

Future Geophysical Facilities Required to Address Grand Challenges in the Earth Sciences



A COMMUNITY REPORT TO THE
NATIONAL SCIENCE FOUNDATION

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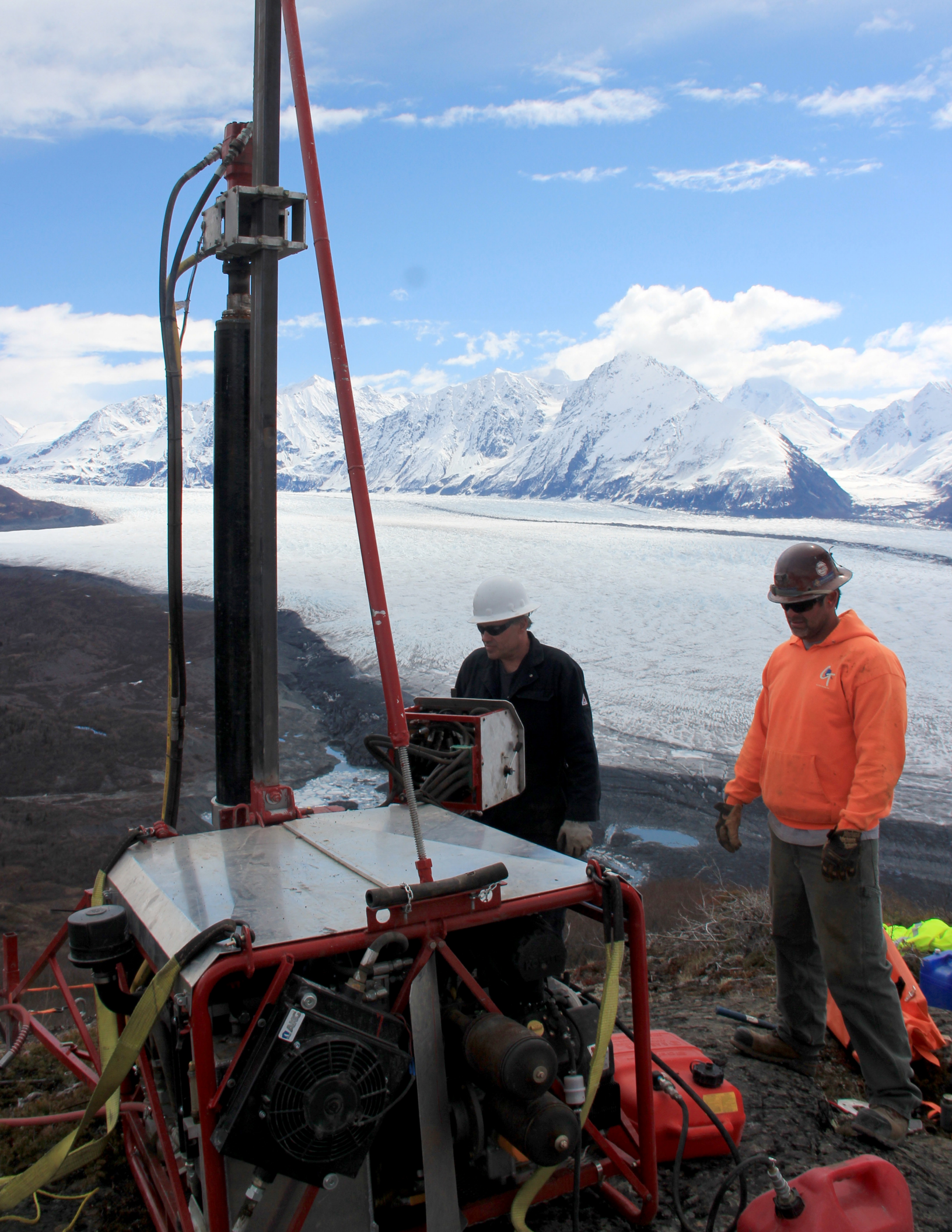
White Papers submitted in support of the Workshop on Future Seismic and Geodetic Facilities Needs in the Geosciences can be downloaded from:
http://www.iris.edu/hq/files/Futures_Workshop_Whitepapers_email_v2.pdf.



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Executive Summary

Seismology and geodesy are mainstays of modern observational geophysics and have experienced remarkable progress over the past several decades. This progress is reflected both within the core disciplines and across the many Earth science fields that now rely on seismic and geodetic results. The highly successful centralized National Science Foundation (NSF)-funded community facilities are key factors enabling these advances. These facilities, frequently supported in partnership with other agencies, have provided essential support that spans instrumentation, data management, experiments, and broader impacts. Economy-of-scale advantages combined with community governance and management have ensured the wide utilization of facility resources across diverse research institutions and have enabled the community to pursue, and NSF to support, both small- and large-scale science projects efficiently and effectively.

This report synthesizes community input on future geophysical facility requirements for the next decade and beyond and provides advice to NSF in advance of the 2016–2017 facility recompetition. This report is the outcome of an NSF-sponsored workshop, “Future Seismic and Geodetic Facility Needs in the Geosciences,” held 4–6 May 2015 in Leesburg, VA, and of associated prior and

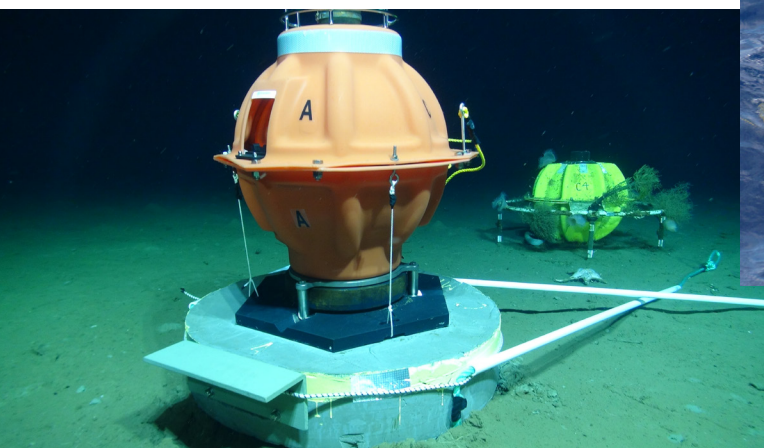
subsequent community activities, which included white papers, broad community email review, webinars, and engagement of a community writing committee spanning diverse specializations.

The needs summarized here include both those judged to be necessary to sustain ongoing funded scientific efforts and those needed to respond to current and future opportunities of the geophysical and broader Earth science research community. In articulating these critical resources for the community, we include a community vision of expectations for the facility material, human resources, and organizational attributes required to continue and advance science, as realized in *Centers of Excellence*. We identify some of the key general areas of research, highlighted in recent community reports, where facility capabilities play essential roles, and elucidate their broader impacts. These research areas include Earth structure and evolution, fault zones and the earthquake cycle, magmatic systems, plate interiors, glacier and ice sheet dynamics, sea level change, surface and near-surface hydrology, structure, and dynamics, and soil moisture, snow, and vegetation water content. Finally, we sort the required facility capabilities into three general categories: *Existing Foundational*, *Emergent Foundational*, and *Frontier* as follows.

EXISTING FOUNDATIONAL

Capabilities that are fundamental and essential to present and near-term science directions, including the continuation of currently funded NSF projects.

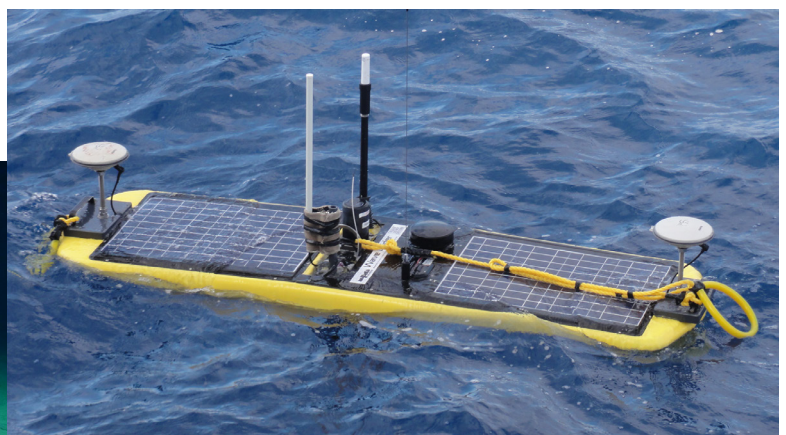
1. Maintained permanent seismic, strainmeter, and geodetic networks
 - A global very broadband seismographic network
 - Permanent and continuously recording GPS networks
 - A network of borehole strainmeters
2. Deployable seismographic systems
 - Portable broadband seismographs for local to subcontinental networks and arrays
 - Controlled-source seismograph systems
 - Seismic source facilities
 - Ocean bottom seismographs
3. Deployable geodetic observation systems
 - GNSS instrumentation
 - Terrestrial lidar instrumentation
 - Continued installation and occupation of campaign-mode seafloor geodetic monuments
4. Land and marine magnetotellurics
5. Data archiving, quality control, and distribution
6. Hosting of community-provided products and services
7. High-level computational modeling tools
8. Professional staff support
9. Workforce development
10. Professionally staffed nationwide education and public outreach



EMERGENT FOUNDATIONAL

Components that incorporate current technologies would drive significant progress on major science challenges and were judged to be high priority for the 2018–2023 time frame.

11. Large-N intermediate-period to high-frequency arrays
12. Instrumentation for rapid response
13. Access to large volumes of InSAR data and products
14. Operational GNSS processing
15. Enhanced capabilities to explore, develop, and apply next generation and emerging instrumentation
16. Instrumentation for geomorphological, glaciological, surface and near-surface, and critical zone geophysics
17. Onshore seismic source capabilities
18. Land and marine EM capabilities
19. Expanded ocean bottom seismographic and geodetic capabilities
20. High-bandwidth and real-time global telemetry
21. Development of instrumentation and telemetry systems capable of supporting multidisciplinary environmental observatories
22. Ubiquitous access to HPC resources
23. National-scale engagement with K–12 education





FRONTIER

Those capabilities that are, to varying degree, nascent, but are of significant interest to the community for their potential to enable transformative science and ensure continued scientific progress.

- 24. Seafloor and free-floating geophysical networks
- 25. Next-generation magnetotelluric and controlled-source electromagnetic capabilities
- 26. Deep borehole access and instrumentation
- 27. Instrumentation for high-risk/high-benefit experiments
- 28. Frontier programs to communicate broad understanding of Earth system science
- 29. Academic and workforce diversity and transformative workforce development



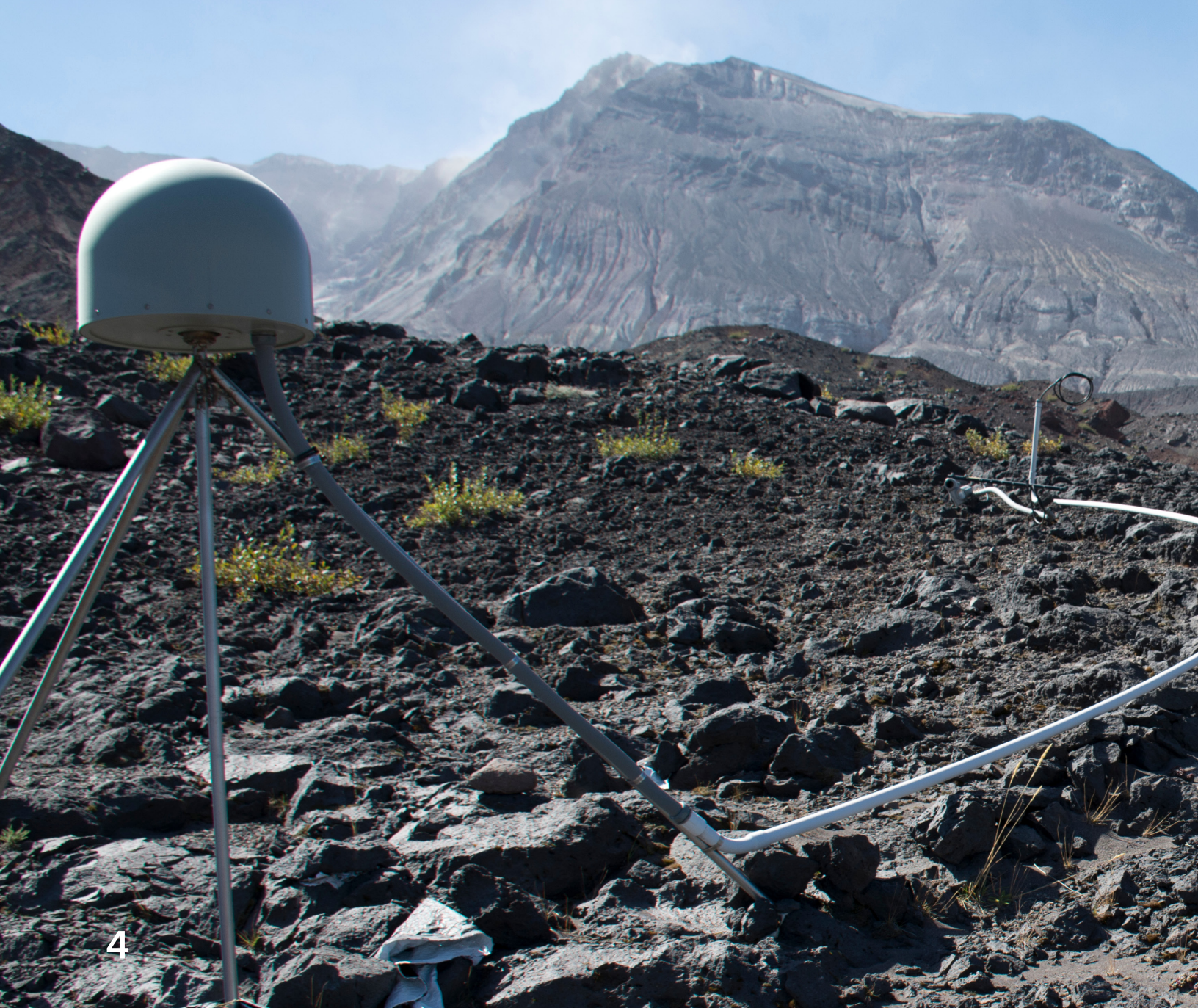
Our *Centers of Excellence* have led our community in many aspects of education at all levels, as well as in efforts to increase diversity in the Earth sciences, workforce development, and public outreach to both increase general scientific literacy as well as to inform necessary officials on critical issues facing local, state, and federal governments. The issue of diversity in Earth sciences continues to be particularly challenging as we go forward. Such outreach activities continued to be a high priority for the community throughout the development process of this report.

