANSS Comprehensive Catalog), and products for engineers served by the Center for Engineering Strong Motion Data.

To meet the expectations of the next decade, the ANSS must focus on improving the robustness of essential services and retaining capacity for future innovation. The ANSS has the capacity to further improve earthquake safety and support response and recovery nationwide. This document 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. Additional funding would be necessary to realize these opportunities.

When the ANSS was formed, it was viewed as an innovative but risky endeavor, yet now it has proved successful despite being only partially funded. Resting on past accomplishments and accepting the status quo will increase exposure to earthquake risks as our nation grows and its structural systems expand and become more complex. To fully realize its loss reduction potential, the ANSS must move forward—the tectonic forces that cause earthquakes are relentless, they will not stop and neither can efforts to reduce their impacts throughout the Nation.

Introduction

Earthquakes are a national hazard (sidebar 1, p. 3), with more than 143 million people exposed to potentially damaging shaking in the United States (Jaiswal, Petersen, and others, 2015). There are tens of thousands of earthquakes above magnitude (M) 2.5 strong enough to be felt in the United States each year. Large earthquakes (≥M5) pose threats to the safety of individuals and to the national economy, infrastructure, and security.

Estimated long-term "annualized earthquake losses" from earthquakes in the United States are over $4.5 billion per year (Jaiswal, Bausch, and others, 2015). This estimate is only for building-related losses, and does not include components such as utility and transportation losses, business interruption, and the losses associated with deaths and injuries. The M7.8 1906 San Francisco earthquake is known as the most devastating U.S. earthquake on record, but the Nation's history contains many earthquakes whose repeat occurrence today would be catastrophic, including those in southeastern Missouri in 1811 and 1812 (three events greater than M7); southern California in 1857 (M7.9); Hawaii Island in 1868 (M7.9); Charleston, S.C., in 1886 (M7.3); the Pacific Northwest in 1700 (M9); and Alaska in 1964 (M9.2). Recent damaging earthquakes in the United States illustrate potential economic losses: $6 to $10 billion in Loma Prieta (M6.9, San Francisco, Calif., 1989), $20 billion in Northridge (M6.7, Los Angeles, Calif., 1994), and $2 billion in Nisqually (M6.8, Seattle, Wash., 2001). International examples include $100 billion in losses in Kobe, Japan (M6.9, 1995), $30 billion in Maule, Chile (M8.8, 2010), $30 billion in Christchurch, New Zealand (M6.1, 2011), and $300 billion in Tohoku, Japan (M9.0, 2011).

The Advanced National Seismic System (ANSS) is a cooperative effort to collect and analyze seismic and geodetic data on earthquakes, issue timely and reliable notifications of their occurrence and impacts, and provide data for earthquake research and the hazard and risk assessments that are the foundation for creating an earthquake-resilient nation. Life-saving and loss-reduction measures require accurate, timely earthquake information, and the benefits of fully deploying the ANSS far exceed the costs of building and operating it (National Research Council, 2006). Members of professions working to mitigate earthquake risks depend on monitoring: for example, earth scientists focused on the cause and nature of strong shaking and the quantification of the hazard, and earthquake engineers working to design safe structures. Other users include emergency managers, insurance professionals, economists, and policy analysts. Earthquake monitoring information is critical for effective building codes that support nearly $1 trillion in new construction each year in the United States.

The **vision** of the ANSS is to provide the earthquake data and information needed to save lives and reduce earthquake economic losses, as a foundation for creating a more earthquake-resilient nation.

The **mission** of the ANSS is to provide accurate and timely data and information on seismic events and their effects on buildings and infrastructure, to cooperatively develop and maintain the system with consistent analytical procedures, and to develop information products and services necessary for earthquake warnings, notifications, impact estimates, hazard and risk assessments, and scientific and engineering research.

There are four areas in which ANSS earthquake monitoring has practical application to public safety through earthquake loss reduction:

Public awareness.—The ANSS rapidly provides information on earthquake occurrence, characterizing any seismic event causing public concern for situational awareness. There is great demand for such information in times of crisis: following a large earthquake, ANSS websites can receive millions of visits. Through the earthquake early warning (EEW) initiative, the ANSS is developing the capability to issue alerts of imminent strong ground shaking.

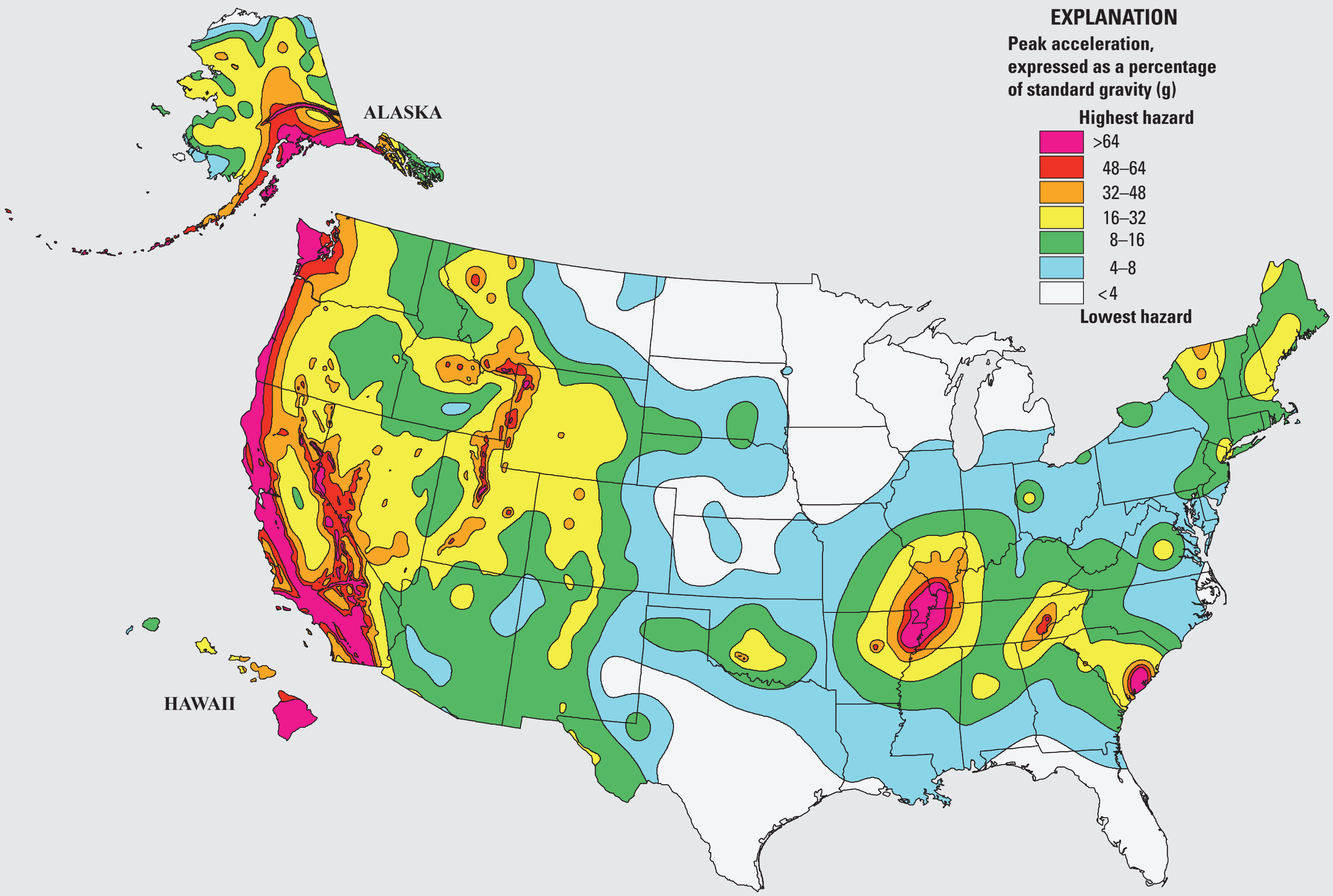
Emergency response.—ANSS information on the severity and spatial distribution of earthquake shaking and the likely societal impacts is essential to give rapid estimation of the scope of damages and losses for emergency response. The ANSS also enables earthquake scenarios that are used in emergency management exercises.

Earthquake hazard assessment and risk mitigation.—ANSS information and complementary geologic data form the basis of hazard assessments used in building codes and other risk-reduction measures (such as the National Seismic Hazard Model, which is a suite of products aimed at improving earthquake-resilient construction in the United States).

Earthquake and engineering research.—The ANSS provides data and derived products needed to develop our understanding of the causes of earthquakes, their likelihood, and their impacts, including impacts on the built environment. ANSS recordings of strong ground shaking and associated building response are used in the development of seismic-resistant engineering design and construction practices.

1. United States National Seismic Hazard Model

Earthquake hazards nationwide are quantified in the National Seismic Hazard Model (NSHM) (such as map below), which is a suite of products aimed at improving earthquake-resilient construction in the United States. Engineers who construct buildings need to know how strongly a particular site might be shaken by earthquakes. The NSHM addresses this question by compiling all known earthquake sources (and proxies for unknown sources), their distance from the site in question, and other seismological and geological information to project potential maximum expected ground motions at a site over a particular period of time (for example, 50 years) (see Petersen and others, 2014). The NSHM is revised periodically to include new research results on earthquake faults, ground deformation, and earthquake ground shaking. The NSHM relies on Advanced National Seismic System information.



Map of seismic hazard across the United States derived from the National Seismic Hazard Model. Colors on this particular map show the levels of horizontal shaking that have a 2% chance of being exceeded in a 50-year period. Shaking is expressed as a percentage of g, which is the acceleration of a falling object due to gravity, with red colors indicating highest shaking and thus highest hazard.

Background

History of the Advanced National Seismic System

The ANSS is an essential component of the U.S. Geological Survey (USGS) contributions to the four-agency National Earthquake Hazards Reduction Program (NEHRP), consisting of the National Institute of Standards and Technology, National Science Foundation (NSF), Federal Emergency Management Agency (FEMA), and USGS. Congress established the ANSS through the Earthquake Hazards Reduction Act of 2000 (Public Law 106–503), directing the USGS "...to establish and operate an Advanced National Seismic Research and Monitoring System to modernize, standardize, and stabilize the national, regional, and urban seismic monitoring systems in the United States into a coordinated system." The original ANSS design was set down in USGS Circular 1188 entitled "An Assessment of Seismic Monitoring in the United States—Requirement for an Advanced National Seismic System" (U.S. Geological Survey, 1999). Technical guidelines for ANSS implementation were detailed in a subsequent document, USGS Open-File Report 2002–92 (ANSS Technical Implementation Committee, 2002).

This current document describing ANSS developmental opportunities and priorities for the next decade (2017–2027) has been written at the recommendation of the ANSS Steering Committee and its parent body, the Scientific Earthquake Studies Advisory Committee (SESAC), which was established by Congress to advise the Director of the USGS on matters related to the USGS participation in the NEHRP.

Basic Concepts of Seismic and Real-Time Geodetic Networks

A seismic station consists of a sensor to measure ground motion—a seismometer—and an instrument to convert the analog electrical signal to digital format. Because of the broad range of motions generated by earthquakes, two types of sensors are typically employed. Broadband seismometers can record ground motions (velocity or acceleration) that vary over many orders of magnitude (1 to 1,000,000) and over a wide range of frequencies, whereas strong-motion seismometers are needed to record the shaking near large earthquakes, both on the ground and in buildings and lifelines. Many ANSS stations consist of both broadband and strong-motion sensors to ensure that the full range motions are recorded with fidelity.

A seismic network consists of a group of stations feeding data to a data analysis center. They are typically described in terms of their scale of coverage. National and global networks provide wide areal coverage, and regional networks consist of more densely spaced seismometers in areas of higher seismic hazard to detect lower magnitude earthquakes and increase the accuracy of earthquake characterization. Data analysis centers aggregate data from many seismic stations to produce accurate earthquake products.

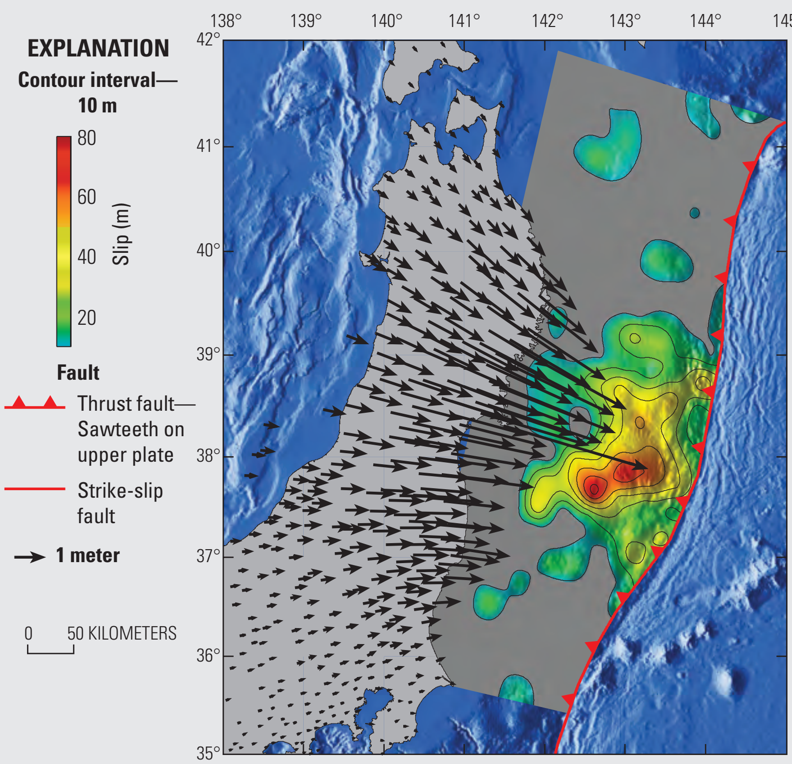
A seismic station with broadband and strong-motion sensors recorded at 100 samples per second would produce approximately 14 kilobits per second of data. These data are transmitted continuously, using various types of communication pathways, to a data center for analysis. A data center using a network of 100 stations would acquire and process over 400 gigabytes of data per month. These data must also be archived and freely and openly distributed for long-term research.

Seismic network operations require an expert staff of scientists, engineers, and technicians who analyze earthquakes; manage software, computers, data flow, and communications; and conduct fieldwork to maintain seismic stations.