Finally, satisfying the rapidly evolving requirements of world-class Earth science requires that all aspects of this endeavor be adaptively and transparently coordinated, managed, and governed. This vision mandates significant and ongoing engagement by the scientific and educational communities for whom these facilities have become critical components of success.

1. Introduction

The Division of Earth Sciences (EAR) in the Directorate for Geosciences at the National Science Foundation (NSF) currently supports two high-quality community-governed geophysical facilities—Geodesy Advancing Geosciences and EarthScope (GAGE) and Seismological Facilities for the Advancement of Geosciences and EarthScope (SAGE). These facilities provide geodetic, seismic, and related geophysical instrumentation, data archiving/quality control/distribution, and educational services to a wide range of EAR and other NSF-supported communities. GAGE is currently managed by UNAVCO (www.unavco.org) and

SAGE is currently managed by the Incorporated Research Institutions for Seismology (IRIS; www.iris.edu). NSF is preparing for a competition for future follow-on cooperative agreement(s) to support one or more facilities following expiration of the current GAGE and SAGE cooperative agreements in September 2018. The planned competition is the second stage in a two-stage process that NSF developed, presented to the National Science Board, and described to the community in 2009 (Dear Colleague Letter NSF 10-021). NSF will release a program solicitation in early 2016, with full proposals due in late 2016.



NSF sponsored a series of activities to gather community input into this process. These activities included topical webinars, a collection of white papers, and a workshop with over 110 attendees, “Future Seismic and Geodetic Facility Needs in the Geosciences” (4–6 May 2015 in Leesburg, VA) to explore and describe future geophysical facility requirements to sustain scientific progress and to respond to current and future opportunities for, and aspirations of, the research community. This report synthesizes the outcomes of these activities. While the totality of geophysical and associated community needs will not be met by the specific facilities being recompeted in 2016–2017, this report includes aspirational elements that should be considered as future opportunities arise within NSF EAR or elsewhere.

The report is structured as follows. **Section 2** summarizes the community vision for the key attributes of our future facilities. **Section 3** examines selected areas of geophysical investigation that rely on these facilities. **Section 4** articulates selected areas of societal relevance. **Section 5** conveys the community consensus of required facility capabilities—categorizing these capabilities as *Existing Foundational*, *Emergent Foundational*, and *Frontier*.



2. Facility Vision and Scope

Geophysical and related Earth science disciplines have been transformed during the past several decades by the advancement of community facilities. Indeed, the present NSF-supported facilities (SAGE and GAGE) can be characterized as *Centers of Excellence*. They have set national and international standards for scientific-community-serving facilities. They provide broad access to instrumentation, as well as training in their effective use, and distribute open and free data to all. They make it possible for diverse PIs and institutions across the research and educational spectrum to pursue research that would otherwise be closed to them.

SAGE and GAGE have continued to maintain extensive disciplinary and interdisciplinary coordination necessary to set and sustain the Earth science facility baseline at a high level. These facility contributions continue to be key to successfully realize targeted community science efforts of exceptional ambition, significance, and scale (e.g., EarthScope). Community oversight of these facilities has ensured the resource optimization and programmatic agility required for continuous and effective adaptation to

the needs of our rapidly evolving fields. Such oversight has also ensured the cost-effective and professional support for the critical development, integration, and deployment of standardized technologies and data formats, and the data tools that support them.

Extensive community involvement in facility committee structures has significantly cultivated leadership skills within the NSF-affiliated academic community. These facilities attract, support, and mentor the diverse next generation of Earth science professionals and facility specialists. These facilities are internationally recognized and influential organizations that catalyze and sustain unique and valuable governmental, facility, and science community collaborations worldwide. These facilities play critical roles in advancing the education and public outreach footprint of Earth science for all audiences, helping to ensure that federally supported science reaches the widest audience and greatest level of prominence and influence. Creating and sustaining of these *Centers of Excellence* has been transformative for the United States and the international geophysical communities.

Community engagement has included budgetary prioritization and planning, as well as responsible fiscal and programmatic governance sustained with broad community representation. This engagement, primarily voluntary in nature, coupled with the presence of dedicated, knowledgeable, and specialized professionals within the facilities, is an essential component of why we view the current facilities as *Centers of Excellence*.

Facility *Centers of Excellence* encompass:

- Providing access to state-of-the-art instrumentation and broader experiment support for both PI-led and larger-scale community-led projects to enable both hypothesis-driven and discovery-mode science.
- Receiving, archiving, and distributing diverse free and open data types, and providing associated community-wide data quality, curation, dissemination, and utilization services within an effective and standardized cyberinfrastructure.

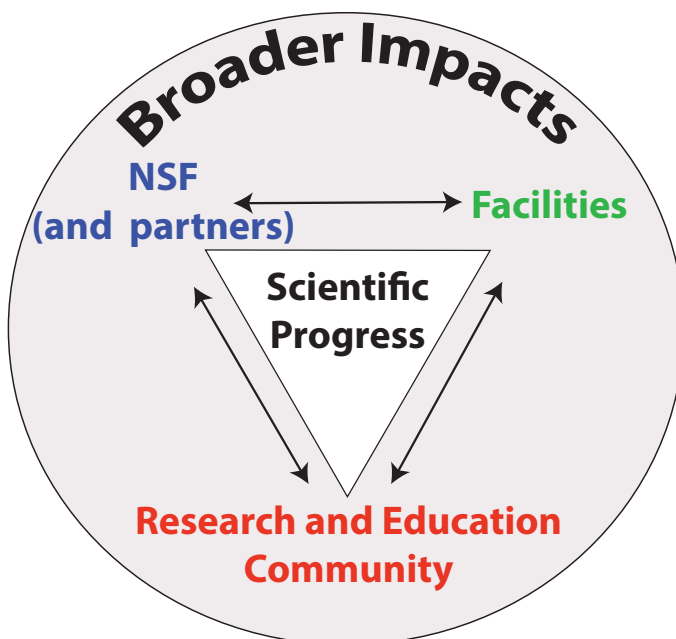


Figure 1. Facility *Centers of Excellence* require strong bidirectional linkages between NSF, the research and educational community, and the facilities.

- Effectively advocating for and exemplifying expanded national and international free and open data and scientific exchanges.
- Enabling access to facility resources for researchers working from institutions encompassing a wide range of sizes and in-house resources.
- Providing expertise and leadership in the exploration, development, and utilization of new technologies.
- Supporting geophysical monitoring as well as hazard assessment, response, and mitigation efforts by academic, state, and federal agencies.
- Serving as community resources and partners for training and education (at all levels), for broader outreach, and for enhancing societal understanding and appreciation of Earth sciences and their relevance.
- Attracting, retaining, and mentoring long-term professional facilities staff.
- Operating transparently, responsively, efficiently, and adaptively to address scientific priorities through community governance and oversight.

To ensure that NSF geophysical facilities remain *Centers of Excellence*, it is imperative to sustain and advance capabilities with an intellectual and operational agility that keeps pace with the rapid scientific and technological developments that characterize Earth science today. For example, the community envisions a future that includes: (1) near-real-time and daily maps of deformation derived from integrated seismic, Global Navigation Satellite System (GNSS) instrumentation, and orbiting radar satellite data;

(2) anchored and drifting seafloor and water column geophysical instrumentation distributed around the globe; (3) arrays of fiber optic cables providing spatially continuous high-rate sampling of surface strain; (4) aerial and marine drones that can be customized to host and/or deploy a range of instrumentation; (5) large instrumentation pools that can be routinely deployed in diverse environments and across a range of scales to record the full spectrum of dynamic events, ranging from coseismic offsets, to slow deformation, to spatially unaliased seismic wavefields; (6) global telemetry providing high-rate and low-latency sampling from any number of remote instruments; and (7) routine access to high performance computing (HPC) and associated capabilities for data reduction and model inference on an unprecedented scale.

In this vision, it is paramount that we embrace our responsibility to train the next generation of diverse Earth scientists and to improve broad scientific literacy in a world that includes rapid and often unpredictable changes. These efforts include enhancing strategies to inform fellow citizens of the growing and critical relevance of Earth science to society. We envision facilities where these broader impacts are vigorously supported by engagement with a wide ranging community of educators and other partners.



3. Scientific Grand Challenges Addressed by Centers of Excellence

In recent decades, community geophysical facilities supported by NSF and partner agencies have catalyzed significant and steady advances in the Earth sciences across the geophysical and associated disciplines. Many fundamental scientific Grand Challenges and associated facility challenges remain and are ongoing targets of highly diverse research efforts, as highlighted in a number of recent community-led documents (see [Appendix](#)). In addition to enabling new experimental concepts and methodologies to be realized in the pursuit of key scientific problems, in some cases envisioned decades earlier, facility capabilities spur entirely new sectors of research at a wide variety of spatial and temporal scales. Examples include the discovery and improved understanding of transient deformation in subduction zones and of dynamic glaciological processes.

Revolutionary methods have evolved to exploit information within seismic and geodetic signals that were previously considered to be “noise.” These methodologies commonly require extensive volumes of very high quality, uniform, openly available, and continuous data, and facility data management systems have thus played an essential role in their advancement. Facilities activities and resources have been key to enabling the dramatically expanded application of seismographic and geodetic instrumentation to oceanographic, hydrological, cryospheric, volcanological, near-surface, and atmospheric research.

Here, we provide an overview of broad areas of research (without prioritization implied) where facility capabilities described in this report have played and are playing essential roles. The overview begins with deeper and global-scale Earth processes on the grandest scales and progresses upward to encompass hydrospheric, cryospheric, critical zone, and surface processes.



3.1. EARTH STRUCTURE AND EVOLUTION

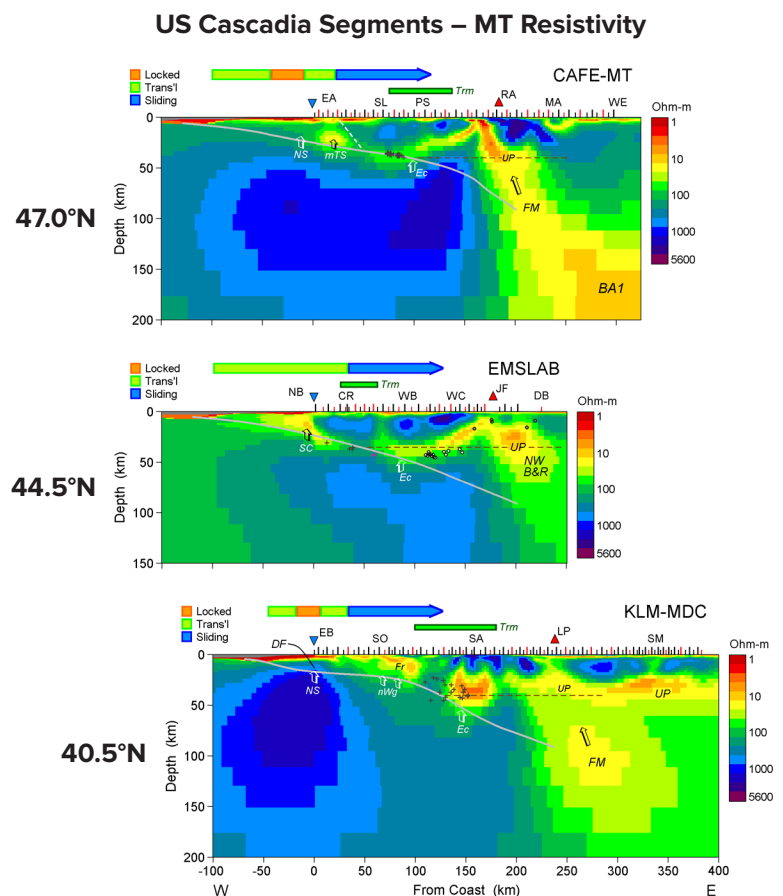
Over the past few decades, major progress has been made in understanding large-scale structures and dynamical processes within Earth's interior at a wide range of spatio-temporal scales. The *New Research Opportunities in the Earth Sciences* report (NROES, 2012) highlights the need for research on “thermo-chemical internal dynamics and volatile distribution” for core and mantle dynamical systems. This research requires improved resolution of global-scale structures, rheology, and deformation that can only be achieved by interdisciplinary efforts in seismology, geodynamics, and mineral physics and through use of additional geophysical techniques such as electromagnetic (EM) induction, with enhanced spatial sampling and improved methodologies for characterizing volumetric heterogeneity, anisotropy, and boundary layer structures throughout the interior.

Half of the Seismological Grand Challenges identified by the community relate to topics of “stress and rheology of the crust and mantle,” “distribution and circulation of fluids

and volatiles in Earth's interior,” “evolution and coupling of the lithosphere and asthenosphere,” “thermo-chemical structures and dynamics of the mantle and core,” and “Earth's internal boundary layer processes.” All of these Grand Challenge topics require continued operation of global broadband geodetic and seismological networks and high-density portable instrument deployments in diverse regions.

Quantifying complex mantle and core dynamical systems is essential to understanding Earth's thermo-chemical evolution. It is also critical to understanding the ongoing circulation systems that generate the magnetic field and drive plate tectonics, and the carbon, water, and other volatile budgets that critically affect the surface environment. With improving resolution, studies of complex volumetric and anisotropic heterogeneity within the inner core may reveal the growth history of the core and the evolution of Earth's geodynamo. Understanding mantle-core coupling and the influence of lateral mantle variations on the geodynamo requires knowledge of dynamic topography and processes affecting the core-mantle boundary. New determinations of outer core thermal conductivity are dramatically

Figure 2. Resistivity cross sections from land magnetotelluric profiles across different segments of the Cascadia subduction system. Below the coastline, high resistivity appears to be associated with plate locking, whereas the poorly locked North Central Oregon interface is conductive, in part reflecting possible subducted sediments. A local zone of oceanic plate detachment and possible ophiolite formation is interpreted from shallow high resistivity and high seismicity under the coast of the Klamath-Modoc (KLM-MDC) profile. Low-frequency earthquakes are coincident with enhanced conductivity, supporting interpretation of eclogitization and fluid release. Such fluids appear to rise through the mantle wedge to the deep and middle crust. Deep long-period earthquakes following the rising low-resistivity layer were observed under the EMSLAB line. Upper mantle flux melting zone below arc observed for the compressional and strike-slip northern and southern segments. Basin and Range style extension is conjectured to destroy E-W melt interconnection under the EMSLAB line, preventing pronounced low resistivity. Magmatic underplating in the deep crust is interpreted on all three lines. Concepts of these three profiles supported by analysis of magnetotelluric profiles across Vancouver Island-southern British Columbia and across southern Oregon. *After Wannamaker et al. (2014)*



Vignette 1. Global Earth Structure

Imaging three-dimensional Earth structure from the crust to the core with increasing resolution is key to improving our fundamental and detailed understanding of the past and present-day dynamic processes that drive plate tectonics and the geological and geochemical evolution of the planet. Global structures couple into the fault and magmatic systems that result in natural hazards such as earthquakes, tsunamis, and volcanic eruptions, and that generate and maintain the magnetic field. Facilities-abetted progress during the last several decades in the quantity and quality of data from globally distributed broadband seismographic stations, coupled with transformational developments in new techniques for the modeling and inversion of the seismic wavefield for complex media and realized with increased high performance computing capabilities, has opened up new horizons in global imaging of the mantle and core. This advance is illustrated, for example, by an improved ability to image and characterize low-velocity regions in the deep mantle associated with upwelling flow. The extent of the top-to-bottom convection system of the mantle has been a subject of vigorous debate for the last 30 years (Figure V1). Modern images of large-scale structures now strongly suggest a connection between processes at the base of the mantle and hotspot volcanoes at the surface. Seismic images have also established in recent years that some slab material reaches the base of the mantle. Global imaging is rapidly advancing. As techniques continue to improve, new data become available from the continents and ocean, and the appropriate data sets are assembled and analyzed, we can expect to image such structures in far greater detail. To make further progress requires expanded global seismic data collection and geographic coverage on continents and in the ocean.

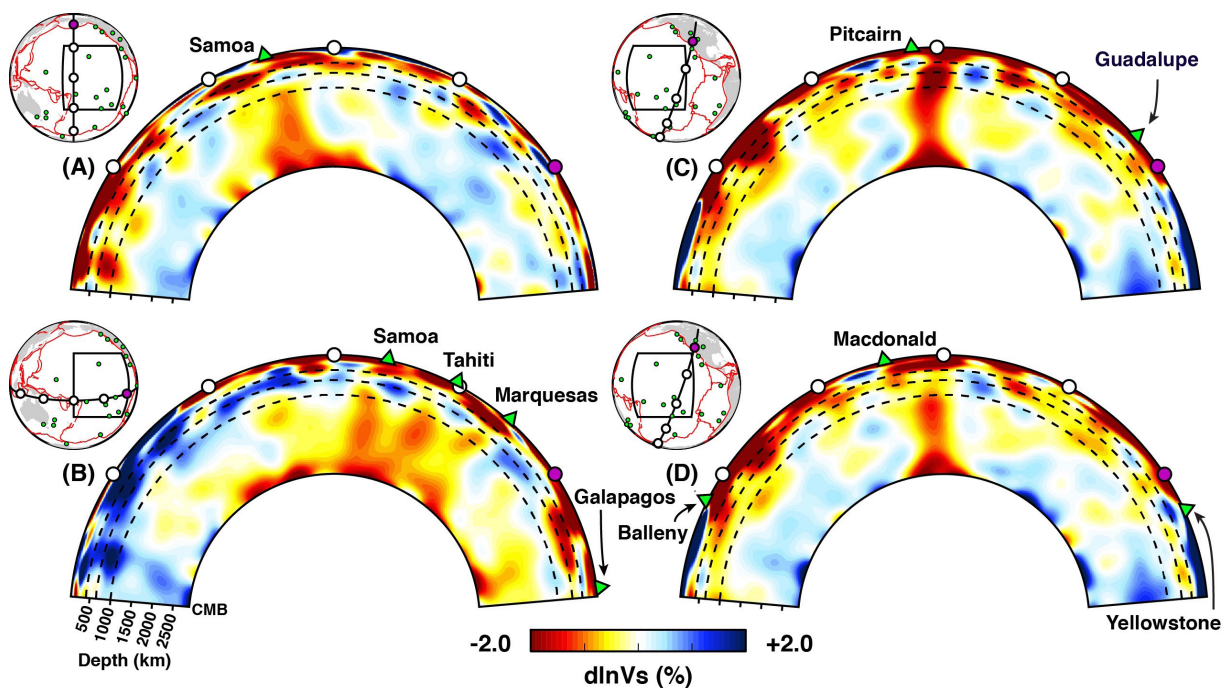


Figure V1. Recent high-resolution imaging of lower mantle shear wave velocity structure achieved with full-waveform seismogram inversion and high performance computing. Shown are several depth cross sections in the vicinity of prominent hotspots (labeled) that span 180° of the whole mantle. Cross section location is shown in map view on the left of each panel. Until recently, the presence of plume-like structures beneath major hotspots was suggested but not unequivocally resolved. Such vertically oriented plume-like low-velocity conduits are shown to be present under all major hotspots that are located above the deep mantle large low-shear velocity provinces. Their morphology, which will be further constrained as data and methods improve, indicates that the classical thermal plume model, with thin tails and wide heads, does not apply to Earth's mantle. After French and Romanowicz (*in press*)

increasing estimates of conductive heat transport, with profound implications for thermal and chemical evolution of the core and mantle. Diverse lowermost mantle structures, including ultra-low velocity zones, strongly laterally varying seismic velocity discontinuities, and large low-seismic-velocity provinces, have been discovered, but higher-resolution imaging is required to clarify their thermal and chemical nature and their role in the mantle convection and differentiation system. Evidence is accumulating for large-scale upwellings in the lower mantle that may connect all the way to the surface, but again, to establish the nature of these structures requires more detailed knowledge of seismic structure. Improved imaging of both global and small-scale structure in transition zone velocity discontinuities is needed to evaluate convective, and possibly water, transport through the upper mantle.

3.1.1. Plate Boundary Systems

Understanding key geochemical and dynamical processes at subduction zones, rift zones, transforms, and mid-ocean ridges is an interdisciplinary endeavor, requiring seismology (global and regional, on land and offshore), geodesy (continuous and campaign GPS, interferometric synthetic aperture radar [InSAR], seafloor pressure and geodetic measurements), magnetotellurics (offshore and onshore MT and controlled-source EM), fault zone drilling, and satellite gravity measurements, as well as geochemistry, petrology, and field geology.

One example of a major recent discovery substantially advanced by geodetic and seismological facilities is that of episodic slow slip, seismic tremor, and upper plate transient deformation in subduction systems (**Vignette 2**). This discovery has opened up entire new research directions that now require sustained data collection in diverse subduction zones to understand their relation to plate processes, including hazardous large earthquakes.

The fate of downgoing material in subduction zones remains a first-order question in the Earth sciences. Subduction zones are where water is recycled into the mantle, where oceanic plates are recycled, where arc volcanoes form, and where the world's largest earthquakes occur. Subduction zones also play a crucial yet poorly understood role in mantle convection and the chemical evolution of Earth as a whole across geological history. Better geophysical images

of the thermo-petrological-volatile structures of subducting slabs, together with improved rheological models of the mantle, are needed to further improve our understanding of these complex, multifaceted systems. Focused multidisciplinary projects in a handful of subduction zones have elucidated critical processes that occur within subducting slabs as they pass through the upper mantle, including serpentinization, fluid release, partial melting, and the deformation of the downgoing plate. This level of detailed understanding is only possible with the high-resolution images of structures and seismicity made possible by such concerted, well-instrumented efforts. Geophysical facilities contributing to such investigations include dense portable seismic and ocean bottom seismometer (OBS) networks, long-term dense continuous geodetic networks,

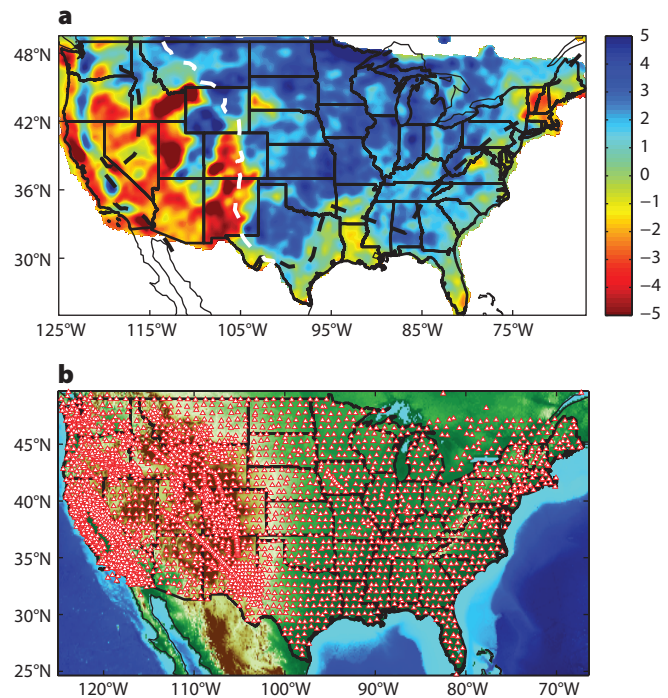


Figure 3. (a) Variations in shear wave speed at 75 km depth imaged using teleseismic body wave tomography. Dashed black lines mark the eastern and western Precambrian rift margins, and the white dashed line marks the Rocky Mountain Front, the eastern limit of most Cenozoic tectonic and magmatic activity. At large scale, lower wave speeds show hot and potentially partially molten upper mantle beneath the western United States, generally cold temperatures beneath the cratonic interior, and intermediate temperature near the passive margin. However, all provinces contain well-resolved thermal and compositional heterogeneities that are correlated with active or prior episodes of magmatism or tectonic boundaries spanning the history of the continent. After Schmandt and Lin (2014) and Whitmeyer et al. (2007) (b) Locations of the 2,812 EarthScope USAArray and selected temporary broadband seismograph deployments spanning North America used to produce the tomographic image shown in (a).

InSAR imagery, onshore and offshore MT data acquisition, and seaborne multichannel seismic imaging. Improved resolution of lithospheric and asthenospheric heterogeneity across varied subduction zones is needed if we are to better understand the global water budget, the flux of water through the mantle, and the influence of volatiles on mantle rheology. Because subduction zones play a critical role in mantle convection, a better understanding of these systems will lead to a better understanding of the driving mechanisms for plate tectonics, the geochemical evolution

of Earth's crust, and the effects of mantle convection on the long-term uplift and subsidence within plate interiors. Improving the seismological constraints within these areas requires continued long-term operation of large-scale global networks and expanded seismological observatories in oceanic regions. Utilization of increasingly easy to deploy and robust broadband arrays with greater numbers of stations will be needed to resolve smaller-scale but dynamically important attributes of the mantle system and their attendant linkages from core to surface.

Vignette 2. The Menagerie of Fault Slip — Earthquakes, Tremor, and Slow Slip

Geological faults are narrow zones in Earth's crust that localize strain and accommodate plate motion. Earthquakes are the most common expression of failure on these faults and represent the rapid release of strain and the generation of elastic waves. However, fault slip behavior is much more varied, with seismogenic events representing one extreme in a wider spectrum of slip behavior. First identified along subduction zones, the preponderance of slow slip and tremor along the world's varied plate boundaries has surprised the community, and the discovery has opened a new field of study. Slow slip and tremor exemplifies the menagerie of fault behaviors, which includes a zoo of tremor streaks, propagating in a mix of directions at distinct velocities, all driven by a slowly evolving, broadly dispersed slipping patch.

Geophysical facilities play a critical role in observing slow slip and tremor, allowing researchers to study the spatial and temporal evolution of these events, and helping to better characterize the deeper extent of fault systems. Research into slow slip and tremor has highlighted the importance of fluids in controlling transient slip behavior. Seismic observations of low-frequency earthquakes have demonstrated a sensitivity to subtle stress perturbations, including the solid tides, which provide critical constraints on the state of stress on the fault interface at great depth. New observational discoveries continue to be made from the growing data archive, and hypotheses about the underlying mechanisms continue to be tested. Geophysical facilities provide foundational capabilities to characterize these transient events through observations of seismicity and deformation, as well as from other emerging technologies.

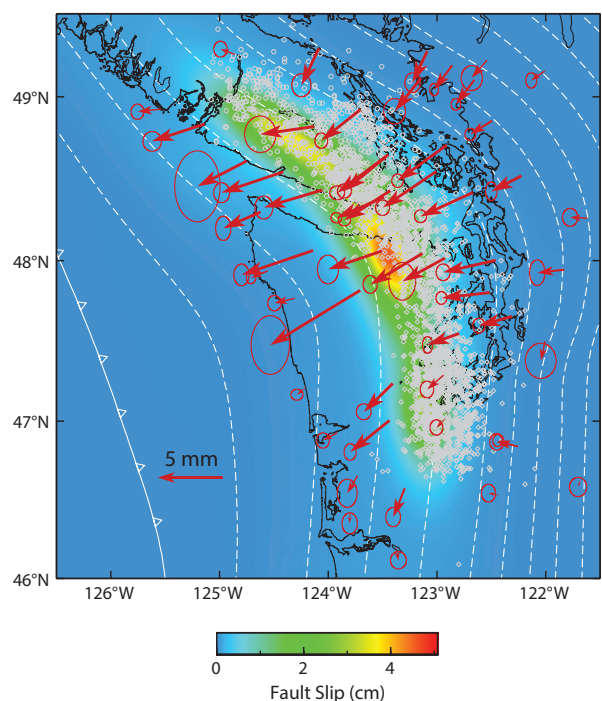


Figure V2. Slow slip and tectonic tremor on the Cascadia subduction zone, as revealed by the locations of tremor sources (gray symbols) and transient surface displacement measured by GPS (red arrows). Fault slip is inferred from an inversion of the surface displacements. For Cascadia, slow slip and tremor map between the 30 km and 45 km depth contours on the plate interface, with major ($M_w \sim 6$) events recurring every 10–22 months. After Dräger and Wang (2011)

To study the large-scale movement and deformation of continents requires similarly large-scale, spatially extensive GPS/GNSS data. Some of these studies use combinations of temporary and permanent instrumentation to extend network aperture over thousands of kilometers, scales needed to parse the relative contributions of the various forces that drive the plate tectonic machine. These data are needed to constrain a number of questions, such as the state of stress in the lithosphere, spatial variations in the strength of tectonic plates, the role of gravitation in driving the collapse of high-standing continental plateaus, pull from sinking slabs, and resistance at plate boundaries in driving large-scale plate motions. Geodetic analyses will be used in combination with seismically derived products such as moment tensors, tomographic models, and estimates of variations in mantle temperature, composition, and physical state to better understand the broad-scale dynamics of tectonic plates. Currently, while there are many GPS stations, there are many gaps within tectonically active zones (e.g., in North America, including in much of Alaska and eastern Nevada).