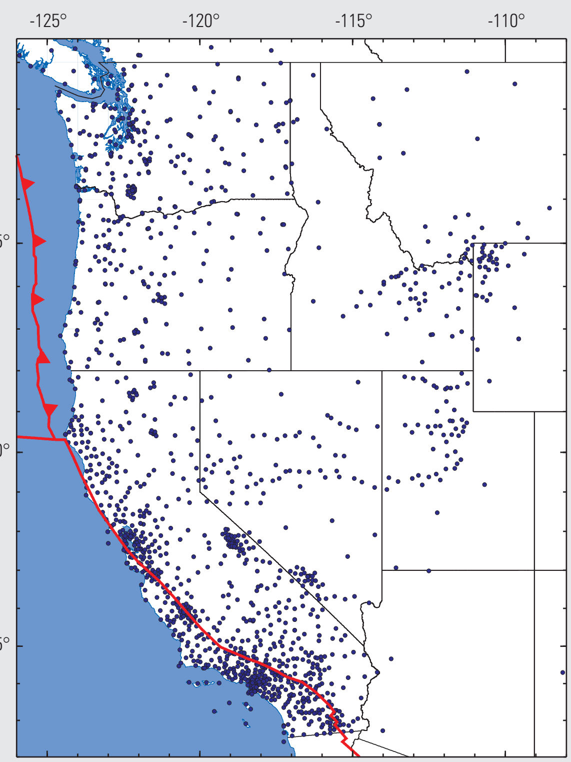
The opportunities described herein include a new role for geodetic networks, identifying a pathway to eventually become participating networks in the ANSS. A real-time geodetic network uses high-precision Global Positioning System (GPS) stations (more generally called Global Navigation Satellite System [GNSS] stations) to rapidly measure ground displacement. Geodetic and seismic data are complementary, and joint analysis can better characterize an earthquake. Real-time GNSS data are particularly important for rapidly characterizing large earthquakes for earthquake early warning and in resolving detailed characteristics of fault slip (sidebar 2, p. 5).

2. Contribution of Geodetic Data in the Advanced National Seismic System

The potential contribution of real-time geodetic data from Global Navigation Satellite System (GNSS) networks to rapid earthquake characterization was demonstrated retrospectively for the Tohoku-Oki earthquake (left plot). For the largest earthquakes, GNSS data can provide a more accurate rapid magnitude estimate than seismic data and simultaneously help to estimate the earthquake source dimensions. The west coast of the United States already has hundreds of continuously operating GNSS that could be incorporated into the ANSS; many of these are operated by USGS cooperator institutions and partners (for example, the Plate Boundary Observatory (PBO) geodetic network, operated by UNAVCO). The Tohoku example emphasizes the role that geodetic data could play in a future great earthquake on the Cascadia subduction zone, the Alaska-Aleutian subduction zone, or the Puerto Rico subduction zone. Geodetic instruments can also record instantaneous large offsets on faults like the San Andreas, contributing to improved earthquake early warning and providing real-time assessment of damage to fault-crossing lifelines.



Map showing real-time geodetic data of the magnitude 9 Tohoku-Oki earthquake collected by Global Navigation Satellite System (GNSS) stations (GNSS displacements are shown as black arrows and fault slip is shown as colored contours). *Figure courtesy of Jessica Murray and Sarah Minson.*



Map showing the locations of GNSS stations (blue circles) along the west coast of the United States that could be used in the same manner (plate boundary shown by red lines, with barbed line indicating subduction zone). *Figure courtesy of Jessica Murray and Sarah Minson.*

Overview of the Current Advanced National Seismic System

The ANSS consists of national and regional seismic networks (sidebar 3, p. 7) and associated data centers. The USGS Earthquake Hazards Program supports national facilities and partially supports regional seismic networks; the latter can receive additional support from their States, their host universities, or other Federal agencies. The USGS Earthquake Hazards Program provided $30.8 million in 2016 to support the ANSS.

The original ANSS design called for the installation of 7,100 modern seismic stations, both in the field and in buildings, bridges, and other structures. The ANSS is currently 42-percent complete in terms of the number of seismic stations installed, and further growth is required to complete the ANSS.

Elements of the Advanced National Seismic System

Regional seismic networks.—Regional seismic networks provide critical station coverage in moderate- to high-hazard regions, perform important functions of analyzing and distributing seismic data and information on earthquakes, and provide local expertise for a region's engineering and emergency management communities and for the public. Most networks monitor a unique geographic region where their earthquake locations and magnitudes are considered the authoritative ANSS result. The 11 networks participating in the ANSS in 2016 are listed below.

- Alaska Earthquake Center of the Geophysical Institute, University of Alaska Fairbanks
- California Integrated Seismic Network (CISN), the principal units of which are networks and data centers operated by the California Institute of Technology (Caltech), the University of California (UC) Berkeley, and the USGS Earthquake Science Center at Menlo Park, which are all participants in ANSS, as well as the California Geological Survey
- Center for Earthquake Research and Information, University of Memphis
- Lamont-Doherty Cooperative Seismographic Network, Columbia University
- Nevada Seismological Laboratory, University of Nevada, Reno
- Pacific Northwest Seismic Network, operated by the University of Washington and University of Oregon
- Puerto Rico Seismic Network, University of Puerto Rico, Mayaguez
- Saint Louis University Earthquake Center
- South Carolina Seismic Network, University of South Carolina
- University of Utah Seismograph Stations
- USGS Hawaiian Volcano Observatory

National elements.—The USGS operates the three national elements of the ANSS: the National Earthquake Information Center (NEIC), the National Seismic Network, and the National Strong Motion Project.

The NEIC receives data from some 3,000 national and worldwide seismic stations. It is staffed 24/7 and serves as a backup for regional networks. The NEIC reports on about 25,000 earthquakes per year.

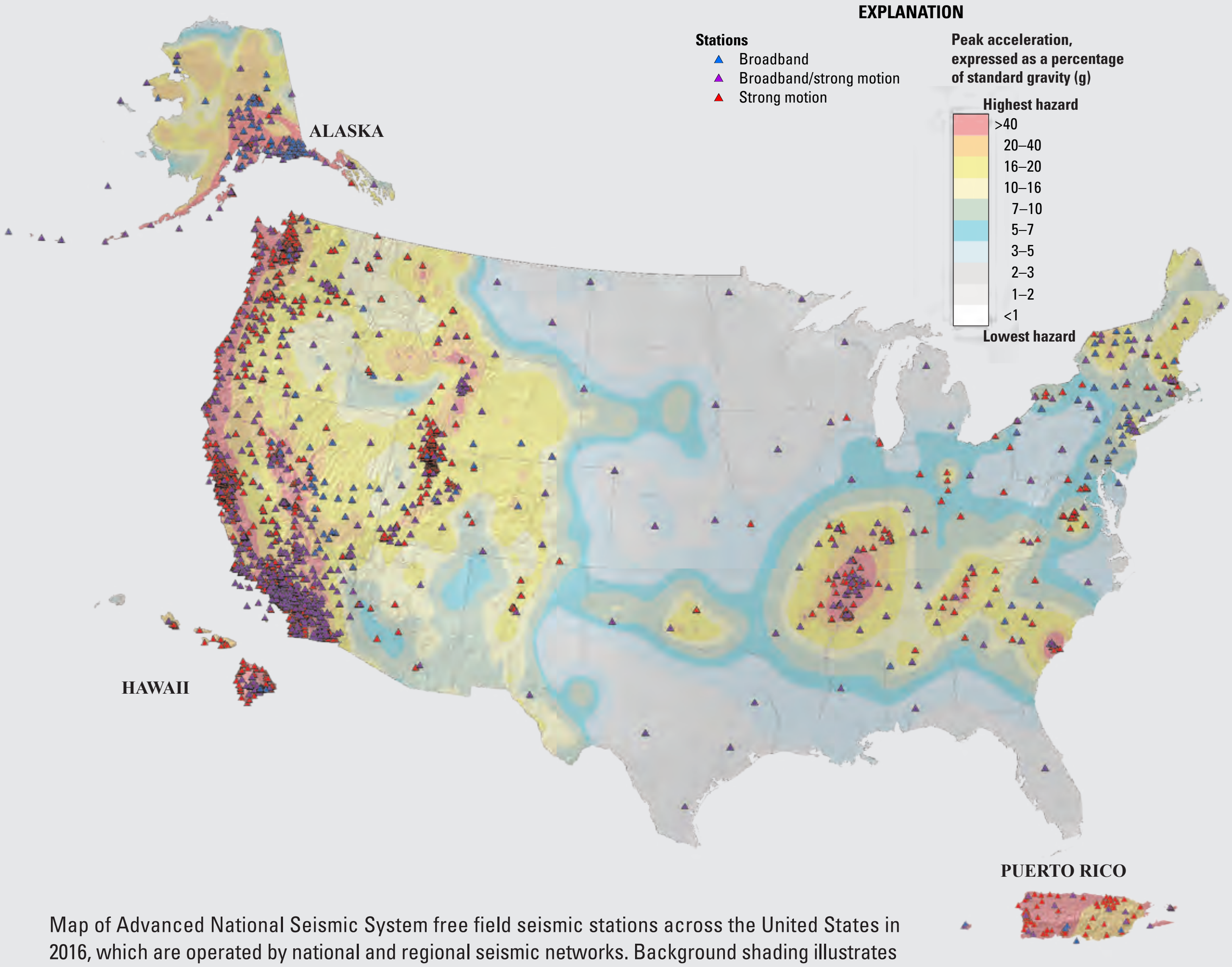
The National Seismic Network, or "ANSS backbone" network, consists of 100 broadband stations providing a national framework for the ANSS earthquake monitoring. These stations are operated by the USGS Albuquerque Seismological Laboratory (ASL), which also operates two regional networks: the New England Seismic Network and the Intermountain West Seismic Network in Wyoming.

The National Strong Motion Project maintains stations designed to record strong shaking near earthquakes, with more than 400 free-field stations and more than 150 instrumented structures (sidebar 4, p. 8) with telemetry. Guidelines for deployments to collect the structural response data were published in USGS Open-File Report 2005–1039 entitled "Guideline for ANSS Seismic Monitoring of Engineered Civil Systems" (ANSS Structural Instrumentation Guideline Committee, 2005).

Portable capabilities.—The ANSS also maintains sets of portable equipment for temporary seismometer deployments, including aftershock monitoring. ANSS portable capabilities have proven important for many earthquake sequences, including the study of induced earthquake sequences in several States and earthquake aftershock investigations, such as after the 2014 M6.0 South Napa, Calif.; the 2011 M5.8 Mineral, Va.; and the 2002 M7.9 Denali, Alaska, earthquakes and the 2007 collapse of the Crandall Canyon mine in Utah.

3. Distribution of Advanced National Seismic System Seismic Stations

The Advanced National Seismic System (ANSS) is composed of national and regional seismic networks, which are made up of modern digital seismic stations that have broadband or strong motion sensors, or both, to permit recording of the broad range of motions created by earthquakes. As the ANSS has grown, stations have been deployed strategically, such as to improve coverage in high hazard regions and in high risk urban areas. The opportunities described later in this report describe how further increases in ANSS station coverage can provide benefits.



Map of Advanced National Seismic System free field seismic stations across the United States in 2016, which are operated by national and regional seismic networks. Background shading illustrates higher hazard regions in the National Seismic Hazard Model (see sidebar 1, p. 3). Notice the greater density of seismic stations in regions with either higher hazard, higher risk, or both. *Figure courtesy of Harley Benz and Gregory Smoczyk.*

4. Instrumented Structures in the Advanced National Seismic System

The Advanced National Seismic System (ANSS) includes instrumented structures as well as free-field stations (sidebar 2, p. 5). Sensors in buildings are needed to help engineers and scientists to understand behavior and performance of the built environment in an earthquake (for example, the instrumented Rincon Tower I building in San Francisco, Calif., as seen in the diagram to the right). Representative structures are instrumented to address unresolved issues in seismic design, retrofitting practices, and building codes as well as provide validation of experimental and simulation research. When a major earthquake occurs, it is important to measure how design and retrofit concepts respond to actual earthquake shaking so that they can be more generally adopted or adapted as warranted.

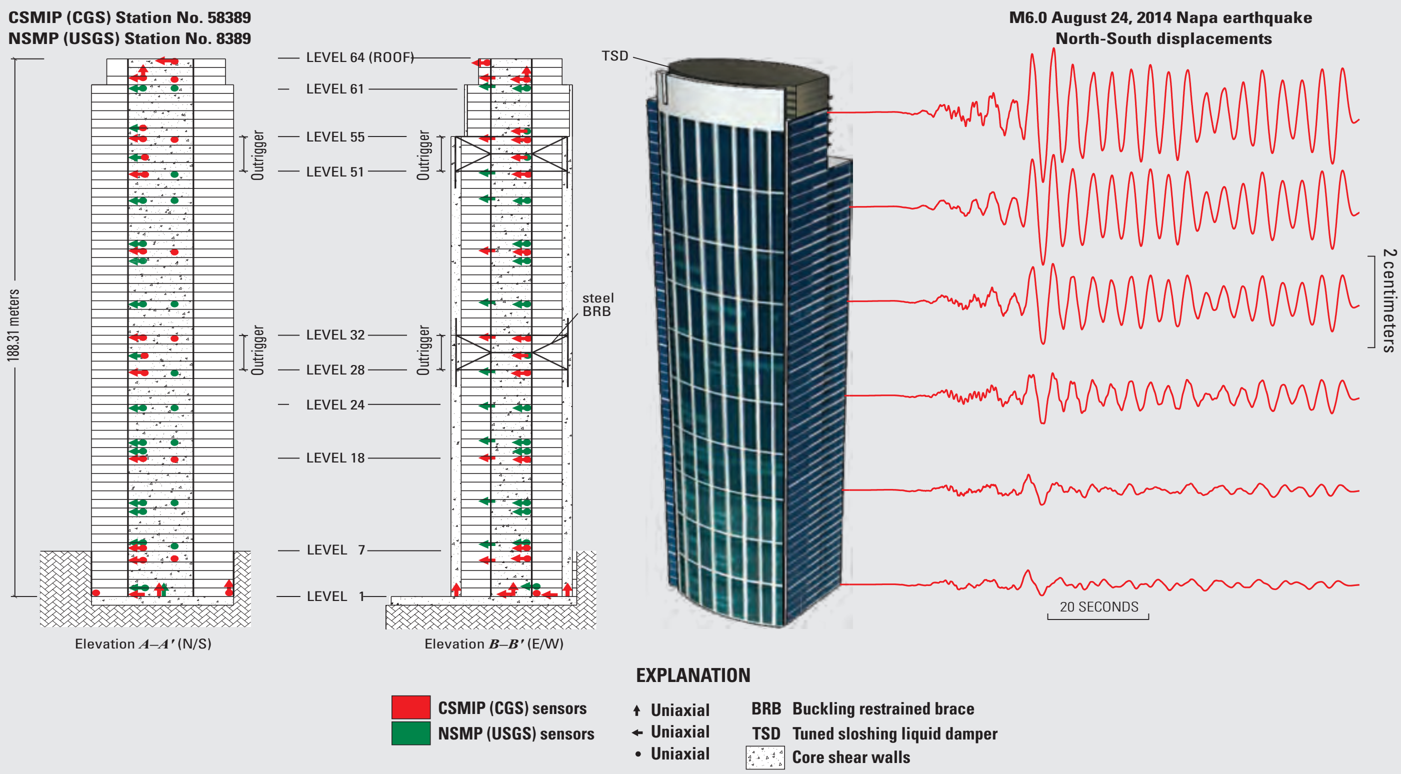


Diagram of one of the 168 instrumented structures in the Advanced National Seismic System (ANSS), showing the placement of sensors and other instrumentation as well as the displacements that were measured during an earthquake. The Rincon Tower I building is a jointly instrumented (by the California Geologic Survey [CGS] and U.S. Geological Survey [USGS]) 64-story reinforced concrete building in San Francisco, Calif. It has core shear walls and an outrigger perimeter column system connected to the core with buckling restrained braces and tuned sloshing liquid dampers. The seismic instrumentation of the building has 72 channels and real-time streaming capability. The schematics on the left are north-south and east-west cross sections of the building showing the locations and orientation of the accelerometers used by the ANSS to monitor the structural response. The central figure shows a 3-dimensional model of the building. The right figure shows examples of north-south displacements at different levels of the building recorded during the magnitude 6.0 earthquake located in South Napa, Calif., on August 24, 2014. *Figure courtesy of Mehmet Çelebi and Vivian Nguyen.*

Organization and Coordination

The ANSS is organized with the following elements to ensure oversight from stakeholders, task managers with responsibilities, and facilitate communication and coordination:

- *National Steering Committee.*—The ANSS National Steering Committee (composed of representatives from various professional groups) provides comprehensive guidance and oversight for the entire ANSS effort. It reports through the SESAC.