At plate margins, Earth's deep dynamic processes drive active deformation that continuously alters and evolves the lithosphere and deeper mantle, while also generating large earthquakes, volcanoes, and other hazards. At mid-ocean ridges and within continental rifts, we are only beginning to understand magma migration and storage and the interaction of magmatic and tectonic extension. Magma-water interactions and hydrothermal circulation strongly affect chemical cycling, while hydration of the oceanic lithosphere affects both plate rheology and the eventual subduction of water. Continental margins are either the locus of active deformation or preserve the record of past rifting events. Surface processes at active continental margins profoundly impact the cycling of crustal material through orogenic zones, weathering rates, localization of deformation, and distribution of sediment loads across the continental crust and its margins. Marine geophysical observatories, both permanent and temporary, are critical to understanding many of these processes. Such observatories must be well integrated, technically and programmatically, with onshore observatories to optimize amphibious science opportunities ranging from mantle dynamics and structure through to coastal processes and other oceanographic studies.

3.1.2. Evolution of the Continents

Society lives on continents, derives much of its energy and mineral resources from continents, and interacts daily with subaerial continental landscapes from mountain belts to coastal plains. The continents have evolved across most of Earth's history, preserving a 4 Gy record of planetary evolution. Depleted mantle lithosphere can form strong roots that stabilize ancient, cratonic lithosphere and act as rheological keels atop the mantle convection system. Mafic crustal rocks originally derived from mantle partial melting can undergo additional distillation within the crust to create large volumes of granitic crust. Continental collision and extension, and the accretion of micro-continental, island-arc, and oceanic plateau terranes add new materials to the continents and transmit deformation far into the plate interior. The combined magmatic and tectonic evolution creates strong complexity in 3-D composition and rheology. Previous tectonic and magmatic events create the inherited rheologic template that determines how the lithosphere will respond to subsequent magmatism and tectonism, which in turn modify the template. Magmatic and aqueous fluids play critical roles in continental evolution. Hydration or metamorphic dehydration strongly influence crustal melting processes and play a key role in rheological properties. Fluids also play key roles in the creation of mineral resources. To understand the role of fluids in the evolving continent, it is critical to obtain integrated geophysical observations (i.e., geodetic, seismic, imaging, and EM). Better-resolved geophysical observations of active deformation and high-resolution topography are needed to better understand crustal and lithospheric strain partitioning in active rift, collision, and subduction zone settings, but to understand the evolution of these processes throughout Earth history requires additional geophysical and integrated geologic and geochemical studies.

3.2. FAULT ZONES AND THE EARTHQUAKE CYCLE

Earthquakes and related fault processes are complex multiscale phenomena that are of great concern due to their destructive potential, including the effects of strong shaking, tsunamis, liquefaction, and other phenomena. The earthquake cycle is characterized by long periods of interseismic elastic stress accumulation punctuated by

transient coseismic rupture, deformation, redistribution of stress, and fault zone healing. Rapid anthropogenic or naturally occurring changes in fluid and gas pressure within rocks can in some instances trigger earthquakes or modify this cycle. Spatial and temporal heterogeneity of material properties, hydrological conditions, triggering sensitivities, and frictional behavior are spatially and temporally complex. A full theoretical structure tying them to earthquake behavior does not exist.

Detailed measurements of crustal deformation, seismicity, and time-varying crustal structure and properties (4-D imaging using geodetic, seismic, electromagnetic, gravity, and geologic techniques) reveal the response of plate boundary and plate interior lithosphere to these changes in stress and inform models aimed at elucidating the mechanics and rheological properties of faults and surrounding rock. Because of the wide range of spatio-temporal scales and diversity of fault behavior in various geological settings, high-quality long-term data are essential to improving understanding of diverse “normal,” “evolving,” and “transient” fault behaviors.

Numerous great subduction zone earthquakes have occurred in the past decade. From these events, we have the first digitally recorded $M_w > 9$ earthquakes and unprecedented global observations by high-quality, permanent seismic observatories. In several cases, we were also able to obtain superb geodetic data sets from campaign and continuous GPS, satellite InSAR, and satellite optical imagery, along with outstanding deepwater tsunami observations from NOAA Deep-ocean Assessment and Reporting of Tsunamis (DART) buoys and acoustic seafloor geodesy. The study of these great earthquakes is a prime example of the importance of combined use of multiple data to maximize spatial and temporal resolution of fault slip behavior prior, during, and following a large earthquake. Plate boundary fault slip processes are now recognized to be much richer in behavior than was thought just a decade ago, suggesting potential breakthroughs in our understanding of fault frictional behavior with further multidisciplinary study of fault zones. In subduction zones, as with other plate boundaries that cross the continental margin, progress requires coupled dense onshore and offshore instrumentation of multiple regions using seismic, geodetic, magnetotelluric, controlled-source electromagnetic, and geological investigations.

Late in the interseismic phase of the earthquake cycle in many faulting environments, deformation and microseismicity may potentially be used to characterize elastic strain accumulation rates, aseismic fault slip rates, and earthquake hazard. Increasingly, deformation, seismicity, and tremor reveal spontaneous or triggered slow slip events and other types of deformation episodes. Indeed, several recent, large subduction earthquakes were immediately preceded by such apparent transients in seismicity and/or detectable deformation. These observations suggest that, in some cases, measurable precursory processes may lead to rupture nucleation, reinforcing the value of real-time geophysical data acquisition. These observations also motivate a critical need to distinguish between elastic (i.e., seismic) and inelastic precursory deformation—a distinction that for subduction environments requires improved and ubiquitous seafloor geodetic observations. Finally, detailed characterization of earthquake nucleation, rupture kinematics, and dynamics are possible from analysis of seismic data and space geodetic deformation data collected at a wide range of frequencies with a commensurate need to push the limits of our observational sensitivities. Real-time systems allow for some of this information to be available for early warning purposes even while a rupture event is still in progress.

Measurements of deformation over a wide range of spatial and temporal scales is essential to further understanding of the relationship between plate boundary configurations, plate tectonic forces, crust and mantle rheology, short- and long-term fault slip rates, and earthquakes. These observations are key to an improved understanding of a variety of earthquake cycle deformation transients (e.g., creep events, afterslip, poroelastic rebound, and postseismic viscous relaxation), some of which can last for decades after earthquakes. Elucidating the complex time variable behavior of slip underlies much of the collaborative efforts of the seismology, geodesy, geology, and hazard communities. Advances in studies of the earthquake cycle thus depend on the existence and enhancement of well-integrated, permanent, dense geophysical networks and an expanding range of remote-sensing observations that can capture observations over a wide range of spatial and temporal scales.

A major challenge to an enhanced observational program is the unpredictable distribution of earthquakes. This unpredictability requires that researchers and facilities have the capability to react to the spatiotemporal evolution of seismicity, taking advantage of the space-time clustering of earthquakes to focus effort in areas with recent changes in significant earthquake activity. This strategy requires a large, flexible, and readily deployed/operated instrument pool, including rapid response elements. Such efforts will be more scientifically valuable if pre-event characterizations exist to provide baseline measurements. Another, complementary, approach is to enhance and broaden permanent geophysical networks that greatly enable earthquake research, but also serve many other scientific and applied purposes.

3.3. MAGMATIC SYSTEMS

Volcanic intrusions and eruptions encompass multiple processes, including deep magma movement, shallow magma storage and differentiation, hydrothermal activity, and the elastic, inelastic, and hydrothermal response of the volcanic edifice to magmatic, tectonic, and hydrothermal forcing. Great advances have been made in recent years in the detection and quantification of shallow magma transport preceding eruptions through analysis of seismic and geodetic data. However, observing, understanding, and acting upon long-term preparatory phases of eruptions that can involve subtle magma migration, evolution, and interactions with the hydrothermal system remain important challenges requiring long-term, multidisciplinary, and stable observations, ideally spanning an arc, rift, or hotspot volcanic region.

Assessing spatial and temporal variations in structure through 4-D tomography using seismic, EM, and geodetic data has potential for probing the evolution of such processes. Collaborative efforts to improve methods and data quality and density are required, along with substantially improved forward and inverse modeling capabilities. Passive monitoring and imaging using dense seismic arrays is a particularly promising approach for monitoring 4-D changes in volcanoes. Long time series records of multi-method volcano monitoring (seismic, gravity, geodesy, EM, and gas data) are needed to better illuminate the relationship among deformation, seismicity, intrusions,

and eruptions, and to establish normal versus transient behaviors. How much magma is present, how and where it is stored, and how much of it is eruptable are long-standing questions in need of modern instrumentation and methods. Advances in understanding of the physics of eruptions and of their precursory signals should allow for steady improvement in forecasting abilities for volcanic activity.

There is a need for a global, continuous, and semi-real-time volcano monitoring system to better understand the patterns of volcanic activity across varied tectonic and geological settings. Such a global system is also necessary to forecast activity on longer time scales, to develop warning systems for volcanoes now temporarily quiescent, and to establish monitoring systems for ongoing eruptions. Remote sensing by satellite and aerial systems tracking surface deformation, temperature fields, and gas emissions has the advantage of being able to capture changes on most of the world's subaerial active volcanoes and can thus be used to identify volcanoes that warrant more intensive field investigations. More comprehensive global monitoring will also help elucidate coupling of related systems, including earthquake-volcano interactions, volcano-volcano interactions, and climate-volcano interactions.

Submarine volcanism forms new oceanic crust, mainly at mid-ocean ridges. Deployments of OBSs are needed to better understand the size and nature of magma convection under mid-ocean ridges and how widely distributed magmas are within the oceanic asthenosphere. Open questions include the nature of horizontal flow, whether and how interconnected porous channels form, and the role of water. Similarly, for intraplate volcanoes, there is an ongoing debate about the depth distribution of magmas and the volume of magma trapped within the crust; seismic data are key to imaging magma transport and storage. Magnetotelluric data show that high-conductivity layers, most plausibly explained by melt and magmatically derived hypersaline fluids, are ubiquitous in the lower crust and uppermost mantle in rift and hotspot regimes. These deep melt accumulations can connect through faults to surface geothermal systems and may play an underappreciated role in global water and volatile cycles. Through underplating and intrusion, these magmatic processes also are important to growth and crustal evolution of the continents.

Vignette 3. Magmatic Systems

Volcanoes are structures that store and release heat. Magma is formed deep in the Earth and rises due to buoyancy. It is stored in the crust and evolves by crystal fractionation and interaction with the surrounding crust and fluids. Under suitable conditions, part of the magma rises to Earth's surface and erupts. The conditions of storage and movement may change with time. Volcanoes are a component of tectonic environments and interact with other parts of these systems as stresses change. Volcanoes are constructional features that cause the crust to grow, not only when visible at the surface, but also at depth through intrusion. At Volcán Uturuncu, Bolivia, the growth of magma bodies at mid-crustal depths may contribute significantly to the pronounced thickening of the crust observed in the Central Andes.

Magmatic systems are studied with a variety of techniques, several of which are illustrated in **Figure V3**; the geophysical facilities play essential roles in realizing such studies. Uplift and subsidence at Uturuncu were identified in InSAR images, and these observations led to the selection of the volcano as a target for further study of magmatic intrusion and related processes. The IRIS PASSCAL instrument pool supported the deployment of focused seismic instrumentation for two years. The MT and gravity studies used instrumentation supported by NSF and the UK's Natural Environment Research Council. These same agencies also support researchers in their evaluation of the multiple data sets.

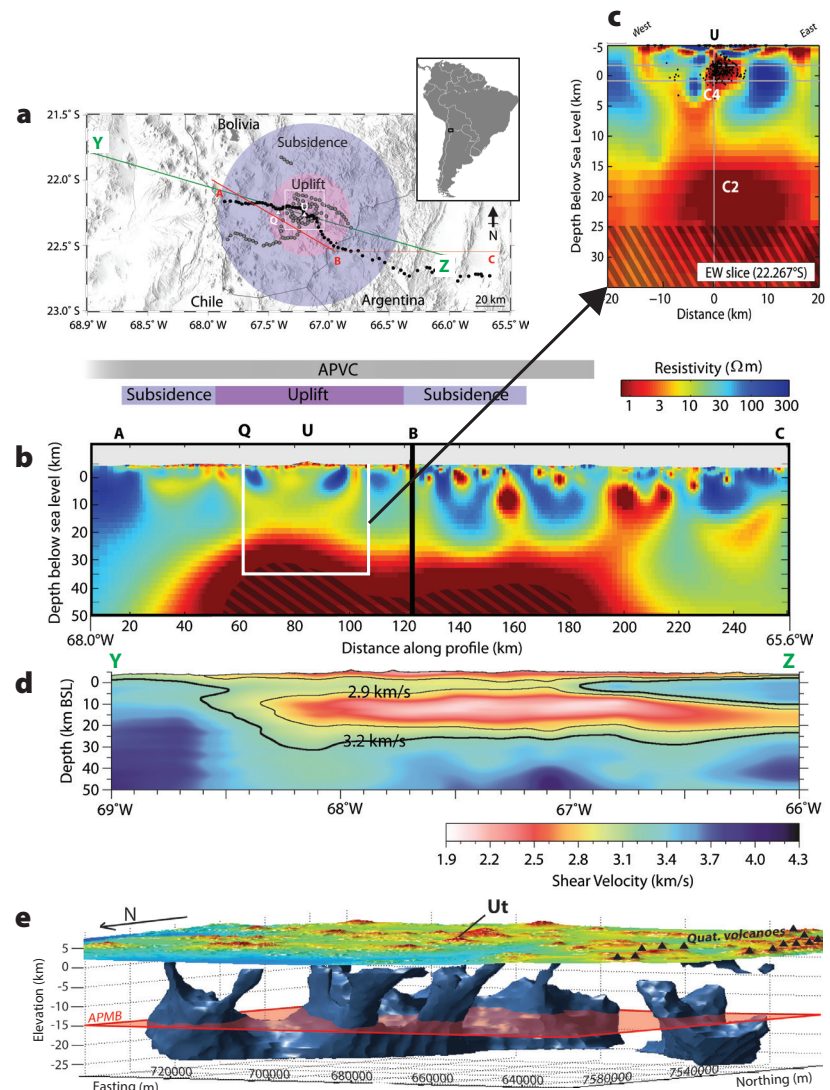


Figure V3. Comparison of subsurface inversion profiles of MT, seismic, and gravity data near Volcán Uturuncu, Bolivia (labeled as U and Ut). (a) The two rings show approximate location of ground uplift and subsidence (originally identified using InSAR). (b) Two-dimensional MT inversion from Comeau et al. (2015), with the smaller region investigated with the 3-D inversion shown by the arrow in (c). (d) Vs from joint inversion of seismic ambient noise tomography and receiver functions (from Ward et al., 2014). (e) Preferred gravity model from del Potro et al. (2013). The differences and similarities of these models place many constraints on the properties of potential magma bodies. *Modified from Pritchard and Gregg (in review)*

3.4. PLATE INTERIORS

"How do tectonic plates deform?" was recently identified as a Grand Challenge of Geodesy. Similarly, "What is the relationship between stress and strain in the lithosphere?" is highlighted as a Seismological Grand Challenge. Over the past decade, research on Earth's lithosphere has progressed beyond the rigid plates first envisioned in early plate tectonic theory to a richer and more comprehensive understanding of plate deformation. Modern geodetic and seismic instrumentation allows us to witness Earth deformation in real time and to understand the specific causes and consequences of plate tectonic movements, including the effect of these movements on continental interiors and plate boundaries, contributions from mantle sources to lithospheric structure and deformation, and the interactions with surface water and groundwater, ocean, and atmosphere. Continental plates also persevere and evolve over geological time, and their cratonic interiors preserve an up to four-billion-year structural and compositional record of Earth evolution that is amenable to interrogation with geophysical imaging methods.

The 23 August 2011 Mineral, VA, intraplate earthquake (M_w 5.8) damaged homes and historical structures as far away as Washington, DC. Ground shaking from this event exceeded the specifications for which the twin reactors at the North Anna Nuclear Generating Station were designed, resulting in the immediate shutdown of the reactors and

\$21 million in inspections. Prior to the event, the Central Virginia Seismic Zone, while recognized, was not considered to be a highly likely location for a significant event east of the Mississippi River. This event highlighted our lack of understanding of both the forces at play in continental interiors (stress) and the deformation (strain) and resulting earthquake potential that these forces cause. Faults abound across much of the central and eastern United States, the product of repeated episodes of continent-continent collision, terrane accretion, and rifting. While the eastern United States has not been located near a plate boundary for ~180 million years, there are numerous indicators of active tectonism. Events such as the 1886 Charleston, SC, earthquake and the 1811–1812 New Madrid, MO, earthquake sequence demonstrate Earth's capacity to produce devastating intraplate events. New research has found evidence of volcanism less than 50 million years old in the central Appalachians and evidence for recent and ongoing localized uplift of local mountain belts.

Our ability to understand such intraplate tectonism hinges on our ability to accurately measure intraplate deformation and to image lithospheric-scale structures. Long-term geodetic observations have resolved very low but non-zero rates of deformation of parts of western North America. Areas previously thought to be rigid, non-deforming microplates, some over 1,000 km from the plate boundary, have been shown to be actively deforming as the detection threshold is pushed ever lower. We know

comparatively little about the lateral variability in both the strength and structure of the plate and the stresses to which it is subjected. Similarly, improved seismic data and analysis methods that push detection thresholds to very small magnitudes advance understanding of natural and anthropogenic seismicity in these regimes.

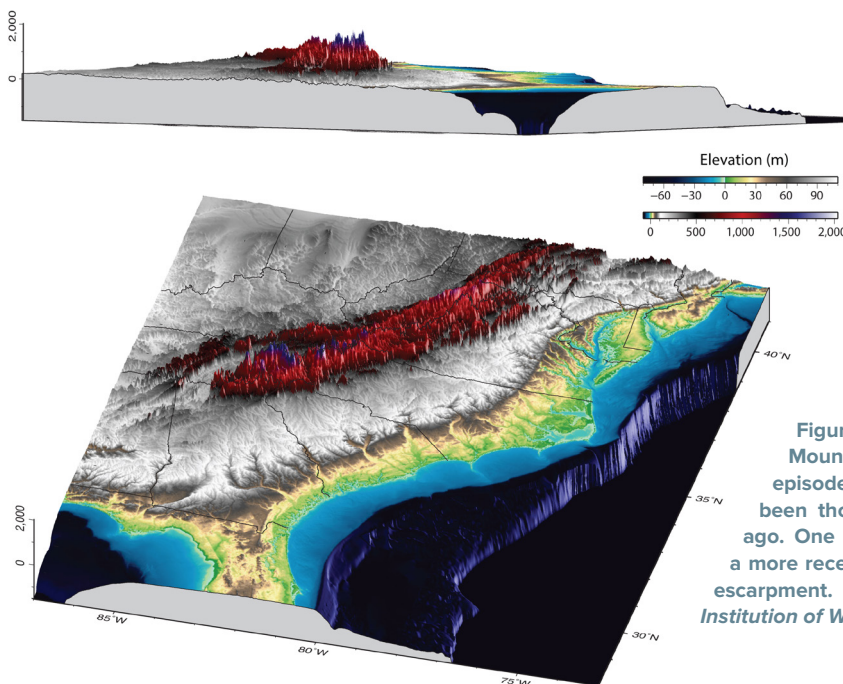


Figure 4. The abrupt topography of the Appalachian Mountains is a scientific mystery, given that the last episode of mountain building in this region has long been thought to have ended over 300 million years ago. One hypothesis is that this topography indicates a more recent intraplate rejuvenation of the Appalachian escarpment. *Figure courtesy of Lara Wagner (Carnegie Institution of Washington)*

3.5. GLACIER AND ICE SHEET DYNAMICS

Glaciers and ice sheets, and their diverse interannual and long-term dynamic behaviors, are fundamentally important to geomorphological, climate, sea level, biological, and hydrological Earth systems. Recent advances in our ability to observe glaciers and ice sheets at all time scales has revolutionized our understanding of their behavior. In glacial systems, processes characterized by relatively short temporal scales (seconds to days) as well as relatively small spatial scales (meters to kilometers) exert fundamental influence on the long-term (>1 year) and large-scale (tens to hundreds of kilometers) stability of glacial systems. These advances have been substantially fostered by the ability of seismic and geodetic facilities to adaptively develop, integrate, and support both the foundational and novel observational technologies necessary to pursue scientific priorities.

Iceberg calving is a highly illustrative example of how data integration has led to improved understanding of glacial processes. Beginning at the start of the century, satellite observations began to show that many of Earth's marine-terminating glaciers were rapidly retreating, motivating renewed interest in collecting observations to constrain physical models of iceberg calving, a dominant mechanism for ice flux from these systems into the world ocean. However, a significant hurdle in studying calving from satellite observations is their relatively low temporal resolution (>1 day) relative to the time scales of a calving event (minutes). A significant advance in the pursuit of improved temporal resolution was the discovery that Greenland's large marine-terminating glaciers generate low-frequency seismic events that could be observed by the Global Seismographic Network (GSN) and other long-period seismic systems. However, it was not until the expanded temporary deployment of geodetic

instrumentation on the glaciers themselves that the origin of these events was clearly linked to iceberg calving. Increasingly, novel facility-supported observing technologies such as terrestrial laser scanning, terrestrial photogrammetry, detection of calving-generated ocean waves from floating seismographic platforms, and terrestrial radar interferometry have been used to fill the need for increased spatiotemporal resolution of observations at the glacier margins. Integration of these data sets is fueling improved understanding into the dynamic behavior of rapidly retreating glaciers.

Numerous other exciting discoveries have been facilitated by the improved ability to deploy both temporary and permanent geophysical networks in polar and ice-covered regions. For example, continuous GPS observations in glacial settings have revealed significant diurnal fluctuations (~100%) associated with tidally induced variations in stresses, including tidally modulated stick-slip behavior and calving that produce large glacial earthquakes (see **Vignette 4**). When coupled with numerical models of glacial flow, these short-term fluctuations are proving useful in discerning the fundamental physics that regulate glacier sliding. Likewise, focused seismic deployments have provided insight into fundamental observations such as basal sliding and allowed detection and study of englacial and subglacial water flow. Equally significant has been substantial facility-supported improvements to and expansions of longer-duration seismic and geodetic networks in polar regions. For example, GPS and seismographic components of the Greenland Ice Sheet Monitoring Network (GLISN) and POLENET project in Antarctica have validated/calibrated recent mass loss observed by the Gravity Recovery and Climate Experiment (GRACE) satellite mission and provided new insights into the viscoelastic and tectonic mantle and crustal properties of the continental interiors that underlie these ice sheets.



Figure 5. Cordiner Peak (Pensacola Mountains, Antarctica) co-sited GPS and seismic observatory. Photo courtesy of Jeremy Miner (POLENET/ANET Group)

Vignette 4. Daily Earthquakes Below Ice Streams

The Whillans Ice Stream (WIS) in Antarctica exemplifies the temporal complexity and richness of glacial phenomena that can be understood only through the integration of diverse observational platforms. Beginning in the 1970s, repeat velocity measurements (including GPS and InSAR) have shown that the WIS is slowing, possibly toward stagnation. High-rate GPS receivers were first used to monitor this deceleration during the early part of this century and resulted in the surprising discovery that the down-glacier portion of the WIS accomplishes most of its motion via minutes-long episodes of basal stick-slip rather than smooth flow. The ice stream nominally goes through two stick-slip cycles per day that are driven by the elastic loading of the stick-slip region by surrounding continuously flowing regions. The presence of high-quality seismographs in Antarctica from POLENET and GSN allowed for the discovery of teleseismic arrivals associated with these WIS slip events. The relatively long duration (~30 minutes) of the WIS slip events results in seismograms that are dominated by long-period energy (~20–120 s). Tidally driven variations in stressing rate introduce complexity into the stick-slip cycle that is reflected in both rupture behavior and far-field seismic records.

Subsequent to this discovery, numerous other detailed geophysical deployments have allowed a better understanding of the system. For example, in situ seismographs were shown to record the “high-frequency” component of ground motion that, when integrated with GPS observations, allowed for broadband reconstructions of the moment-rate function, leading to improved interpretations of far-field seismograms and understanding of the processes governing the asperity interface. Additionally, in situ seismographs have revealed a range of microseismic activity associated with basal slip during the events, including a newly identified type of seismic tremor. Importantly, emerging results are now showing that the stick-slip behavior is inextricably linked with the physical processes leading to decadal slowdown of the ice stream.

The discovery of the WIS stick-slip events and associated seismic manifestations were enabled by both novel (i.e., high-rate GPS) as well as foundational (i.e., GSN network of broadband seismographs) observations. While unique, the stick-slip behavior of the WIS is representative of the need for robust and nimble facilities that to can provide unfettered access to specialized equipment for the study of glaciers across all time scales to better understand their newly recognized and highly complex behaviors.

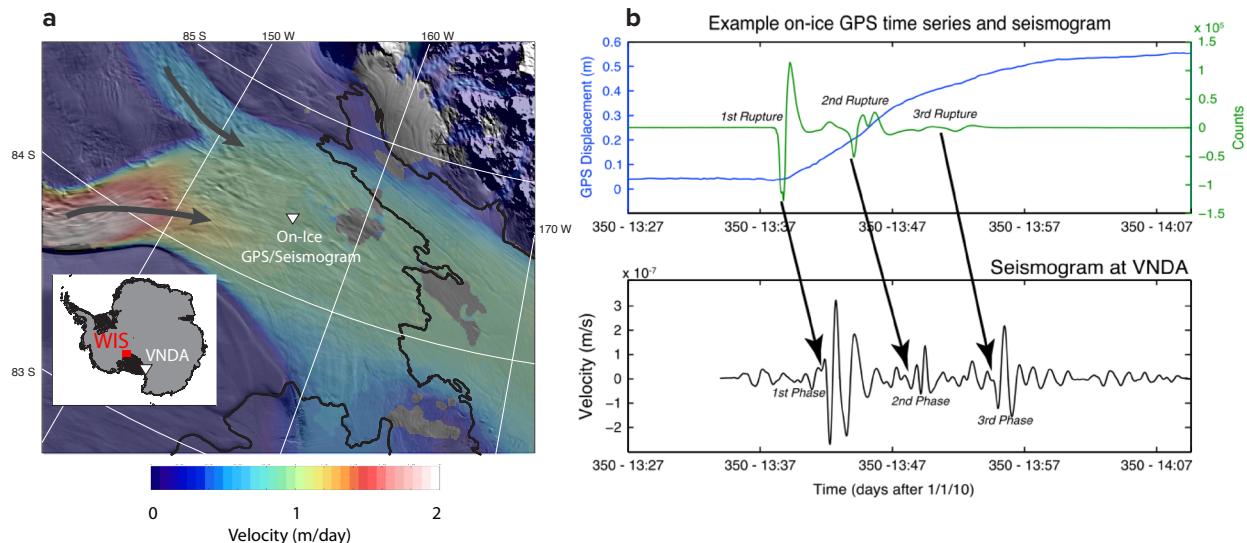


Figure V4. (a) InSAR-derived surface velocity of the Whillans Ice Stream (WIS) in Antarctica. Inset shows study area and location of seismic station VNDA. *From Rignot et al. (2011)* (b) Top panel shows the in situ GPS and seismograph response during a representative 30-minute duration WIS glacial earthquake. Note the seismograph records the relatively high-frequency component of motion (<200 s). The lower panel shows the associated far-field seismic record at VNDA (30–100 s). Seismic arrivals are associated with the relatively high-frequency component of ice stream motion. *From Pratt et al. (2014)*

To fully harness the potential of geophysical techniques to study glacial systems, continued advances in instrumentation technology are required (e.g., see APOS report, 2011). At present, both logistical burden (installation time and weight) and cost remain impediments to deployments of more ambitious extent and duration in these characteristically remote and environmentally challenging regions, indicating a strong continued role for future facilities.

3.6. SEA LEVEL CHANGE

Future sea level rise in response to climate warming poses a global threat to coastal communities, economies, and environments. Aspects of sea level research significantly intersect with the scientific areas encompassed by geophysical facilities discussed in this document (e.g., glaciology, hydrology, seismic imaging, geodetic deformation). The Intergovernmental Panel on Climate Change and the geodetic community Grand Challenges documents have identified understanding the contributing factors, spatial patterns, and temporal variability of sea level changes as essential for climate change mitigation efforts. Sea level effects drive significant accuracy and reference frame requirements for global geodesy. Thus, understanding them is a priority for the global geodetic community.

Sea level varies on a wide range of temporal and spatial scales. To accurately capture sea level variability and detect the signals from different contributing processes (e.g., ocean dynamics, thermal expansion, steric effects, coastal uplift and subsidence, and glacial isostatic adjustment) requires globally distributed measurements over long time scales. Changes in grounded ice cover dominate over centennial and millennial time scales and are likely to make the greatest contribution to future sea level changes. Gravitational, deformational, and rotational effects associated with the melting of ice sheets and mountain glaciers lead to distinct patterns of sea level change (“sea level fingerprints”). These effects are characterized by a greater than average sea level rise at great distance from a region of ice loss and a sea level fall close to the retreating ice that reaches an order of magnitude or more greater than the global average. Although the sea level signal due to ice mass flux is largest and most easily detected in polar regions, records of sea level change are currently sparse near ice cover where data collection is challenging.