- *Regional Advisory Committees.*—ANSS Regional Advisory Committees (composed of end users of seismic information, such as practicing engineers, emergency managers, seismologists, utility operators, transportation officials, and so forth) provide guidance and oversight for the ANSS at their respective geographic levels.

- *National Implementation Committee.*—Implementation and operations are carried out under the oversight of the ANSS National Implementation Committee composed of regional and topical representatives.

- *ANSS Coordinator and ANSS Technical Manager.*—The ANSS Coordinator on the staff of the USGS Earthquake Hazards Program oversees the activities of the ANSS, including the seismic network cooperative agreements, and is also the chief spokesperson for the ANSS at the national level. The ANSS Technical Manager provides scientific and technical expertise for the effort.

Overall responsibility for implementation and operation of the ANSS lies with the USGS, but this organization allows collaboration with other Federal and State agencies and with the earth science and engineering communities with interests in seismic monitoring. Fundamental to the success of the ANSS is the need to promote partnerships among those working at local, regional, and national levels committed to reducing earthquake losses. These partnerships are necessary in order for the ANSS to be coordinated nationally, designed and implemented regionally, and supported locally. Recognizing that earthquake hazard and risk varies from region to region, the ANSS management structure emphasizes regional implementation and national integration.

Advanced National Seismic System Progress to Date (2000–2016)

ANSS progress from 2000 to 2016 can be categorized in four broad areas—network infrastructure, standardization and coordination, partnerships in growth, and products and services.

Network Infrastructure

When the ANSS began in 2000, most seismometers used in the United States could record earthquakes only over narrow amplitude and frequency ranges and thus were not capable of recording the signals generated by large earthquakes. Data were transmitted over noisy, unreliable analog circuits, and some data were still entered and analyzed by hand.

The ANSS has since modernized and expanded the participating seismic networks and data analysis centers. By end of FY 2016, the ANSS was 42-percent complete in terms of the number of seismic stations (sidebar 5, p. 11). An acceleration of growth in 2010–12 was mostly due to a one-time increase in funding ($19 million) to modernize networks, received under the American Recovery and Reinvestment Act. The ANSS is now capable of detecting almost all humanly felt earthquakes in the United States, except in parts of Alaska. The ANSS has also expanded its portable deployment capabilities.

The ANSS has spurred innovation: for example, the ANSS worked with private-sector manufacturers to develop a relatively inexpensive “NetQuakes” strong motion sensor and, from 2009 through 2014, over 400 NetQuakes sensors were deployed in select urban areas (for example, Anchorage, Alaska; Boston, Mass.; Las Vegas, Nev.; Los Angeles, Calif.; Memphis, Tenn.; New York, N.Y.; Portland, Oreg.; Salt Lake City, Utah; Reno, Nev.; San Francisco, Calif.; Seattle, Wash.; and Washington, D.C.), hosted by private citizens in their homes. Advances in low-cost, micro-electro-mechanical system (MEMS) sensor technology hold future promise for the ANSS. Strong-motion recordings of damaging seismic waves in the proximity of an earthquake provide information that is essential for advances in ground-motion prediction estimation, improved modeling of ground deformation and soil-structure interaction, validation of structural simulation and loss assessment tools, and improvements in seismic design standards for buildings, bridges, and other critical infrastructure.

Standardization and Coordination

The ANSS has advanced the coordination and standardization of operations, implementing common instrument standards, data formats, software, and operational procedures. Each seismic network is assigned a geographic region where its solutions are considered "authoritative." ANSS components act as a well-coordinated, collaborative system. The ANSS promotes communication and coordination between various Federal, State and private agencies, as well as scientists and engineers involved with earthquake monitoring both regionally and nationally.

Partnerships in Growth

Partnerships have increased the effectiveness of the ANSS. Host academic institutions; the States of Alaska, Arkansas, California, Nevada, Oregon, Tennessee, Utah, and Washington among others; and other Federal agencies, such as the U.S. Departments of Energy and Veterans Affairs, have contributed to ANSS growth and operations. The California Governor's Office of Emergency Services supports the CISN, which also received supplemental funding from FEMA requested through the cities of Los Angeles and Long Beach for network expansion. The Gordon and Betty Moore Foundation contributed significantly to the development of earthquake early warning, and the Keck Foundation and the Murdock Foundation have contributed to regional network improvements under the ANSS.

Growth of the ANSS National Seismic Network ("ANSS backbone") and certain regional networks was enhanced through the USArray element of EarthScope, a National Science Foundation (NSF) facility implemented through the Incorporated Research Institutions for Seismology (IRIS). Prompt Assessment of Global Earthquakes for Response (PAGER) development was supported by the U.S. Agency for International Development, Office of Foreign Disaster Assistance (USAID/OFDA). ShakeCast development was supported by the International Atomic Energy Agency, the U.S. Nuclear Regulatory Commission (NRC), and the U.S. Department of Veterans Affairs (VA). The California Department of Transportation has also been an important supporter of ShakeCast development, and the Departments of Transportation (DOTs) in the States of Idaho, Mississippi, Oklahoma, Oregon, South Carolina, Texas, Utah, and Washington have recently made plans to commit support to further customize ShakeCast to meet the needs of State DOTs.

Strong-motion data are archived and distributed by the Center for Engineering Strong Motion Data (CESMD), a partnership between the ANSS and the California Geological Survey. The Northern California and Southern California earthquake data centers are operated by UC Berkeley and Caltech, respectively. With NSF funding, the IRIS Data Management Center archives and provides distribution for a portion of ANSS seismic data.

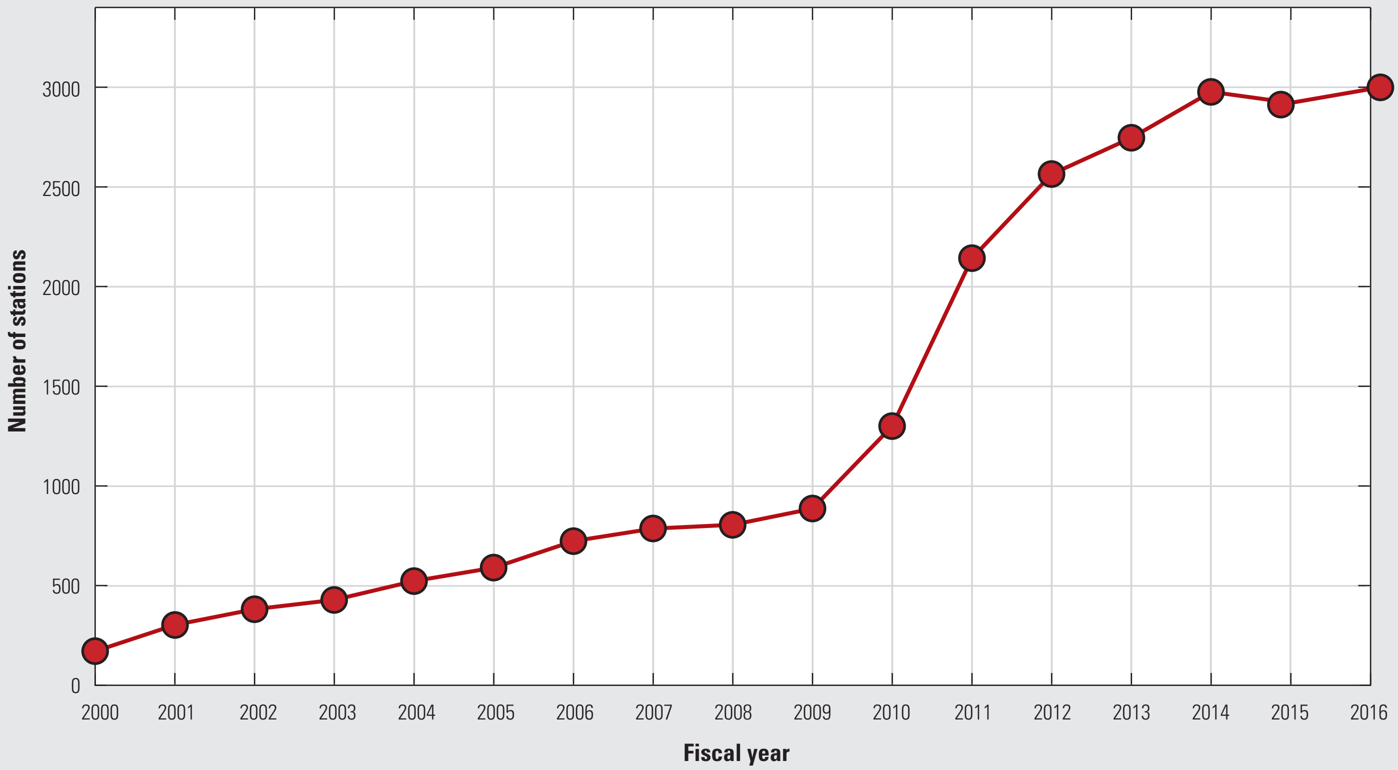
The Global Seismographic Network, operated as a partnership among the USGS, NSF, and IRIS, is of critical importance for the following hazard monitoring efforts:

- the NEIC's global monitoring of earthquakes,
- the National Oceanographic and Atmospheric Administration's (NOAA's) tsunami monitoring, and
- the U.S. Air Force and U.S. Department of Energy research programs for nuclear-test monitoring.

The ANSS National Steering Committee includes representatives from the Association of American State Geologists, the Consortium of Organizations for Strong Motion Observation Systems, the Earthquake Engineering Research Institute, IRIS, the National Emergency Management Association, and the Seismological Society of America. Members of the scientific, engineering, and emergency response communities participate in ANSS Regional Advisory Committees. The Southern California Earthquake Center and the Pacific Earthquake Engineering Research Center have also provided noteworthy forums for the users of ANSS data.

5. Growth in the Number of Advanced National Seismic System Stations

Since its inception, the U.S. Geological Survey (USGS) and its university partners have deployed over 2,900 Advanced National Seismic System (ANSS) stations. ANSS station growth accelerated in 2010–12 through an influx of funding to the USGS under the American Recovery and Reinvestment Act. Growth rates since then have remained high owing to investments in a west coast earthquake early warning system. However, a small decline occurred in fiscal year 2015 when, because of funding limitations, the USGS ended support for two regional seismic networks and because of the closure of some additional stations.



Graph showing the total number of Advanced National Seismic System (ANSS) stations in each fiscal year (FY) from FY 2000 through FY 2016. *Figure courtesy of Cecily Wolfe.*

Products and Services

The reporting of earthquakes has been revolutionized as a result of ANSS investments. Example ANSS products and services include the following:

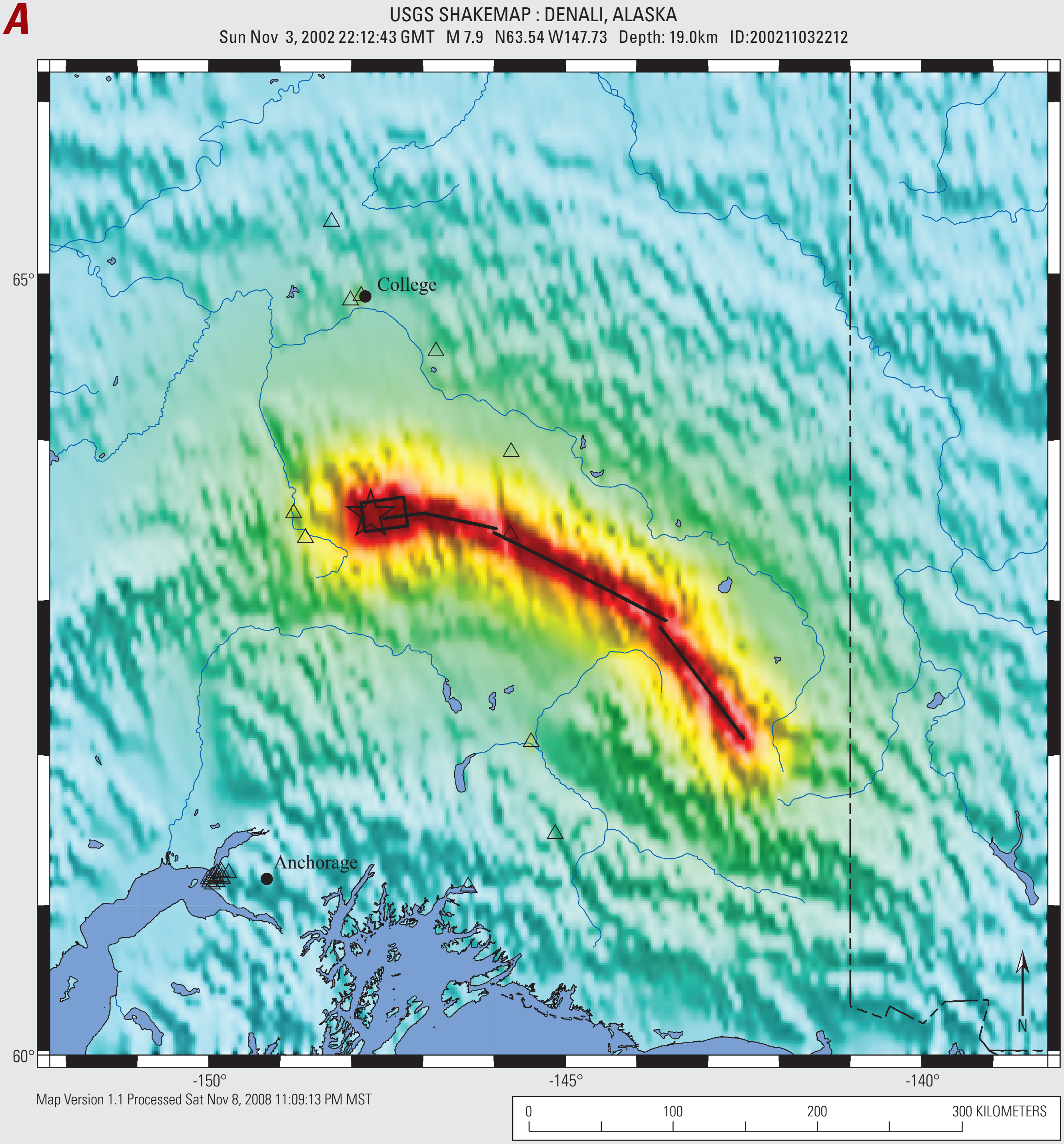
- **Immediate earthquake notifications to governments and emergency managers.** The ANSS reports on potentially damaging earthquakes to the White House; the Departments of Defense, Homeland Security (including FEMA), Transportation, Energy, Commerce (NOAA, National Institute of Standards and Technology), Veterans Affairs, State, and Interior; State offices for disaster services; and the news media. Additionally, regional seismic networks serve as resources for State and local community information needs.
- **Earthquake Notification Service (ENS).** The ENS is a free public service sending rapid earthquake notifications via e-mail and text message to approximately 400,000 users. Notification criteria can be tailored to meet users' needs via an easy-to-use web interface.
- **Web presence.** The USGS and regional seismic networks each maintain websites that provide authoritative and coordinated information on recent earthquakes, including maps and lists of recent seismicity. Following a large earthquake, these sites can receive millions of visits within hours. For example, the earthquakes.usgs.gov website is one of the most heavily trafficked sites in the Federal Government. Technical information on ANSS operations can also be found on these websites.
- **ShakeMap.** Based on ANSS data, a ShakeMap, a map of the severity and spatial distribution of earthquake ground shaking following an earthquake, is generated. It provides a rapid assessment of the scale of an earthquake's potential impact (sidebar 6, p. 13–17). This informs response officials and personnel at all levels of government, transportation and lifeline managers, and the public of what damage levels to expect and the scope of the needed response.
- **ShakeCast.** ShakeCast is an application for automating ShakeMap delivery to critical users and for facilitating notification of shaking levels at user-selected facilities. It is used by numerous public and private infrastructure management centers (such as, State DOTs, utilities, school systems, Federal agencies, private companies, and critical facilities) to prioritize earthquake response actions. Users identify site locations beforehand and set thresholds for shaking levels of concern. Immediately after an earthquake, a ShakeMap is distributed to clients with estimated shaking levels at their sites and information about potential problems. ShakeCast is particularly useful for transportation or lifeline networks, where there may be hundreds of bridges and overpasses to oversee, and helps clients prioritize safety inspections. After the 2011 Mineral, Va., earthquake, ShakeCast alerted the Nuclear Regulatory Commission that the design shaking levels at the North Anna nuclear power plant may have been exceeded.
- **Prompt Assessment of Global Earthquakes for Response (PAGER).** The PAGER system (sidebar 7, p. 19) estimates dollar losses and fatalities immediately after significant earthquakes nationally and worldwide, using ShakeMap results along with inventories of buildings and construction types and historical loss data. PAGER has proved invaluable in informing emergency responders, government and aid agencies, and the media of the scope of potential disasters associated with both domestic and foreign earthquakes.

6. ShakeMap

A ShakeMap is made with Advanced National Seismic System data and provides a near-real-time map of ground motion and shaking intensity following a significant earthquake. ShakeMaps are used by Federal, State, and local organizations for post-earthquake response and recovery, public and scientific information, as well as for preparedness exercises and disaster planning.

ShakeMap examples from several earthquakes: ***A***, the 2002 M7.9 Denali, Alaska, earthquake (black lines indicate fault locations used in the earthquake rupture model; the earthquake rupture began with reverse faulting, indicated by the black box, then evolved to strike-slip faulting); ***B***, the 2003 M6.8 Nisqually (Seattle), Wash., earthquake (open circles indicate Did-You-Feel-It? reports); ***C***, the 2015 M5.8 Pawnee, Okla., earthquake (open circles indicate geocoded Did-You-Feel-It? reports); and ***D***, the 2014 M6.0 American Canyon (South Napa), Calif., earthquake (dark gray line indicates the fault location used in the earthquake rupture model, whereas red lines indicate other faults in the region). Red star denotes earthquake epicenter and triangles indicate locations of seismic stations. Notice how yellow-to-red colors indicate regions of strong, very strong, to severe shaking from each earthquake. *Maps courtesy of the National Earthquake Information Center and the California Integrated Seismic Network.*