Tide gauges have been measuring water depth changes near coastlines around the world for centuries, and geological constraints provide information about sea level changes over much longer time scales. In recent decades, satellite altimetry and gravity missions, as well as GPS/GNSS

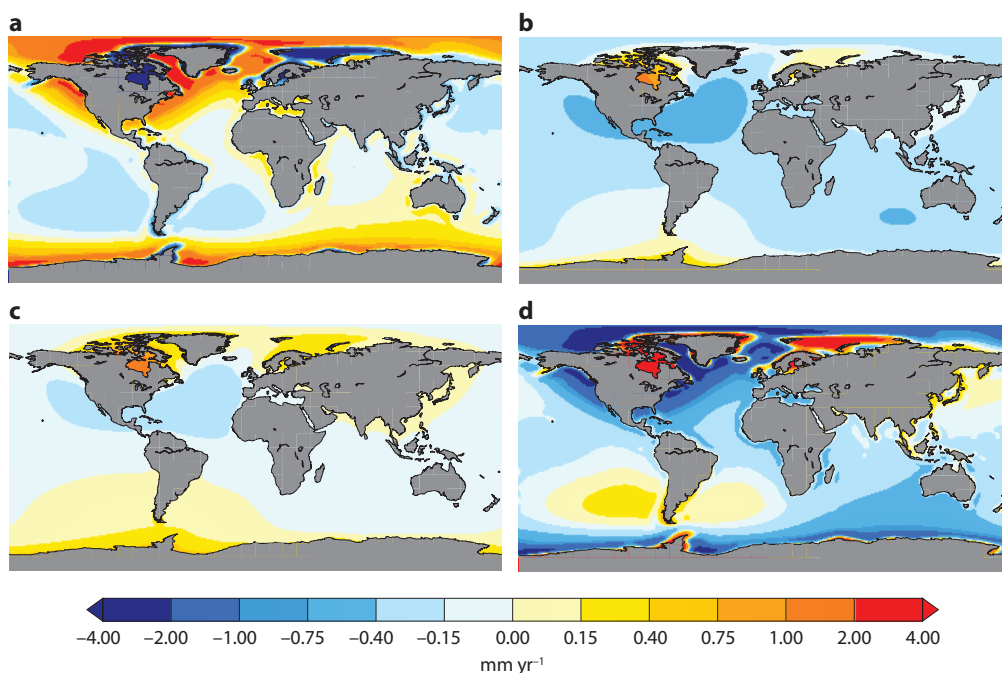


Figure 6. Example glacial isostatic adjustment modeled manifestations of sea level rate demonstrating global variability: (a) tide gauges; (b) sea surface height (altimetry); (c) geoid height (from GRACE); (d) crustal motions (GNSS). After Tamisiea et al. (2014)

coverage, have detected surface deformation associated with past and present sea level and regions of ice sheet change. An increase in coverage of these regions, with a focus on collocating different types of measurements in conjunction with acquiring longer records, will play a key role in furthering our understanding and projections of sea level variability. Maintaining and improving the preservation and documentation of full records, data accessibility, and centralized and transparent data processing are also essential.

Glacial isostatic adjustment (GIA), the ongoing adjustment of the land and sea surface due to past ice cover changes, impacts every measurement of sea surface, relative sea level, and solid surface deformation. The timing, amplitude, and spatial patterns of Earth deformation in response to surface (ice and water) loading changes depend both on the ice history and on Earth's rheological structure (i.e., lithospheric elastic thickness and mantle viscosity). In some regions (e.g., Antarctica), recent facilities-supported seismic and geodetic research has shown that lateral variability of the mantle significantly impacts the viscoelastic response of the ice-solid Earth system at important temporal and spatial scales. Seismic, mineral physics, and geodynamic constraints on lateral variations in lithospheric thickness and mantle viscosity are thus required as inputs for GIA models to be applied to the past and future evolution of ice, sea level, and the solid Earth. Continued advances in instrumenting remote outcrops, ice sheets, and mountain glaciers, and an increase in the number of records of sea level and ice sheet evolution in these regions, are needed to accurately estimate ice-associated contributions to sea level change.

Newly emerging types of geodetic and seismic data show potential for pushing sea level research forward. For example, while tide gauges that measure relative sea level are constrained to shorelines, bottom pressure gauges are beginning to be deployed on the ocean floor to measure water column mass. As another example of emerging technology, GPS stations have been positioned with a view of the ocean, which allows them to act as pseudo tide gauges via the processing of multipath effects. Frontier work is also underway to improve altimetry measurements of sea surface height near coastlines so that they may be combined with land GPS data. Other useful coastal products, including accessible high-resolution topography/bathymetry

data and information about erosion, groundwater, subsidence, and storm surges, will be necessary for establishing sea level hazard maps and informing planning and mitigation efforts. Finally, developing new methods of processing and using a wider range of data collected from existing and future satellite missions, in conjunction with other geophysical data, has the potential to significantly improve estimates of ongoing sea level changes.

3.7. SURFACE AND NEAR-SURFACE HYDROLOGY, STRUCTURE, AND DYNAMICS

The surface and near-surface environment is Earth's "breathing skin," where rock, soil, water, and air create life-sustaining ecosystems. Recently, this system has been dubbed the "critical zone" (CZ), in view of its importance to supporting life on Earth. The CZ can be viewed as a weathering reactor, in which bedrock slowly transforms into soil. At steady state, the production of new soil is perfectly balanced by erosion, so that CZ thickness is maintained. The CZ encompasses a broad array of processes and scientific disciplines, from hydrology, to geomorphology, to biogeochemistry, to geophysics, so that an interdisciplinary approach to studying them is required. This breadth and diversity creates rich opportunities for scientific discovery, yet also brings challenges. Several recent reports document the increased attention to these processes (see [Appendix](#)). NSF support for a national network of CZ observatories recognizes that human prosperity depends on the continued health of ecosystems and surface/near-surface processes that are poorly understood and beset by natural and anthropogenic change.

Satellite, airborne, and terrestrial sensing methods, including lidar, InSAR, and GNSS, are revolutionizing our ability to image Earth's surface and measure mass fluxes and short-term deformation and alteration. However, we have only a limited ability today to peer into the shallow subsurface at the scales and resolution required to address key CZ research questions. As a result, our knowledge of the subsurface CZ architecture, its variation across landscapes, and the processes that control that variation and its coupling to the land surface is also very limited. In fact, we lack a unifying theory of CZ evolution. It is clear that the vertical and lateral distribution of porosity and permeability

in the subsurface varies within and between watersheds, strongly affecting, for example, the relationships between precipitation, recharge, and runoff. The lack of knowledge of CZ architecture and physical properties at scales from pores to landscapes is a primary limitation to progress in testing models. Acquiring this knowledge requires using a broad range of geophysical techniques, including high-resolution topographic imaging, active-source seismic, electromagnetic, ground-penetrating radar, electrical, magnetic, gravity, and borehole.

The facilities of the future should provide geophysical instrumentation, technical expertise, and training in high-resolution shallow imaging methods. In particular, progress is currently hampered by a lack of broad access to near-surface geophysical instrumentation and expertise and by the lack of a national strategy for efficiently facilitating the use of these instruments.

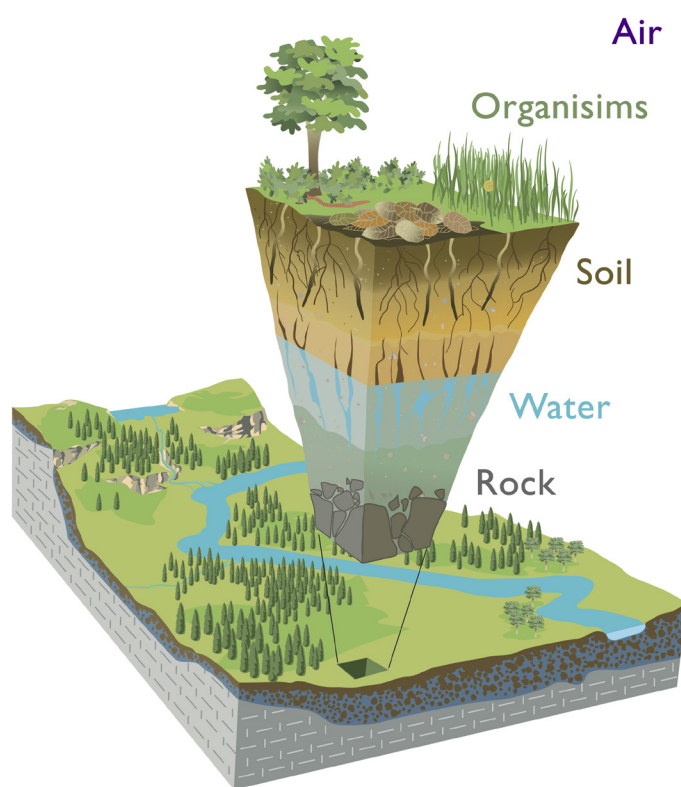


Figure 7. The “critical zone,” Earth’s outermost layer, hosts an interacting array of biological, physical, hydrological, and geological processes that transform bedrock into soil, release nutrients, and create subsurface water storage capacity. Geophysical tools are needed to address emerging questions about critical zone structure and processes, from the pore scale to the landscape scale. *After Chorover et al. (2007)*

3.8. SOIL MOISTURE, SNOW, AND VEGETATION WATER CONTENT

Rainfall and snowmelt are temporarily held at Earth’s surface as soil moisture before water returns to the atmosphere via evapotranspiration, flows to rivers, or infiltrates to groundwater. Therefore, soil moisture storage is a fundamental component of the terrestrial hydrologic cycle. Soil moisture dynamics influence the ecosystem response to climate variability and change, feedbacks between the land surface and atmospheric elements of the climate system, recharge of groundwater aquifers, and flood magnitude and frequency. Accordingly, soil moisture is typically a state variable in hydrologic, ecological, and climate models, and values are sought for model initialization and data assimilation purposes. Measurement of the amount of water stored in the snowpack is essential for management of water supply and flood control systems. Distributed snow measurements are also used to evaluate gridded snow products. Knowledge of the water content of vegetation is critical for phenology studies—as well as for monitoring drought and guiding fire management practices. Quantifying the amount of water in plants is also critical for retrieval of soil moisture from satellite data. As in previous community documents ([Appendix](#)), geodesy is able to provide valuable measurements of soil moisture, snow depth, and vegetation water content to the hydrologic and climate communities using reflected GPS signals. These measurements are currently derived from GPS receivers operated by the EarthScope Plate Boundary Observatory (PBO), but can be adapted to operate in worldwide GPS networks and eventually to all GNSS signals.

Environmental products derived from GPS reflections have two primary advantages. First, the reflection region for a typical GPS site ($\sim 1,000 \text{ m}^2$) is significantly larger than most currently used in situ sensors. Because these environmental parameters are spatially variable, the larger footprint is more useful to hydrologists and climate scientists. Secondly, these environmental products are derived entirely from GPS data collected by geodesists and surveyors. There is no extra cost for operating the GPS site or for telemetering the data, thus making the measurement cost efficient. The geodetic community needs to become aware of the limitations of the method, and future GNSS installations should be optimized to simultaneously provide measurements for tectonic, cryosphere, and hydrologic investigators.

4. Societal Imperatives

The SAGE and GAGE geophysical facilities currently support a wide range of activities with broad societal impacts. They play essential roles in enabling key observations and, in many cases, exchanging data and data products with state and federal government agencies, including the U.S. Geological Survey (USGS), National Oceanic and Atmospheric Administration (NOAA), National Aeronautics and Space Administration (NASA), and Department of Energy (DOE). A number of critical hazard monitoring and evaluation efforts (e.g., earthquake and tsunami early warning, volcano monitoring, and nuclear explosion monitoring) currently utilize existing facilities. They contribute to the development and implementation of new instrumentation systems that migrate across national and international communities. NSF facilities and associated science programs, via their close association with academic partners and with other state and federal agencies, also provide the central experiential and educational support of future geosciences professionals for the hazards, resource, energy, and ecosystem management workforce, applied research, education, and mission, planning, and regulatory agencies and organizations.

4.1. HAZARDS

4.1.1. Earthquakes and Tsunamis

The elastic strain energy released during earthquakes results in seismic shaking that disrupts the built environment and also produces highly hazardous secondary effects, including tsunamis, liquefaction, and landslides.

Earthquakes may also in some cases trigger volcanic eruptions via elastic wave, landslide, or static coupling processes. Combined seismological, geodetic, geological, and magnetotelluric investigations of earthquake faults are integral to quantifying the stress/strain accumulation and release process at the earthquake source in regions of active deformation. The complexities of fault rupture dynamics and the subsequent propagation of seismic waves through the highly heterogeneous near-surface environment causes great variability in strong ground motion that can be anticipated by seismological and geological characterization, by rapid inversions for slip history, and through the development of high-resolution crustal models in populated areas in advance of earthquakes. In regions with extensive seismological and geodetic instrumentation, automated systems can be developed for rapid characterization of fault rupture. Accurate estimation of strong shaking patterns then can guide rapid response to earthquake disasters. Synoptic damage assessments can be accelerated by InSAR imagery detection of changes before and after failure, again enhancing emergency response activities. Early warning systems based on rapid analysis of seismic and geodetic observations very close to fault ruptures are already starting to provide early warning of imminent strong shaking and tsunami arrivals (see [Vignette 6](#)). These applications require dense networks of stations that provide continuous, telemetered seismic and geodetic



Vignette 5. The 2015 M_w 7.8 Gorkha (Nepal) Earthquake

On April 25, 2015, a devastating M_w 7.8 earthquake struck Nepal, resulting in excess of 8,000 fatalities, 22,000 casualties, and 600,000 homes destroyed. Within minutes, the USGS National Earthquake Information Center estimated the location, mechanism, and magnitude of the earthquake. The event began approximately 80 km WNW of Kathmandu at ~15 km depth along the shallowly dipping thrust fault that forms the primary interface where the Indian Plate subducts under the Eurasian Plate below the Himalaya. This information alone was sufficient to know that a major humanitarian disaster had occurred. This initial rapid assessment was only possible by the real-time availability of GSN data. Within a day, these same data allowed estimation of fault slip distribution in the subsurface, indicating that fault rupture had propagated from the hypocenter toward and beyond a region just north of Kathmandu—nearly a direct hit. In situ estimates of coseismic ground movement derived from the GNSS and hand crafted satellite InSAR measurements became available within a few days. These observations confirmed and refined estimates of the distribution and amplitude of subsurface fault slip and ground shaking and demonstrated that little if any significant surface or near-surface fault break occurred. Taken together, these data led to the conclusion that this earthquake was not “the big one” that is expected for this region. These diverse data are providing extraordinary constraints on our basic understanding of seismic hazard, earthquake source physics, and associated strong ground motions, as well as regional tectonics processes that shape this plate boundary. Satellite radar data were also used effectively by field teams looking for surface cracking, liquefaction, and triggered shallow fault slip. The satellite-radar-derived damage proxy maps (DPMs) provided 2,000 km²-scale assessments with building-scale resolution of the distribution of devastation resulting directly from seismic ground shaking or indirectly from landslide burial. DPMs were rapidly validated and circulated to emergency response and recovery assistance groups.

Our ability to save lives, provide situational awareness, and begin the recovery process after a disaster depends entirely on rapid access to accurate information. Similarly, our ability to address critical questions about earthquake physics relies on capturing processes in the earliest phases of the post-seismic period. The inherent latency for GNSS data is limited only by the access to raw data. For the 2015 Nepal earthquake, many of near-field GNSS sites were only accessible manually with no telemetry. Future availability of robust, high-bandwidth satellite telemetry from all reaches of the globe would allow routine use of GNSS data to increase our resilience to earthquakes, tsunamis, and volcanic eruptions. In contrast to GNSS data, the latency of post-catastrophe satellite InSAR data is driven primarily at present by the orbit repeat times of the international constellation of satellites and open access to their data. By 2020, we expect average latencies of freely available data to be less than a day—with access to products such as DPMs for disasters around the globe then limited only by our capacity to rapidly, automatically, and robustly ingest the large volume of data from the international constellation.

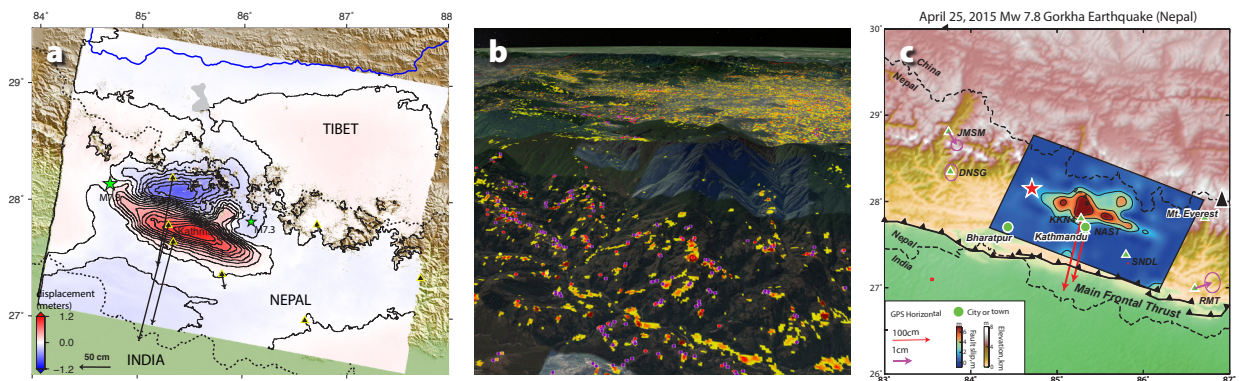


Figure V5. (a) Satellite line-of-sight displacement field for the 2015 M_w 7.9 Nepal earthquake from ALOS-2 data. *Raw data courtesy of JAXA; InSAR processing and figure courtesy of Eric Fielding and Cunren Liang (JPL/Caltech).* Red/blue colors indicate movement toward/away from the radar. *Raw and processed GPS data courtesy of Galetzka et al. (2015) and Susan Owen (JPL/Caltech), respectively.* (b) A perspective view of the damage proxy map derived from COSMO-SkyMed SAR data, showing regions of likely devastation in the Kathmandu region. Yellow to red pixels indicate locations of increased likelihood of damage. Also shown are the National Geospatial-Intelligence Agency's estimates of severely damaged (red dots) and collapsed buildings (purple dots). *Figure courtesy of Sang-Ho Yun (JPL/Caltech)* (c) Estimate of subsurface fault slip constrained by teleseismic, high-rate and conventional GPS, and InSAR observations. *Figure courtesy of Han Yue and Mark Simons (Caltech)*

data delivery in seismogenic areas around the world as well as data analysis, along with the coverage provided by global seismographic networks. The permanent global component allows quantification of faulting in regions that lack dense local networks. Improved understanding of strong ground shaking and mitigation of associated hazards requires dense recordings in vulnerable areas.

4.1.2. Induced Seismicity

Isolated instances of induced seismicity due to anthropogenic perturbation of fault systems have been documented and studied since the 1960s. However, the ongoing hydrocarbon revolution that has substantially improved U.S. energy independence across the past decade, and the attendant expansion of Class II injection wells (wells used for the disposal of saline waters, which are often prolifically produced from oil and gas recovery, into deep receptive geological formations and that are regulated under state and federal laws), has induced an unprecedented increase in seismicity in some regions of the central United States. Ongoing research into the conditions by which a small percentage of these wells induce appreciable basement seismicity has shown that this problem may be highly manageable, provided that there is improved monitoring of seismicity and injection, and that states and their regulatory agencies implement policies and procedures for successful mitigation. The growing understanding of the induced earthquake process, and the implementation of optimal strategies for continuous assessment and mitigation of this anthropogenic hazard, is a dynamic and ongoing effort that is currently engaging geophysicists, regulatory agencies, industry, the legal and insurance professions, and the general public. Induced seismicity systems are also important laboratories for addressing basic science questions involving the hydraulic connectivity, structure (e.g., segmentation and maximum event size), seismogenic space, time, and magnitude statistics, and stress/strain conditions of fault systems and surrounding geological formations.

4.1.3. Volcanic Eruptions

While volcanic eruptions are spectacular, they are clearly also extremely hazardous. Hence, long-term and high-quality monitoring, advanced data interpretation, and the development of associated protocols in concert

with local to national partners are required for effective hazard mitigation. Monitoring is a vital component of volcano, earthquake, and many other areas of Earth science. Data sets produced by high-quality and sustained monitoring provide the baseline for determining the onsets and effects of changes, as well as a basis for assessing when a perturbed system has returned to the less-alarming normal or background state.

Forecasting of volcanic eruptions has been a significant societal benefit of Earth science. Successful forecasts include estimates of the times, sizes, types, durations, and



Figure 8. An explosive eruption of Sakurajima Volcano, Kyushu, Japan, viewed from a distance of 3 km on May 20, 2015. Sakurajima is a stratovolcano within the Aira caldera and is representative of the 55–70 arc volcanoes that erupt each year worldwide. This eruption produced an infrasound signal of 740 Pa at a distance of 3.6 km and created an ash column 5 km high. Because of the persistent hazard, local children are required to wear hard hats when walking to school in the villages near the volcano. The volcano is instrumented with seismic, geodetic, and infrasound equipment, which allows collection of data that are used to interpret the physical processes associated with magma rise, fragmentation, and other processes during eruptions. *Photo courtesy of Steve McNutt (University of South Florida)*

Vignette 6. Early Warning

Earthquake early warning (EEW) provides seconds to minutes of warning after an earthquake has been detected but before strong shaking arrives. EEW also would add valuable seconds to tsunami warnings. The principal goals of EEW are to reduce deaths and destruction and mitigate subsequent societal disruption. Estimates suggest that EEW may reduce the costs resulting from earthquakes by tens of percent, which are estimated to be five billion dollars per year in the United States on a long-term basis.

A number of other countries have already built EEW, and design and implementation is underway in the United States. Although sustained funding has not yet been established, EEW development and implementation require continued operation and fortification of regional seismic and geodetic networks; upgrades in hardware, telemetry, and new software; and improved maintenance and monitoring efforts. Current EEW system designs utilize comparable fractions of strong motion seismometers, broadband seismometers, and GPS sensors.

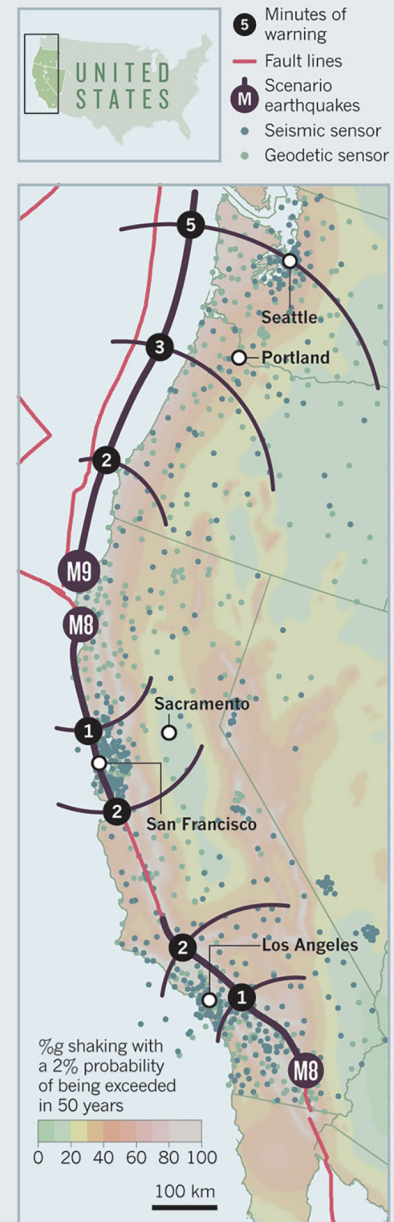
The enhanced capabilities of EEW-tuned networks are strongly complementary with the needs of earthquake and structural geology research and hazard mitigation. The potential to expand monitoring to the seafloor is particularly promising and would improve the response and robustness of EEW, drive new discoveries, and enable more accurate assessment of the hazards posed by Earth's largest faults.

An additional early warning capability for tsunamis is possible by using GNSS receivers to observe ionospheric disturbances coupled to propagating Rayleigh waves, permitting tracking of both tsunami development and propagation. These observations would complement ongoing tsunami monitoring and warning efforts to improve advance warning of an approaching tsunami for at-risk populations in coastal communities, including more precise estimates of the tsunami's magnitude and arrival time.

Figure V6. Earthquake early warning consists of tracking earthquake rupture in very-near-real time, within 2–20 s of ground breakage, so that warning of impending shaking can be given to areas not yet shaken. Shown are scenarios for an M9 earthquake in Cascadia and a pair of M8 earthquakes on the San Andreas Fault. A few minutes of warning are possible for these important cases. Figure courtesy of Richard Allen (UC Berkeley)

US WEST COAST HAZARD MAP

Public alerts of large earthquakes could give the populations of major cities along the West Coast several minutes advance warning.



hazard-informative effects of different types of eruptive activity. Seismic and geodetic (GPS and InSAR) data are critical components for inferring structures and processes within magmatic/volcanic systems, including determining the size, shape, orientation, and depth of intrusions (dikes and sills), rates of magma and gas ascent, volume of magma and gases erupted versus those remaining within the plumbing system, and the space-time distribution of seismic and aseismic strain. The evolution in time of such parameters provides keys to the underlying processes, which then inform decision making during crises. As recognized by the EarthScope program, there are cross linkages between InSAR and GNSS networks that are highly relevant to volcano studies. For example, GNSS data provide geodetic tie points for the InSAR imagery and can also be used for characterization and removal of noise related to the wet troposphere and ionosphere. The continuous spatial patterns of deformation provided by InSAR and the continuous time series of position at GNSS stations are required to more fully constrain and understand the processes and timing of change.

Once an eruption begins, the operational emphasis of the scientific community and monitoring and emergency response efforts substantially shifts to “nowcasting” or the rapid characterization of eruptions in progress. Here, the emphasis is on near-real-time data assessments. Seismology is a key indicator because the location, intensity, and type of activity are closely related to eruption tremor. Infrasound data are also valuable for determining fluxes of ash and gases, and lightning radio frequency emission and visual data can help reveal electrical processes that affect ash particle aggregation. Ash clouds are important hazards that can have effects at large distances from volcanoes and can be monitored using satellite and ground-based remote sensing, as well as GNSS data. For example, the eruption of Eyjafjallajökull in Iceland during April 2010 affected commercial airline flights between the United States and Europe, and flights within Europe, for five days, with losses to the aviation industry alone in the billions of dollars. Scientific issues pertaining to ash cloud characterization and the mitigation of attendant aviation hazard include rapid determination of height, volume of ash, size distribution of ash particles, electrical properties, volume and composition of gases, and magma chemistry, and their evolution. Robust determinations require local, regional, and space-based assessments from a range of geophysical data.

While ash is the most widespread hazard, lahars, lava flows, and poison gases are local hazards at volcanoes. Lahars generally occur in channels, are long lasting (up to decades), and may be seasonal if they are triggered by rainfall. Seismometers placed near channels have been effective at detecting lahars. Lava flows are slower moving features best tracked by visual and remote-sensing methods. For example, photogrammetry and InSAR have been used to determine volumes of lava domes and flows. Key scientific issues are volume versus time, flow rates, cooling effects (some flows contract as they cool), and interaction with surface waters.

4.2. ECOSYSTEMS AND RESOURCES

4.2.1. Water Resources and Ecosystems

In the upcoming decades, worldwide water resources will be increasingly stressed. Continued population and economic growth will lead to increased industrial and urban and agricultural water usage to support populations and enhance food production. Managing and meeting this growing demand will require better characterization and monitoring of water resources at local, regional, and national scales. GPS/GNSS, InSAR, and gravity data constraining surface (including snowpack) soil and atmospheric water and hydrological loading and land subsidence will permit characterization of long-term water storage and the effects of drought and other meteorological and climate variability. Geodetic networks can currently estimate changes in water storage on regional scales by observing and interpreting the loading effects in groundwater systems (see [Vignette 7](#)), and the continuation and advancement of such facilities is necessary to inform sustainable water use strategies. Tracking all components of water storage (soil moisture, vegetation, surface water, snowpack, groundwater), their fluxes at variable spatial and temporal scales, and their linkages with remote-sensing and ground-based seismic, geodetic, and other data can help forecast crop productivity, flood vulnerability, drought severity, and wildfire risk, and can usefully inform the mitigation of these phenomena.

Expanding urbanization significantly alters physical land properties and is often accompanied by subsidence resulting from settlement and increased groundwater extraction.