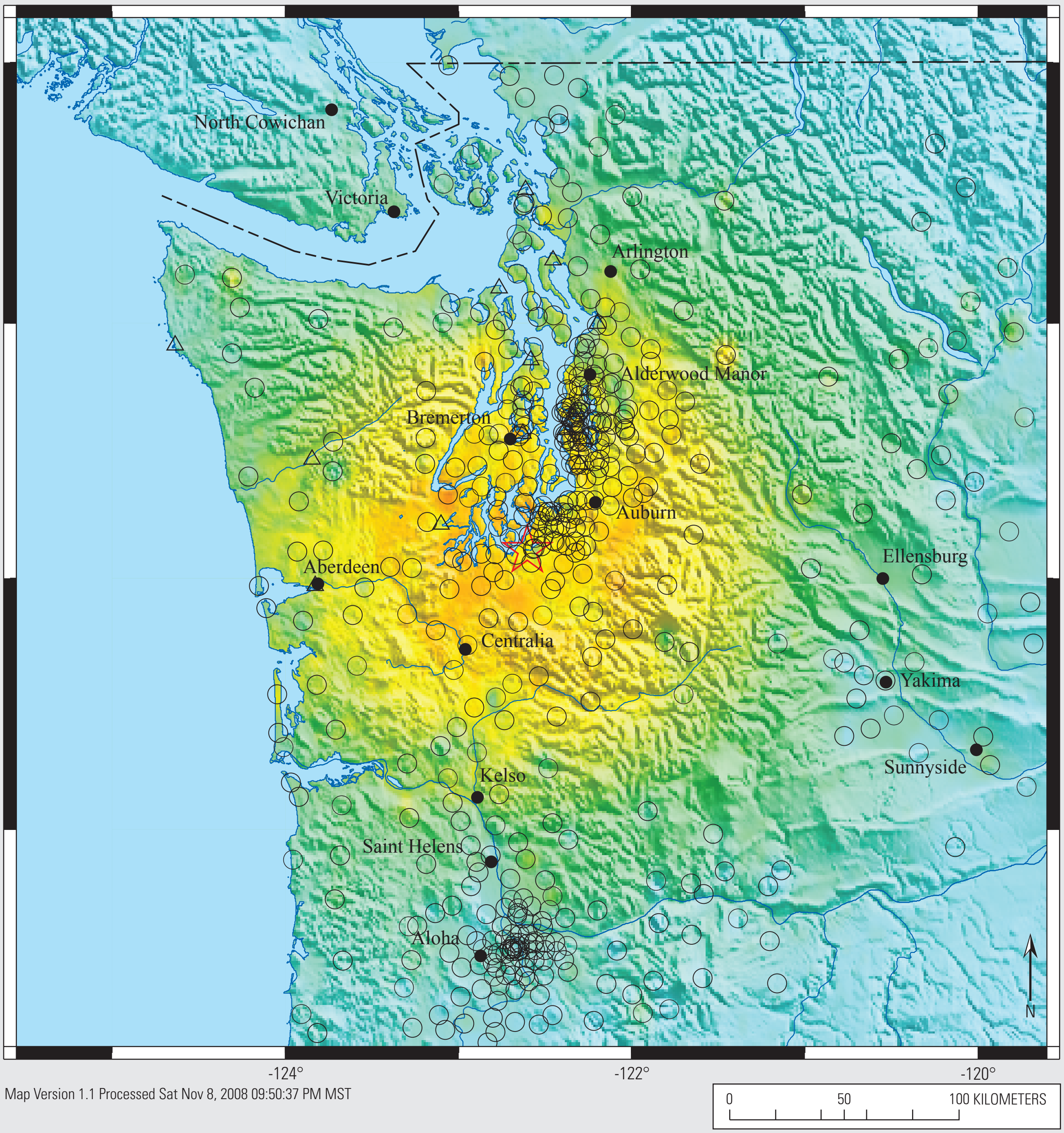
A



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

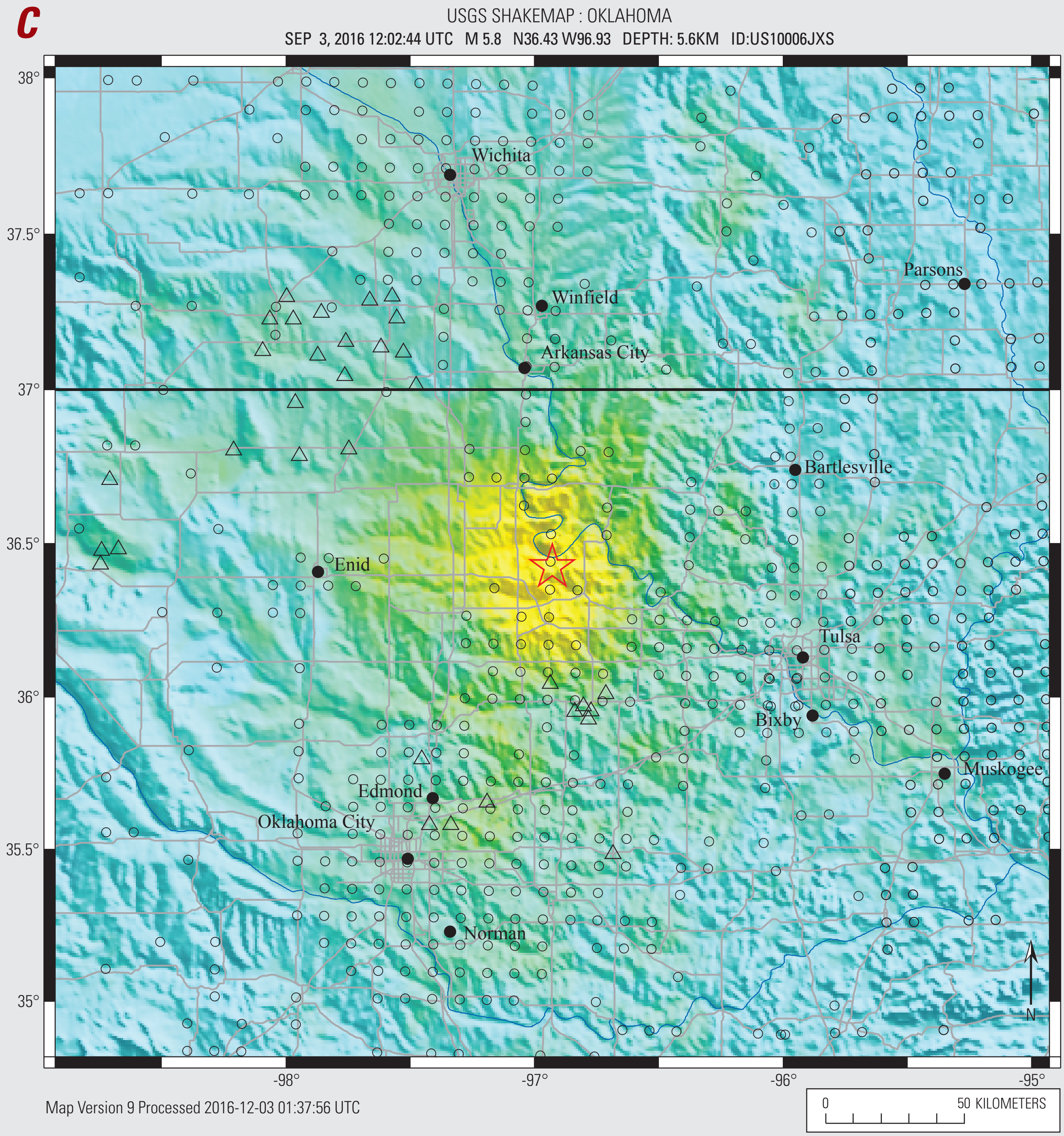
B

USGS SHAKEMAP : NISQUALLY, WASHINGTON
WED FEB 28, 2001 18:54:32 GMT M 6.8 N47.11 W122.60 DEPTH: 54.0KM ID:200102281854



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

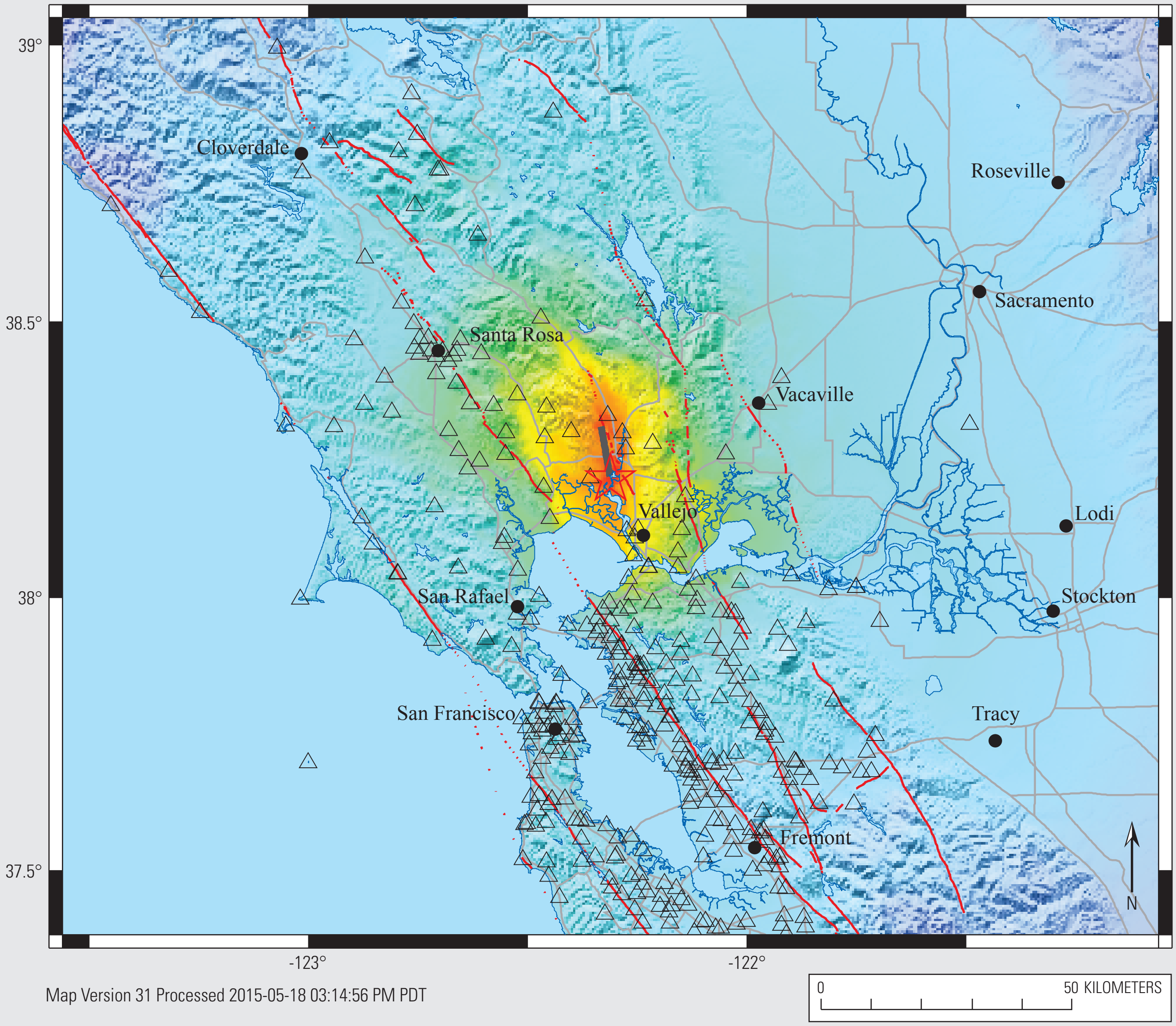
C



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

D

CISN SHAKEMAP : 6.3 KM (3.9 MI) NW OF AMERICAN CANYON, CA
AUG 24, 2014 03:20:44 AM PDT M 6.0 N38.22 W122.31 DEPTH: 11.2KM ID:72282711



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	*<0.1*	*.5*	*2.4*	*6.7*	*13*	24	44	83	>156
PEAK VEL.(cm/s)	<0.07	0.4	1.9	5.8	*11*	*22*	*43*	*83*	*>160*
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

- **Did-You-Feel-It? (DYFI).** DYFI (sidebar 8, p. 20) provides a means for people feeling an earthquake to report their experience at an ANSS website, which enables crowd sourcing to augment the body of scientific information. These responses from citizen scientists produce a geographic view of earthquake shaking intensity as humanly experienced. To date, almost 4 million DYFI reports have been submitted and more than 27,000 earthquakes have generated DYFI reports.
- **ANSS Comprehensive Catalog.** An important task is compiling an earthquake record based on standardized analysis using data from validated sources. The ANSS produces such a comprehensive earthquake catalog—ComCat—using ANSS networks. ComCat is continuously updated in real time and is available via the web for customized data searches.
- **Earthquake Source Characteristics.** Following significant earthquakes, ANSS networks routinely produce scientific information about the earthquake's rupture. Seismologists estimate the orientation of the fault, the length of the fault, and the distribution of slip along the fault. These results are used to better constrain the shaking estimates produced by ShakeMap and consequently improve the estimates of fatalities and economic loss produced by PAGER.
- **Center for Engineering Strong Motion Data (CESMD).** CESMD products provide ground motion and structural response data to the earthquake engineering community that are essential to improve the resilience of our Nation's buildings and infrastructure by providing data that directly serve engineering applications and research.

Advanced National Seismic System Development Opportunities (2017–2027)

Although the ANSS has made considerable progress toward full implementation, since 2000, the development of earthquake monitoring capabilities has not kept pace with the nation's increasing earthquake risk owing to urban and economic development, with technological advances, or with opportunities to deliver improved products and services. The ANSS has significant capacity to grow in order to improve earthquake safety, to support response and recovery, and to achieve greater resilience nationwide.

The specific opportunities and priorities for ANSS growth in the next decade, listed thematically, are described below. As described in the appendix, additional resources will be required to fully achieve the ANSS mission and implement these opportunities, which are essential to ensure ANSS readiness in an earthquake crisis, advance earthquake safety in urban areas, and expand the observational database for earthquake risk reduction.

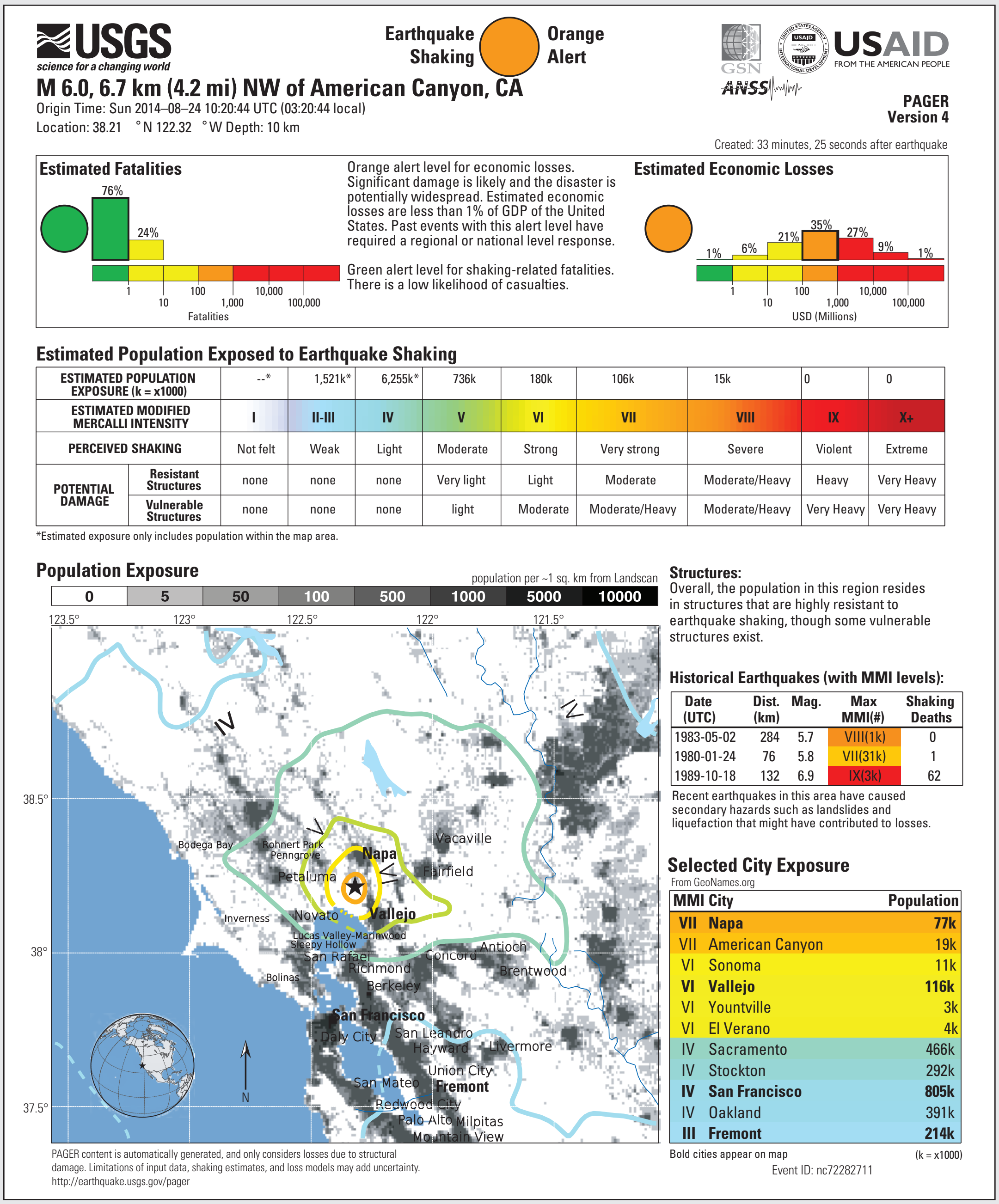
Ensuring Readiness in an Earthquake Crisis

The timeliness and usefulness of ANSS products have increased the expectations of its capabilities within government agencies, emergency responders, the public, and the engineering and scientific communities. However, with limited resources to sustain current ANSS capabilities, meeting the needs in an earthquake crisis represent a real challenge. To meet the expectations of the next decade, the ANSS must focus on improving the robustness of essential services and retaining capacity for future innovation.

ANSS operations are complex, its staff is limited, and its aging and incomplete infrastructure is expensive to maintain and replace. Should a regional seismic network be incapacitated in a crisis, the NEIC can step in to "back up" that network, but the resulting products would be degraded and suboptimal. The Earthquake Notification Service needs hardening to ensure more robust delivery of messages. Improvements are needed so that data are posted more quickly to the CESMD. More work is needed to achieve greater utilization of ShakeCast, which is underutilized even within Federal Government agencies. Conducting preemptive "stress tests" of national and regional elements would help to identify weaknesses and likely failure points. Based on the results of these tests, resources could be invested to train and supplement personnel, harden communications and analysis center operations, and improve backup for all critical components. Such strengthening of ANSS is needed to ensure that the system is highly functional during a crisis.

7. Prompt Assessment of Global Earthquakes for Response (PAGER)

***PAGER** provides shaking and loss estimates following significant earthquakes anywhere in the world (see Wald and others, 2010). These estimates are generally available within 30 minutes and are updated as more information becomes available. Rapid estimates include the number of people and names of cities exposed to each shaking intensity level as well as the likely ranges of fatalities and economic losses. PAGER does not consider secondary effects such as landslides, liquefaction, and tsunami in loss estimates at this time.*



USGS science for a changing world

Earthquake Shaking Orange Alert

M 6.0, 6.7 km (4.2 mi) NW of American Canyon, CA

Origin Time: Sun 2014–08–24 10:20:44 UTC (03:20:44 local)
Location: 38.21 °N 122.32 °W Depth: 10 km

PAGER Version 4

Created: 33 minutes, 25 seconds after earthquake

Estimated Fatalities

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

Green alert level for shaking-related fatalities. There is a low likelihood of casualties.

Estimated Economic Losses

Estimated Population Exposed to Earthquake Shaking

ESTIMATED POPULATION EXPOSURE (k = x1000)		--*	1,521k*	6,255k*	736k	180k	106k	15k	0	0
ESTIMATED MODIFIED MERCALLI INTENSITY		I	II-III	IV	V	VI	VII	VIII	IX	X+
PERCEIVED SHAKING		Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	Resistant Structures	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
	Vulnerable Structures	none	none	none	light	Moderate	Moderate/Heavy	Moderate/Heavy	Very Heavy	Very Heavy

*Estimated exposure only includes population within the map area.

Population Exposure

PAGER content is automatically generated, and only considers losses due to structural damage. Limitations of input data, shaking estimates, and loss models may add uncertainty.
http://earthquake.usgs.gov/pager

Structures:
Overall, the population in this region resides in structures that are highly resistant to earthquake shaking, though some vulnerable structures exist.

Historical Earthquakes (with MMI levels):

Date (UTC)	Dist. (km)	Mag.	Max MMI(#)	Shaking Deaths
1983-05-02	284	5.7	VIII(1k)	0
1980-01-24	76	5.8	VII(31k)	1
1989-10-18	132	6.9	IX(3k)	62

Recent earthquakes in this area have caused secondary hazards such as landslides and liquefaction that might have contributed to losses.

Selected City Exposure
From GeoNames.org

MMI	City	Population
VII	**Napa**	**77k**
VII	American Canyon	19k
VI	Sonoma	11k
VI	**Vallejo**	**116k**
VI	Yountville	3k
VI	El Verano	4k
IV	Sacramento	466k
IV	Stockton	292k
IV	**San Francisco**	**805k**
IV	Oakland	391k
III	**Fremont**	**214k**

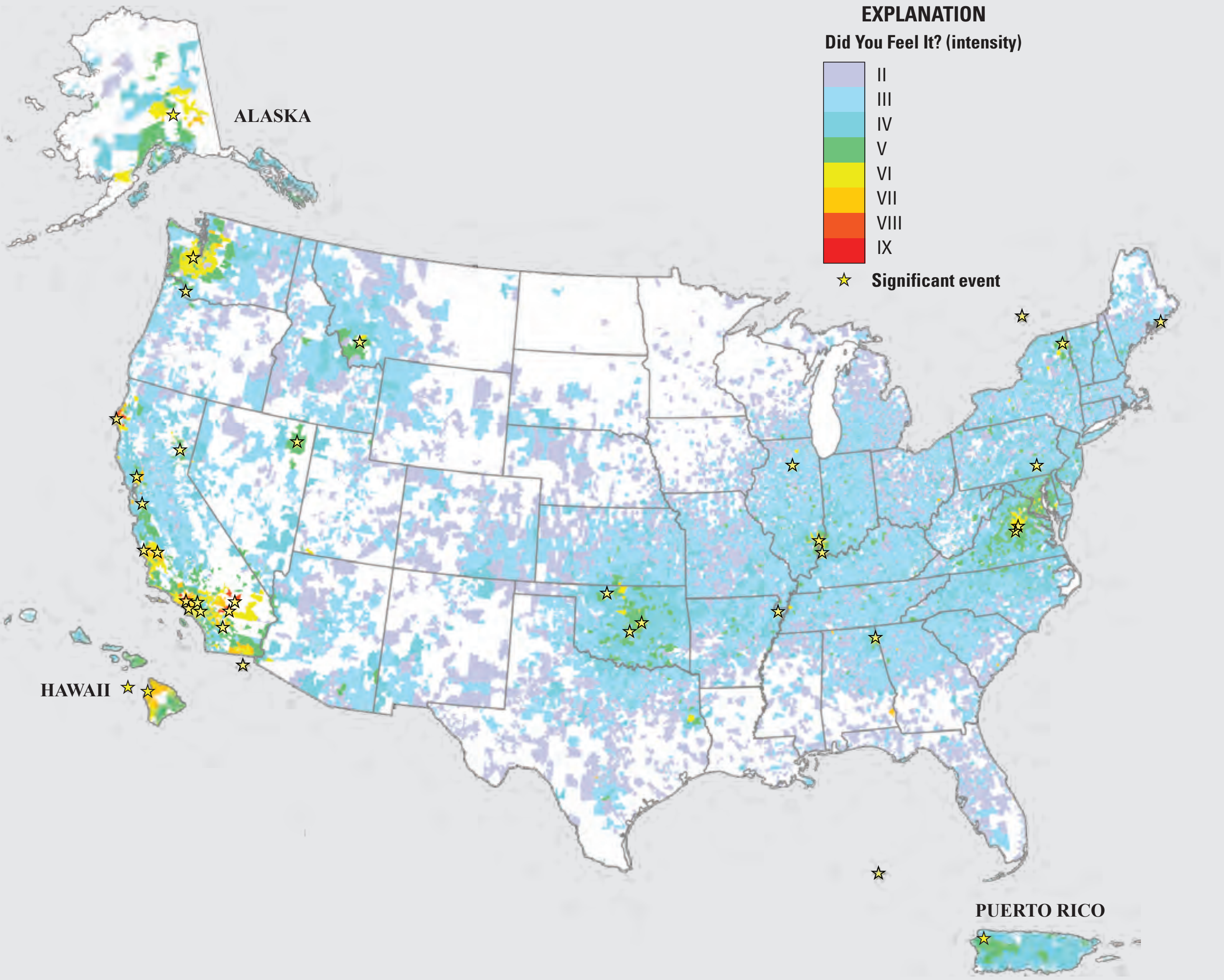
Bold cities appear on map (k = x1000)

Event ID: nc72282711

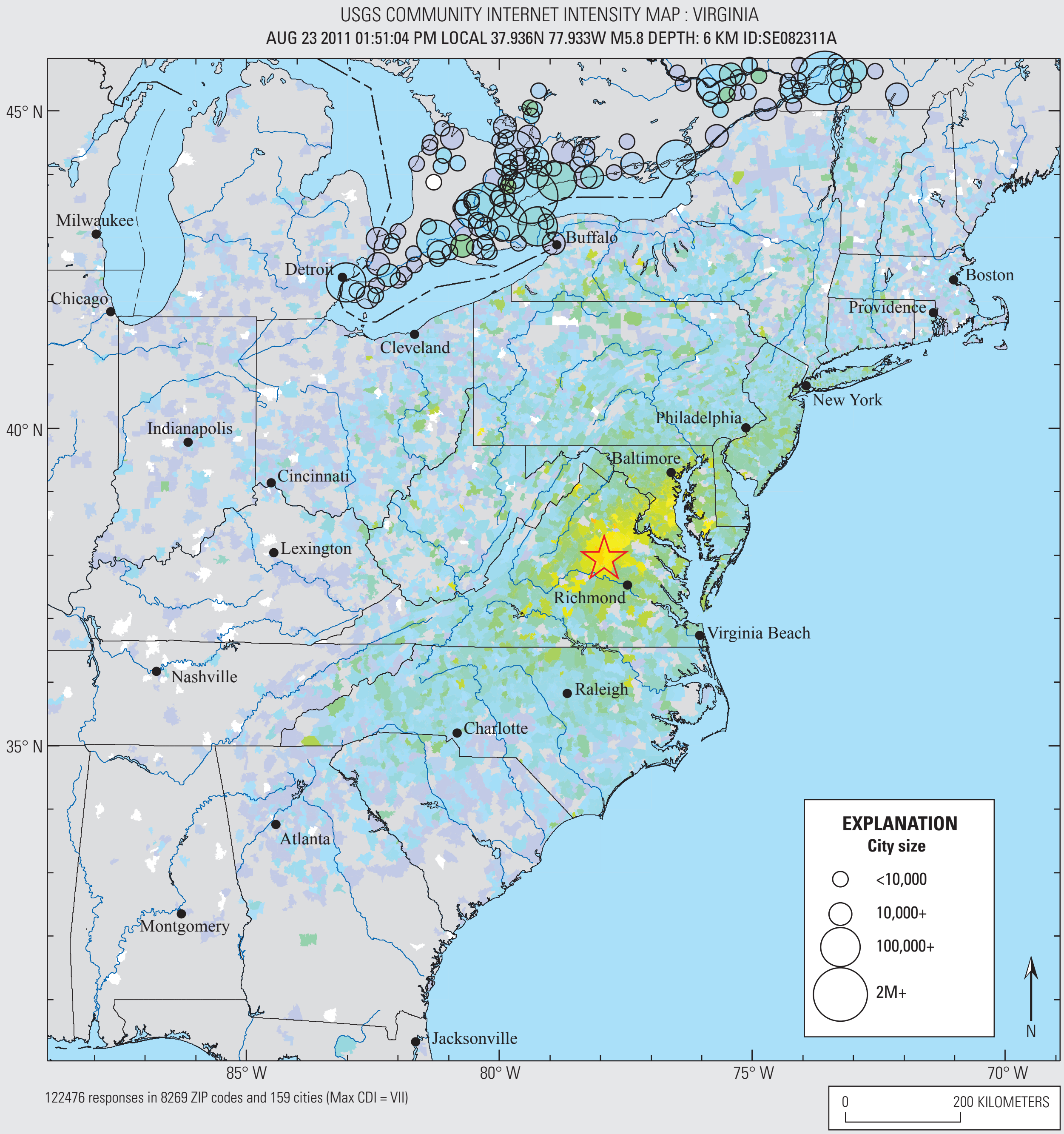
An example Prompt Assessment of Global Earthquakes for Response (PAGER) alert from the August 2014 M6.0 American Canyon (South Napa), Calif., earthquake. In this example, the PAGER alert level is green for fatalities but orange for economic losses. *Figure courtesy of the National Earthquake Information Center.*

8. Did-You-Feel-It?

Did-You-Feel-It? (DYFI) is a tool by which people may report their experiences of an earthquake, providing crowd-sourced information to supplement instrumental data. DYFI is an important product of the Advanced National Seismic System and DYFI-based shaking intensity information is used to improve ShakeMap and PAGER products.



Maps showing cumulative Did-You-Feel-It? (DYFI) reports in the United States from 1991 through 2015, which illustrates the national use of the DYFI tool. *Maps courtesy of the National Earthquake Information Center.*



INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+
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

Processed 2011-08-24 11:12:51 PM PDT

An example of a DYFI community shaking intensity map for the 2011 M5.8 Mineral, Va., earthquake. Over 122,000 people provided responses that were used in generating this earthquake's DYFI map. The earthquake was felt as far south as Georgia and as far north as Canada. Open circles in the northern part of the map denote Canadian cities color-coded to DYFI intensity legend and with circle size proportional to city population. *Maps courtesy of the National Earthquake Information Center.*

Advancing Earthquake Safety in Urban Areas

The ANSS can better ensure public safety and effective societal response during earthquakes through expanded instrumentation in and around urban areas to enable earthquake early warning, high-resolution assessments of earthquake shaking intensity and associated damage potential for emergency response and management of critical facilities and lifelines, and aftershock forecasting. For example, ANSS situational awareness products such as ShakeMap or ShakeCast are used by emergency responders immediately after an earthquake to conduct damage assessment of critical infrastructure (such as hospitals, bridges, water systems), to inform decisions to evacuate of areas vulnerable to dam collapse, to prompt actions by utility operators, or to help guide the design of search and rescue operations.

Developing Earthquake Early Warning Systems

If seismic and geodetic data to determine the size and location of an earthquake are rapidly available and quickly analyzed, a warning of imminent shaking can be broadcast to areas not yet shaken. Earthquake early warning (EEW) (sidebar 9, p. 23) enables protective actions before the damaging shaking arrives: people can take protective actions, such as “Drop, cover, and hold on,” and systems can make automated responses, such as the slowing or stopping of trains. The technical concepts to provide seconds to minutes of warning of expected ground shaking have been established. The immediate goal of the ANSS is to build and operate the “ShakeAlert” EEW system along the west coast of the United States (Given and others, 2014), with subsequent expansion to other regions. Significant additional resources are needed to raise the west coast EEW system to a fully operational level. At the Federal level, the USGS is tasked with developing an EEW system in the United States, as codified in the Earthquake Hazards Reduction Act of 1977 (42 U.S.C. 7701 et seq.).

Developing High-Resolution Damage and Impact Assessments for Urban Areas

Because the intensity of shaking in a major earthquake can vary dramatically over small distances, the ANSS needs to increase the number of strong-motion instruments in high- to moderate-risk urban areas. For example, in the Loma Prieta earthquake, the Marina District of San Francisco and certain parts of Oakland experienced amplified shaking that caused much more extensive damage and fatalities as compared to other regions. Dense, urban strong-motion networks are needed to measure the variation in shaking across different geologic conditions to produce rapid high-resolution damage and impact assessments following an earthquake. This information can be disseminated within minutes via ShakeMap and CESMD products to provide situational awareness to aid the emergency response, save lives, and reduce disruption. Such data are also valuable for informing decisions on rebuilding and improving building codes, earthquake-resistant design, and construction practices after an earthquake, because dense networks ensure that damaged structures have nearby reference seismic records on which to base an engineering analysis. In addition to free-field stations, sensors in buildings would support more informed assessment of building damage and decisions on re-occupancy and functionality following an earthquake.

Developing High-Resolution Damage and Impact Assessments for Critical Facilities and Lifelines

An earthquake disaster can be compounded by damage to critical facilities and lifelines, which are vital to the function of a community. The same justification for high-resolution monitoring of shaking in urban areas can be applied to critical facilities, lifelines, and infrastructure elements and nodes. The ANSS needs to increase the number of instrumented critical facilities and lifelines. High-resolution information is essential for the rapid determination of infrastructure damage, response actions, and the restoration of services. The actual shaking levels recorded at instrumented critical facilities and lifelines would be disseminated through ShakeCast. ANSS work with the VA provides an example of this type of application. In 1971, several hospitals collapsed in the M6.6 San Fernando, Calif., earthquake: since then, the VA and the USGS have collaborated to install instrumentation in VA medical centers in high-risk regions and have built the capability to rapidly assess structural health after an earthquake.

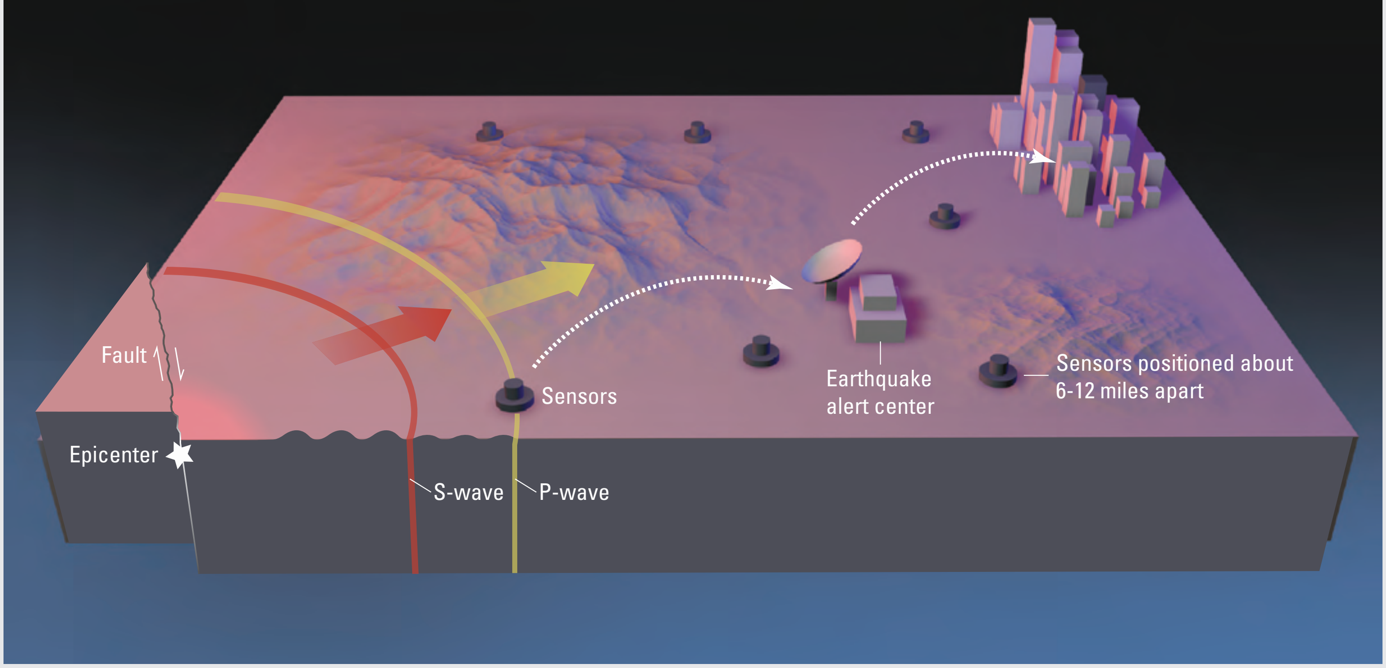
9. Earthquake Early Warning

Earthquake early warning systems, like the ShakeAlert system currently in development on the west coast of the United States, work because the warning can be transmitted almost instantaneously, while the damaging shaking waves from the earthquake travel through the Earth at speeds of a few miles per second. The faster but weaker P-waves trip a sensor, causing alerts to be sent out before the arrival of the slower but stronger S-waves and surface waves, as shown in the image below.

Seismologists are testing an earthquake early warning system similar to one being used in Japan that can send out warnings of earthquakes to your computer or mobile device seconds to minutes in advance. Here's how the system works:

EARTHQUAKE EARLY WARNING BASICS

1. In an earthquake, a rupturing fault sends out different types of waves. The fast-moving P-wave is first to arrive, but damage is caused by the slower S-waves and later-arriving surface waves.
2. Sensors detect the P-wave and immediately transmit data to an earthquake alert center where the location and size of the quake are determined and updated as more data become available.
3. A message from the alert center is immediately transmitted to your computer or mobile phone, which calculates the expected intensity and arrival time of shaking at your location.



U.S. Geological Survey image showing the basic concepts of earthquake early warning systems, such as ShakeAlert from Burkett and others (2014).

Implementing Aftershock Forecasting as a National Capability

After a major earthquake, the possibilities of significant aftershocks or even stronger events are continuing hazards that threaten a community. Public fear is high and emergency responders are at risk. The ANSS aims to provide short-term forecasts of earthquake aftershock activity for time periods of hours, days, months, and years. Authoritative, time-dependent information regarding the likelihood of aftershocks and additional large events is needed to help communities and individuals prepare. As recommended by the National Earthquake Prediction Evaluation Council in 2016, the ANSS will work to incorporate aftershock forecasts into routine seismic analysis and public notifications. To highlight the danger of earthquake sequences, note that the New Madrid earthquakes of 1811–12 in the central United States consisted of three greater-than-M7 earthquakes occurring over a period of less than 2 months.

Expanding the Observational Database for Earthquake Risk Reduction

Most advances in earthquake science and earthquake engineering research for risk reduction are achieved through access to reliable and comprehensive data resources. Continued improvement of our understanding of the causes and effects of earthquakes and their impacts on manmade structures will be heavily dependent on the scope of ANSS data.

Monitoring Data for Determining the Seismic Response of Structures and Lifelines

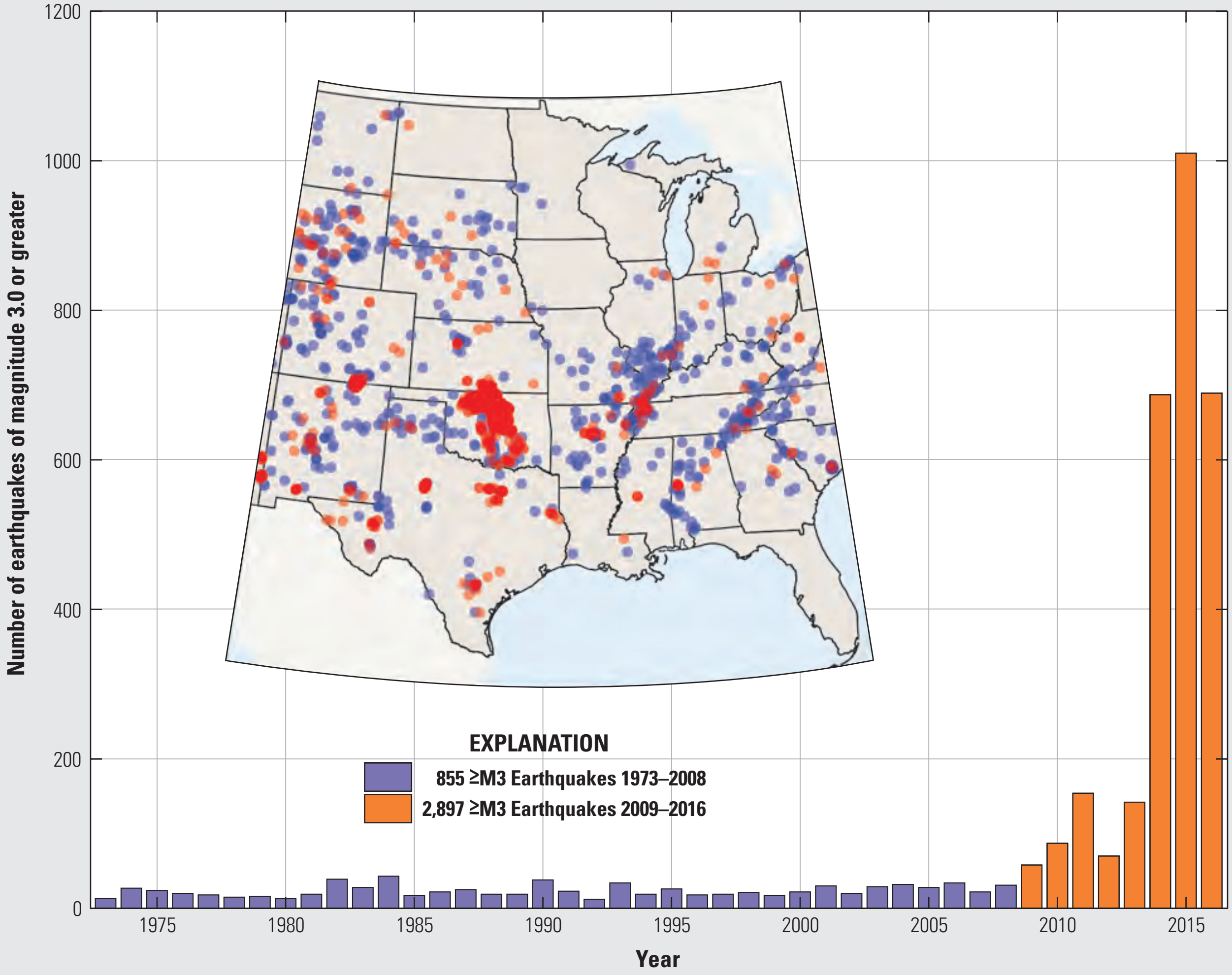
Each major earthquake provides a new learning opportunity for earthquake engineers, who use ANSS information to improve the nation's built environment. The ANSS deploys seismic instruments within representative structures to address unresolved issues in seismic design, retrofitting practices, and building codes as well as to provide validation of experimental and simulation research. When a major earthquake occurs, instrumented buildings provide data to understand the dynamics of structures and soil-structure interaction. It is important to measure how design and retrofit concepts respond to actual earthquake shaking so that they can be more generally adopted, or adapted as warranted. For example, after the Northridge earthquake, engineers were surprised by the widespread damage to moment-resisting steel-frame buildings, leading to improvements in design and construction of this building type and improved building codes. The ANSS inventory of instrumented structures should be increased to better align it with the characteristics of recent urban development (such as tall residential buildings) and hardened infrastructure for water, sewer, gas, electric, and major transportation projects. More instrumented buildings would help inform and refine policies being put in place in various cities for hazardous existing buildings (such as nonductile concrete buildings, soft-story wood frame buildings, and potentially deficient tall steel-frame buildings built in the 1950s through 1970s).

Developing Comprehensive Assessments of Human-Induced Earthquake Hazard and Risk

It has long been understood that earthquakes can be induced by certain human activities: impoundment of reservoirs, surface and underground mining, withdrawal of fluids and gases from the subsurface, and injection of fluids into underground formations. Since 2009, there has been a dramatic increase in seismic activity in some States in the central and eastern United States, including Arkansas, Colorado, Kansas, Ohio, Oklahoma, and Texas (sidebar 10, p. 25). Most of this increase is believed to be caused by the deep underground disposal of waste water resulting from oil and gas recovery processes (for example, Weingarten and others, 2015). The ANSS is making a significant contribution to the study of induced seismicity through cooperation with State agencies and networks, deployment of portable seismometers to the active areas, and special analyses of data from portable and permanent stations. The ANSS provides the infrastructure so that data from these State networks can be disseminated and integrated with ANSS participating regional seismic networks. This opportunity would increase ANSS efforts in order to provide the scientific understanding and products needed by regulatory agencies as they work to reduce the seismic activity and manage the hazard. These efforts would also support the assessment of the natural earthquake hazard in the central and eastern United States and also may reveal new information about the fundamental nature of stress in the Earth's crust.

10. Induced Seismicity

The number of earthquakes in the central and eastern United States has dramatically increased over the past decade, as shown in the figure on the right. Most of this recent increase is believed to be induced seismicity caused by the deep underground disposal of waste water resulting from oil and gas recovery processes (see for example, Weingarten and others, 2015).



Map and graph showing the locations and cumulative number of earthquakes with a magnitude of 3.0 or greater in the central United States recorded from 1973 through 2016. The rate of earthquake occurrence increased sharply beginning in 2009; there were 855 such earthquakes from 1973 through 2008 (locations shown as purple dots) and 2,897 earthquakes from 2009 through 2016 (locations shown as orange-to-red dots). *Figure courtesy of Justin Rubinstein.*

Incorporating Geodetic Data into Rapid, Comprehensive Earthquake Impact Assessments

The incorporation of geodetic data is a new element for the ANSS: the earthquake early warning implementation plan (Given and others, 2014) relies on real-time GNSS stations as an essential component of the system. Advancing the use of geodetic data is needed to help rapidly characterize the surface or ocean bottom deformation of large magnitude events, such as ruptures along the Cascadia and Alaska-Aleutian subduction zones. Information from both seismic and geodetic data will lead to more accurate understanding of the earthquake source, thereby improving earthquake early warnings, ShakeMaps, and impact assessments. Challenges lie in developing the analytical techniques for joint interpretation of seismic and geodetic data and in further development of real-time geodetic networks and data-management structure.

Improving Coverage in the Central and Eastern United States

Earthquake risk is significant in the central and eastern United States. Severe losses can occur from even moderate-size earthquakes close to major metropolitan areas and (or) critical facilities, owing to the more vulnerable building inventory and because of stronger shaking over wider areas for a given magnitude (an effect of the generally lower attenuation[1] of seismic waves and higher earthquake stress drops[2] in this region). However, the ground-motion database is too sparse and more ANSS instrumentation is needed to capture close-in recordings of major earthquakes—such as the 2011 M5.8 Mineral, Va., earthquake—to better quantify the hazard and improve the National Seismic Hazard Model. The NRC shares an interest in collecting more high-quality ground-motion data for the design and construction of nuclear facilities, as do other Federal agencies. The USGS has been working with the Office of Science and Technology Policy, the NSF, the Office of Management and Budget, the Department of Energy, and the NRC to make 158 permanent EarthScope Transportable Array stations in the central and eastern United States. An ANSS priority is to be able to assume the operation of these stations and integrate their data into analysis centers, as well as to continue to expand this region's monitoring infrastructure.

Expanding Coverage in Areas of High Seismic Hazard

Many regions with high hazard, particularly in Alaska and the Intermountain West, need expanded ANSS instrumentation, including the areas within the Alaska-Aleutian subduction zone and the Intermountain West (areas struck by the 1983 M6.9 Borah Peak earthquake in Idaho, the 1959 M7.3 Hebgen Lake earthquake in Montana, the 1934 M6.6 Hansel Valley earthquake in Utah, and the 2008 M6.0 Wells earthquake in Nevada). For all of these past earthquakes, close-in on-scale instrumental records were lacking or limited to one or two recordings. Similarly, improved monitoring is needed of earthquake swarms that could escalate into larger earthquakes, such as the recent swarms near the 1983 Borah Peak rupture and near Sheldon, Nevada. Capturing ground motions from large earthquakes would greatly improve the understanding of ground-motion prediction equations and site amplification as well as how fault segments interact and fault rupture initiates and propagates. Improving earthquake monitoring in the State of Alaska would provide data to support energy and natural resources development and to improve understanding of the Alaska-Aleutian subduction zone.

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[1]Seismic waves decay with distance owing to attenuation and geometrical spreading. Attenuation is a function of the Earth's material properties, which

[2]Stress drop is a property of an earthquake source. Earthquakes with higher stress drops have greater radiated seismic energy.

Conclusions

The ANSS began in 2000 as a bold endeavor to change earthquake monitoring in the United States. Remarkable progress has been made toward building a state-of-the-art system. As a result of investments made in the ANSS and the forging of strong partnerships, any earthquake of significance in the United States or anywhere in the world can now be rapidly characterized by a suite of products, providing situational awareness during times of crisis. ANSS monitoring serves scientific research and earthquake engineering needs.

But challenges lie ahead, and the full potential of ANSS is not yet realized. After 16 years, the ANSS is less than halfway completed and its capabilities have not kept pace with the nation's increasing earthquake risk. As described previously, the ANSS has the capacity to grow in order to improve earthquake safety and to support response and recovery and resilience nationwide. ANSS priorities for the next decade are to ensure ANSS readiness in an earthquake crisis, advance earthquake safety in urban areas, and expand the observational database for earthquake risk reduction. The ANSS community has achieved progress through their spirit of hard work, cooperation, innovation, and dedication to public service and safety. They will meet the challenges in the same spirit.

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Appendix: Planning Considerations for 2017–2027

The opportunities cited in this circular set the framework for ANSS planning into the future. Useful plans must be practical, taking into account the funding needed in addition to fulfilling current operational responsibilities. This appendix reviews the current financial status of the ANSS, the estimated resources needed for its development opportunities and priorities, and the expected outcomes.

Current Resources and Responsibilities

Total funding for the ANSS from the USGS Earthquake Hazards Program in fiscal year (FY) 2016 was $30.8 million, including $8.2 million for the implementation of earthquake early warning (EEW) on the west coast. This funding provides the support for the ANSS to meet its responsibilities in the activities listed below.

- Eleven regional seismic networks operated by academic institutions. Some of these networks are operated jointly with the USGS.
- The “ANSS backbone” National Seismic Network, providing uniform coverage nationwide in areas not covered by regional networks.
- The National Earthquake Information Center (NEIC), a 24/7 data analysis center for national and worldwide earthquakes.
- The National Strong Motion Project providing data on very strong earthquake shaking, both on the ground and in buildings, for earthquake-resistant engineering research and design and for ShakeMap.
- Continuing development of ShakeAlert EEW operational capability on the west coast.
- ANSS management and organizational support.
- Support of data centers for archiving and distribution.
- Portable instrument cache for temporary deployments.

With the exception of funding for the EEW development effort, all of the USGS ANSS funding in FY 2016 was applied to ongoing operations, maintenance, and management. Thus, new funding is needed to fully realize the opportunities listed in this circular.

Development Needs and Outcomes for 2017–2027

The ANSS planning structure for the next decade is based on three major opportunities and their associated priorities. Notional budgets to advance each opportunity are given below, in 2016 dollars. Implementing all of the opportunities would require a substantial increase in the USGS annual budget for the ANSS, which was $30.8 million in FY 2016, or obtaining additional contributions from non-USGS supporters of the ANSS.

Opportunity A. Ensuring Readiness in an Earthquake Crisis

Resources needed: Moderate ($5 million per year). Resources would address practical issues, such as providing adequate staffing levels, hardening communications, supporting the amortization and replacement of aging equipment, improving software, deploying better backup capabilities, and improving quality control by performance tracking.

Result: Users will have greater assurance that they will receive the high-quality ANSS products and services in an earthquake crisis, leading to improved response and recovery. ANSS systems and procedures will be tested under realistic earthquake crisis conditions and hardened to be sufficiently robust.

Opportunity B. Advancing Earthquake Safety in Urban Areas

Priority B.1. Developing Earthquake Early Warning Systems

Resources needed: Substantial. An EEW planning document (Given and others, 2014; USGS Open-File Report 2014–1097) estimates that a capital investment of $39 million and an ongoing $16.4 million per year would be needed to operate and maintain a complete EEW system along the west coast (note that congressionally appropriated EEW funding grew to $8.2 million by FY 2016, which is about one-half of the needed yearly funding). This funding would be in addition to the regular ANSS and State support of west coast networks. Additional funding would be needed to expand EEW capabilities to other regions in the United States.

Geodetic data would be integrated along with seismic data into the ShakeAlert earthquake early warning system. Development of geodetic applications is dependent on long-term support for and improvements to real-time geodetic network operations, so that they can be added as participants in the ANSS.

Result: A fully operational ShakeAlert earthquake early warning system that reliably issues public warnings of imminent ground shaking within a few to tens of seconds of an earthquake onset on the west coast of the United States.

Priority B.2. Developing High-Resolution Damage and Impacts Assessment for Urban Areas

Resources needed: Moderate ($5 million per year). Coverage of dense strong-motion instruments in high- to moderate-risk urban areas would be expanded. The ANSS would work with industry to develop a low-cost sensor package to meet this objective, following on from the previous, successful NetQuakes sensor project.

Result: High-resolution information on the ground shaking intensity and variation will be available across select urban areas following an earthquake. Having such information will support effective earthquake response and rebuilding and advances in earthquake engineering and improved hazard assessments. Engineering methods now exist that use seismic records as part of post-earthquake inspections to assess the safety and functionality of a structure, and high-resolution information would support more frequent use of these sophisticated methods.

Priority B.3. Developing High-Resolution Damage and Impact Assessments for Critical Facilities and Lifelines

Resources needed: Moderate ($3 million per year). The ANSS would work with regions to identify the highest priority targets for instrumentation and to establish a deployment strategy with facility owners and lifeline managers. ANSS costs also include instrumenting facilities, collecting and analyzing the data, and pushing results to operators. This effort would build on the existing ShakeCast service. As in priority B.2, a next-generation, low-cost sensor technology would be developed.

Result: Ground-shaking information that will allow more rapid restoration of vital services to a community when a major earthquake strikes. For example, State Departments of Transportation (DOTs) may oversee hundreds to thousands of bridges and overpasses. Several DOTs already use ShakeCast to obtain automatic notification about which facilities in their inventory have possibly been damaged in an earthquake. ShakeCast output will help a DOT to set priorities for traffic rerouting, closures, and inspections, illustrating how timely and accurate ANSS data is important to ensure public safety and to reestablish critical functions.

Priority B.4. Implementing Aftershock Forecasting as a National Capability

Resources needed: Moderate ($2 million per year). Concepts and procedures have been developed for aftershock forecasting. Additional funds would support personnel to implement the forecast procedures to run in real time as a part of the NEIC, as well as for research and development in the field and for end-user education. Because forecasts would be built from the ANSS Comprehensive Catalog (ComCat), further enhancements of ComCat would be needed, including the completion of the loading of regional seismic network historic catalogs and the implementation of version control so that forecasts can be reproduced and methods can be improved by the scientific community.

Result: Routine notifications of aftershock likelihoods after significant earthquakes nationwide, calculated for time periods of hours, days, months, and years, to improve public awareness and readiness and to inform emergency managers.

Opportunity C. Expanding the Observational Database for Earthquake Risk Reduction

Priority C.1. Monitoring Data for Determining the Seismic Response of Structures and Lifelines

Resources needed: Moderate ($5 million per year). The ANSS would substantially increase the number of instrumented structures and lifelines, choosing targets to address specific unresolved issues in seismic design, retrofit practices, and building codes. The ANSS also would need support for data management and analysis.

Result: A breadth and depth of data on the response of common types of structure design and construction to seismic shaking will be successfully recorded in a major earthquake, resulting in transformational breakthroughs in the engineering of cost-effective structures that perform well in an earthquake.

Priority C.2. Developing Comprehensive Assessments of Human-Induced Earthquake Hazard and Risk

Resources needed: Moderate ($3 million per year). Resources would be used to support and cooperate with State networks and for ANSS data analysis and interpretation. To pinpoint the location and depth of induced seismicity sequences, portable arrays of closely spaced seismic instruments would also be needed in a study area.

Result: Providing data needed to develop science-based protocols for activities that have potential to induce earthquakes, such as to achieve safe, deep underground disposal of waste water associated with oil and gas production.

Priority C.3. Incorporating Geodetic Data into Rapid, Comprehensive Earthquake Impact Assessments

Resources needed: Moderate (to be determined; note that some costs are included in priority B.1). Geodetic data would be integrated along with seismic data into ANSS products. Analytical techniques for joint interpretation of seismic and geodetic data and real-time geodetic networks and data-management structure will be developed and expanded.

Result: More rapid and accurate characterization of earthquake sources for earthquake early warning and impact assessments; inclusion of real-time geodetic networks as ANSS participants.

Priority C.4. Improving Coverage in the Central and Eastern United States

Resources needed: Moderate ($1.5 million per year). This funding would be used to support the operations of the Central and Eastern United States Network (CEUSN) seismic stations, to integrate data from these stations into existing data analysis procedures, and to further improve strong-motion station coverage.

Result: Better monitoring and increased understanding of the seismic hazard and societal risk in the eastern half of the United States. Key data for improved ground-motion prediction equations will be successfully captured in a major earthquake, resulting in significantly reduced uncertainty in the National Seismic Hazard Model.

Priority C.5. Expanding Coverage in Areas of High Seismic Hazard

Resources needed: Moderate ($6 million per year). Funds would be used to deploy additional sensors and to support their operation in areas of high seismic hazard, in order to address gaps in coverage. Additional planning would be undertaken at the regional level.

Result: Better seismic monitoring and increased understanding of earthquakes at active faults, with particular focus on the Intermountain West and Alaska.

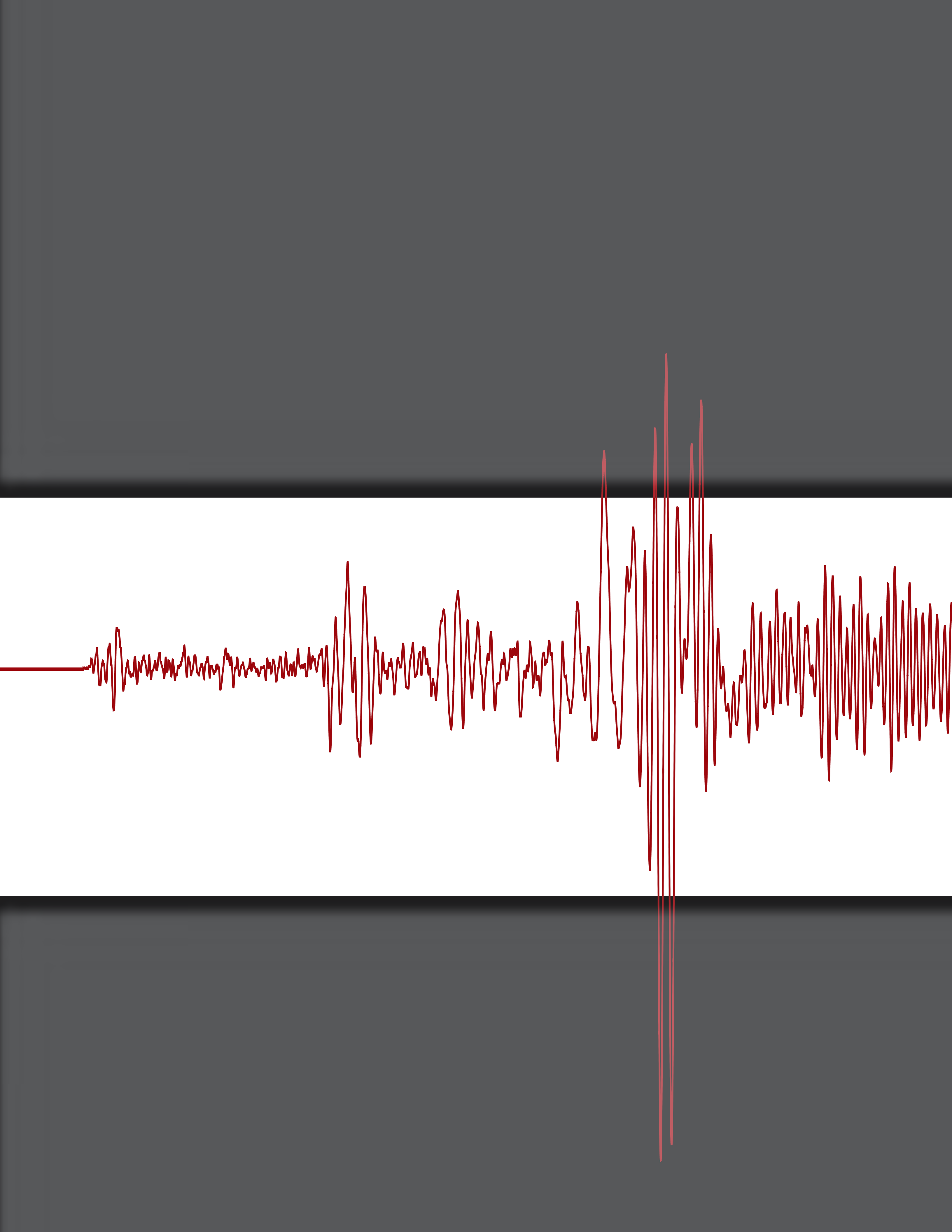
Resources—Existing and Needed

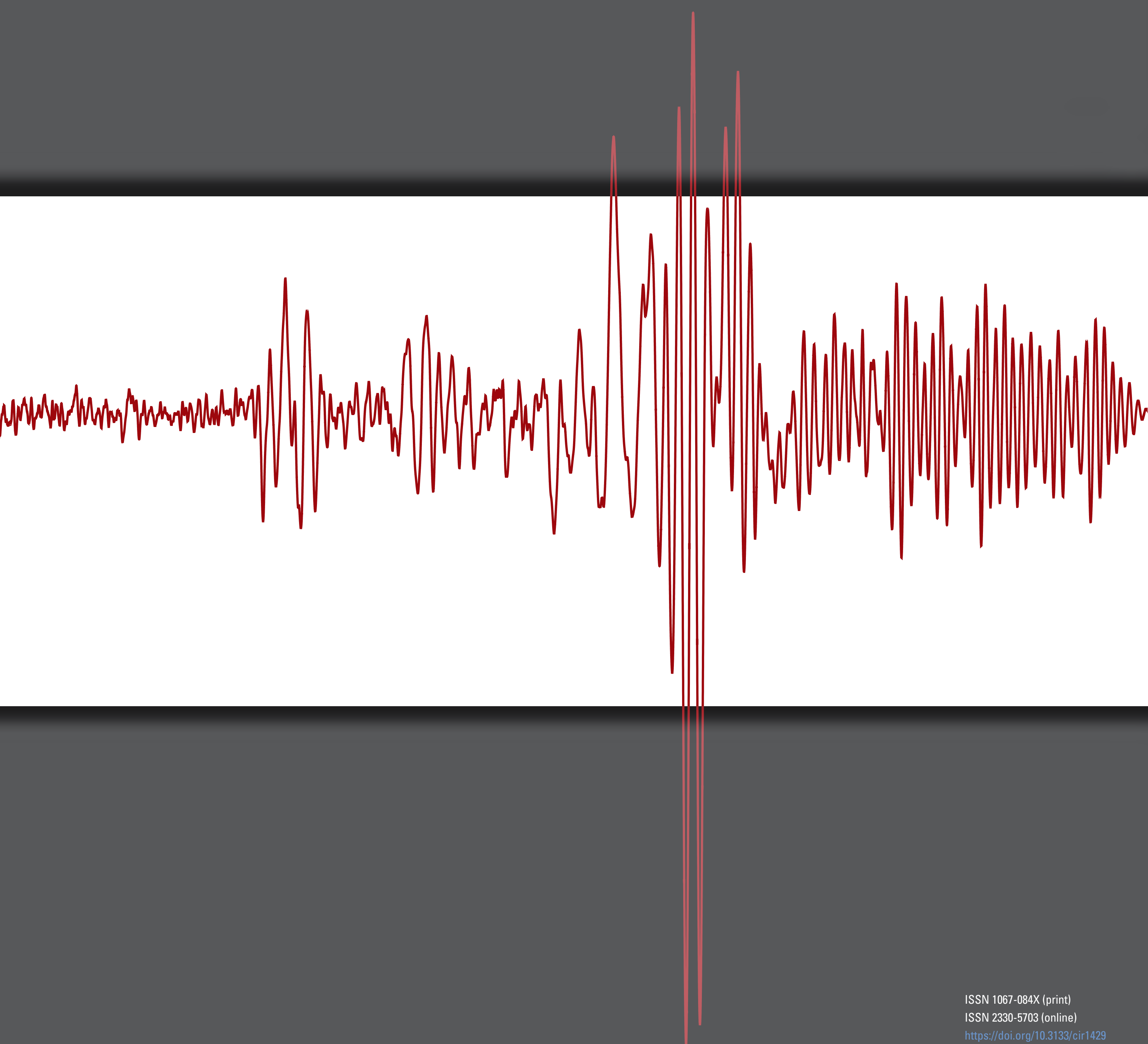
Table A1 breaks down how much of the annual ANSS budget is currently being spent on activities that are broadly related to the above priorities as well as the augmentation to the annual resources that would be needed to fully implement these opportunities over the next decade (2017–2027). In addition to the annual resources to implement and maintain these opportunities, additional funds for capital investment into the earthquake early warning system on the west coast would also be needed.

Table A1. Advanced National Seismic System current annual resources and estimated augmentation to resource allocation needed to fully implement each development opportunity from 2017 to 2027.

[Abbreviations used: NA, not applicable; TBD, to be determined]

Development opportunity		Annual resources (millions of 2016 dollars)		
Code	Short title	Current	Augmentation	Total
A	Earthquake crisis readiness	6.2	5.0	11.2
B.1	Earthquake early warning	8.2	8.2	16.4
B.2	Monitoring of urban areas	1.7	5.0	6.7
B.3	Monitoring of critical facilities	0.4	3.0	3.4
B.4	Forecasting aftershocks	NA	2.0	2.0
C.1	Monitoring of structures	1.0	5.0	6.0
C.2	Monitoring of human-induced seismicity	NA	3.0	3.0
C.3	Incorporating geodesy	NA	TBD	TBD
C.4	Monitoring in central and eastern United States	2.5	1.5	4.0
C.5	Monitoring of high-hazard areas	10.1	6.0	16.1
Other	Management and coordination	0.7	0.5	1.2
Total		**30.8**	**39.2**	**70.0**





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