Vignette 7. Water in the West

Severe drought in the western United States since 2012 is leading to record drops in groundwater and surface water storage, resulting in ground subsidence in areas with unconsolidated, permeable material and rebound of the solid Earth due to decreased loading. Space-based geodetic measurements provide invaluable information about this water loss. Satellite and airborne-based InSAR can monitor groundwater levels by measuring surface deformation resulting from water withdrawal and recharge. In the Central Valley (CA), excess groundwater extraction compared to replenishment is leading to rapid ground subsidence, which is a challenge for managing groundwater resources and mitigating associated hazards. Even in high precipitation years, water deliveries fell short of requests, suggesting that decline in groundwater levels will continue. In the Santa Clara Valley (San Francisco Bay Area), the first area in the United States where land subsidence due to groundwater withdrawal was recognized, remedial actions were taken, including importation of surface water from the Sierra Nevada, installation of aquifer recharge facilities, and decrease of well-water withdrawal. Using InSAR, uplift of 3–4 cm in the Santa Clara Valley was detected from 1992–2012, corresponding to 3–7% of the original subsidence. Because the inelastic compressibility is one to three orders of magnitude larger than the elastic compressibility, only a small portion of the initial compaction is recovered with recharge through poroelastic rebound. The longer-term response of aquifer systems is also overprinted with seasonal water-level cycles corresponding to elastic deformation. The characteristics of the seasonal deformation, constrained with GPS and InSAR, can be integrated with continuous water-level measurements to enable identification of storage properties and prediction of elastic versus inelastic response.

In addition to extreme drops in groundwater level in the last three years, overall water storage in the form of surface waters, snow, and reservoirs in the western United States is at a record low. The water mass loss associated with the recent drought induces instantaneous vertical and horizontal displacements that can be measured at the millimeter level using continuous GPS. Time series of vertical positions from PBO stations show that the loss of surface and near-surface water mass results in a broad region of uplift, with an average of 4 mm and up to 15 mm in California's mountains between 2011 and 2014. The corresponding total water deficit is estimated to be about 240 Gt, equivalent to the current annual mass loss from the Greenland Ice Sheet. Quantitative observations of the decrease in water mass have also been illuminated by other space-geodetic methods, such as satellite gravimetry (NASA's GRACE satellite). GRACE data reveal that, since 2011, the Central Valley lost 4 trillion gallons of water each year (15 km^3), more than what is used each year by California's 38 million residents. The combination of GPS (spatial resolution of 50 km) and GRACE data (resolution of $>200 \text{ km}$) enable evaluation of local to large-scale water changes. Additionally, vertical GPS measurements resolve strong seasonal fluctuations. California's mountains subside up to 12 mm in the fall and winter due to the added load of snow and near-surface water storage, and rise by a similar amount in the spring and summer when the snow melts, surface water runs off, and soil moisture evaporates.

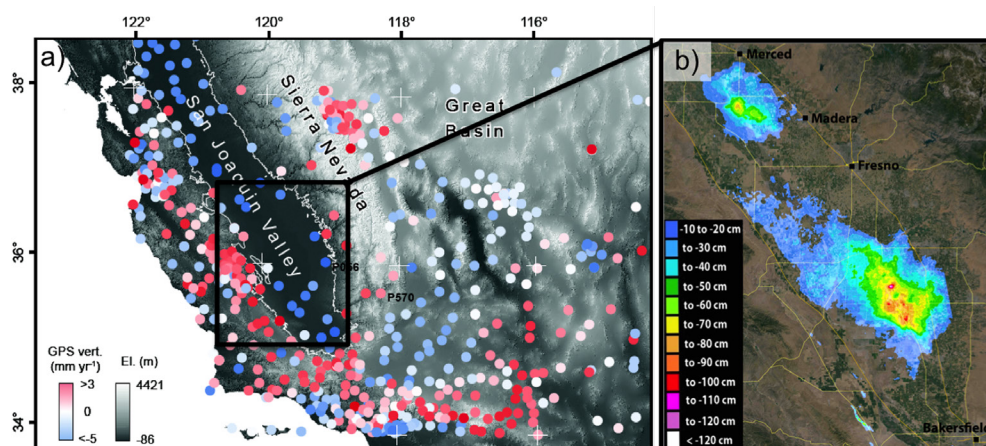


Figure V7. (a) Vertical GPS velocities in California showing uplift (red) in the coastal ranges and in the Sierra Nevada and showing subsidence (blue) in the San Joaquin Valley aquifer. *Figure modified from Amos et al. (2014)* (b) Subsidence in the San Joaquin Valley from InSAR (red colors) from 2007–2011 resulting from intense groundwater extraction of the aquifer system. *Figure courtesy of Tom Farr (JPL)*

Land subsidence has been quantified with GPS and InSar for a large and rapidly increasing number of cities worldwide, with consequences ranging from damage to buildings and infrastructure to increased coastal flooding. By integrating near-surface geophysical and remote-sensing methods, a better understanding and quantification of land subsidence processes can be achieved. Such information is needed to inform water management policies and associated planning and hazard mitigation programs.

4.2.2. Energy Resources

Earth-sourced energy is currently essential to civilization. Geosciences and associated engineering disciplines are the foundation upon which the hydrocarbon industry, one of the world's largest commercial sectors, is built. Seismology, in particular, is globally essential to prospecting for and to the conventional and unconventional extraction of hydrocarbon and geothermal energy resources. Seismology and geodesy play important roles in the monitoring and management of energy reservoir production and optimization; the characterization, understanding, and, where necessary, mitigation of induced seismicity in hydrocarbon or brine aquifer systems; and in the broader management of injected fluids, including enhanced recovery methods and the geological sequestration of CO₂. Seismological methods provide by far the highest resolution of all geophysical techniques in elucidating key geological features of these reservoirs in both land- and marine-based operations. Three- and four-dimensional seismic imaging problems are among the most computationally demanding of all data and processing problems, and they pose first-order cyber-infrastructure challenges that are being addressed with some of the most advanced computer systems. Imaging and interpretation principles and associated theory and methodologies essential to the hydrocarbon industry share fundamental commonalities with challenges posed by tectonic, earthquake, deep Earth, volcano, and other research areas that are supported by NSF geophysical facilities. As noted in [Section 4.3.2](#), the energy industry is a principal employer of graduates from U.S. Earth science programs. University departments that extensively utilize NSF-supported seismology and geodesy facilities for undergraduate and graduate education and research are also principal sources of career-path production specialists hired into energy disciplines.

4.3. FACILITY SUPPORT FOR EDUCATION, OUTREACH, AND WORKFORCE DEVELOPMENT

Current facilities support a broad range of educational and outreach activities that are vital to training the next generation of academic and applied geophysical scientists and to educating and informing society at large. These aspects of our facilities play key and integrated roles in the *Centers of Excellence*.

College and University Geoscience Education

Current seismic and geodetic facilities make important and unique contributions to undergraduate and graduate geoscience education, and it is critical to the future of the discipline that the future facilities retain and advance these capabilities. Because of their longevity, stability, expertise, and organizational strengths, facilities have sustained educational impacts that strongly complement and strengthen both general educational (e.g., non-geosciences majors) and geoscience professional preparation at academic institutions. The fundamental, high-quality, and unique aspects of research support provided by the facilities are essential to graduate research projects and theses in geophysics programs across our community. Classroom and laboratory exercises across the United States and internationally use data sets from the facilities' archives and educational materials developed and disseminated by their education and outreach programs. The wide availability and high quality of these data and materials for education is particularly important for institutions without extensive geophysical programs, such as two-year colleges, where approximately half of today's geoscience majors begin their college careers.

Systems borrowed from the portable instrument pool and data distributed by facilities are essential to NSF-funded research, but are also widely and effectively used for advancing education and professional preparation. The current easy availability and broader educational use of these resources should continue. For example, most undergraduate and graduate seismology courses taught in the United States incorporate broadband seismic data from the GSN. Similarly, any course in geodesy would typically use raw or processed data available from the UNAVCO-managed GPS and SAR archives. Portable instrument data collection and

analyses are commonly integrated into field exercises and provide an efficient avenue for academic institutions to incorporate locally collected geophysical data into post-secondary curricula for geoscience majors and non-majors. Facilities-enabled undergraduate and graduate research is a key element of professional education and mentorship and workforce development (see below).

Workforce Development

In 2012, the American Geosciences Institute estimated that 300,000 geoscientists are employed in economic sectors that contributed \$100 billion to the U.S. economy. The health and competitiveness of these geoscience professional industries depends critically upon a strong, diverse, and highly qualified workforce. More broadly, the 2012 President's Council of Advisors on Science and Technology report concluded that the United States must increase the number of STEM undergraduate degrees awarded by about 34% annually over current rates to satisfy future workforce needs. As elaborated in [Section 4.2.2](#), geophysicists, in particular, are essential employees in a wide range of economically critical professions, including the energy industries (prospecting, recovery, sequestration), geotechnical engineering, environmental, navigation, surveying, recreational, defense, transportation, natural hazards and water resources. The working professional degree for many of these jobs is the M.S. degree, and many of the associated theses incorporating seismology, geodesy, and related methods and disciplines will continue to make use of and benefit from the diverse NSF facility-supported resources discussed in this report.

Training the next generation of geoscience professionals depends upon university education and research programs that use the current geophysical facilities, and the above statistics suggest that the workforce need is getting more acute. As one example, the workforce pipeline is enhanced through undergraduate internships that attract students to geoscience careers and immerse them in challenging geodesy and seismology research programs where they work closely with professional mentors (see [Vignette 8](#)). Field research programs also provide undergraduates and graduate students with hands-on experiences with geophysical equipment and cutting-edge research. Dedicated facility-run workshops train graduate students and early career scientists in specialized methodologies that mesh

with facility capabilities as well as with community resources and standards. International training efforts in data collection and distribution catalyze unique professional networks that span from students through senior international network management and staff. Overall, facility-coordinated community training through broadly accessible workshops, webinars, internship programs, and focused short courses have been highly successful in providing valuable and effective contributions to standard graduate and undergraduate education and should be continued.

Science Literacy

Healthy geophysical facilities provide a steady stream of high-quality and well-described geophysical data that allow for the continued dissemination of important and exciting research to the public. Our facilities should continue to support public education efforts through lecture series, museum displays, articles in popular magazines, webinars, timely authoritative information following significant geophysical events, and online pedagogic videos. Lecture series, in particular, should seek to expand their presence in nontraditional venues. In addition, outstanding opportunities exist for facilities to develop educational activities that involve large numbers of teachers and/or informal educators at science centers, national parks, and other locations, particularly those that target minority and underrepresented communities.

Our future facilities should support training workshops that enable teachers as well as informal educators (e.g., at museums and parks) to more effectively engage on geoscience topics and provide opportunities for educators to interact directly with scientists. Undergraduate faculty, particularly those who teach at smaller or majority-minority institutions that are not major players in geophysical research should be engaged by the facilities in these efforts. This engagement is likely best accomplished by collaborating with programs that presently focus on these groups.

The facilities also are essential to the key research that allows the community to inform policy makers and the media on critical geoscience-related topics, such as those related to the development of energy resources and the impacts of humans on Earth systems. Journalists find geoscience topics relevant (biomedicine is the only science field

Vignette 8. Facility-Linked Research Internships and the Future Workforce

Geoscience students and professionals often start their academic careers in other STEM or in non-STEM majors. Undergraduate research experiences can significantly influence a student's decision to pursue an Earth science related career. Encouraging underrepresented students to participate in an Earth science themed Research Experiences for Undergraduates (REU) program, in particular, requires sustained effort and the building of institutional and personal relationships with the students and with minority serving institutions. Two successful examples of these efforts coordinated by facilities staff in recent years have been the IRIS Intern and UNAVCO Research Experiences in Solid Earth Science for Students (RESESS) programs.

The summer IRIS Intern program begins with a group orientation (conducted in recent years at the IRIS PASSCAL Instrument Center in Socorro, NM) where students participate in a range of interactive learning experiences, including deployment and recovery of facility-supported equipment and rapid data analysis. Following the orientation, the interns conduct fieldwork at widely distributed university and/or field sites arranged with an academic mentor. Interns typically present their research results at the Fall American Geophysical Union meeting that December. RESESS is a multiyear program, where students spend their first summer in Boulder, CO. In their second and third years, students work with researchers at university and/or field sites distributed throughout the United States; some students also join the IRIS intern cohort. For example, one RESESS intern was also a summer IRIS intern. He then went onto graduate school with an NSF fellowship, where he was a minority recruitment lecture series speaker. This former intern is now a practicing volcanologist. The UNAVCO RESESS and IRIS REU programs have sufficient history to have alumni who have transitioned from undergraduate to graduate student, and then to the workforce, including faculty positions at facility-affiliated research institutions, where some are now hosting their own interns.

To further build these connections, these programs have developed a minority recruitment lecture series. Early career ambassador alumni visit physics departments at Historically Black College and Universities or predominately Hispanic Serving Institutions to deliver lectures focused on cutting-edge research with explicit connections to core physics content. The lectures incorporate information on geophysics as a possible career option for physics majors, emphasizing the role an internship through UNAVCO or IRIS can play in developing this career path. Repeated contact with the schools has resulted in placements in both programs.



Over 220 students have participated in one or both programs, and over 80% of interns in either program who have completed their undergraduate degrees are pursuing an advanced degree in the geosciences or are working in a geoscience field. These efforts are attracting students to the discipline, creating a networked community of early career scientists who can become future research leaders, and are enhancing ties between industry, NSF, and academia.

Figure V8. Ann Marie Prue (University of Wisconsin-River Falls) and Crystal Burgess (Alfred University) investigate carbon-rich mudstone at a road cut during a RESESS field trip. Morrison, Colorado, June 2015. *Photo courtesy of Benjamin Gross (UNAVCO)*

that appears on the front pages of major newspapers more often than geoscience), and surveys have shown that most Americans are generally interested in and fascinated by geophysical processes such as earthquakes and volcanoes. The public education aspect of the facilities/academic partnership is critical because geoscience has not historically been part of the standard K–12 curriculum. Thus, most citizens have not had formal education in the Earth sciences.

Public Outreach

Current facilities have successfully coordinated significant public outreach efforts with the community, including high-profile museum engagement and national public lecture series. To further enhance community engagement, our future facilities should continue to exploit new forms of communication (e.g., social media, apps, crowd sourcing); improve visualizations of data and concepts; provide additional opportunities that connect scientists, educators, decision makers, stakeholders, and journalists; and integrate these efforts with programs that maximize research experiences for students and articulate career pathways. The facilities have become important communication hubs for the science community, and in the future they should implement a wider range of methods to expand and broaden their audience.

5. Facility Capabilities

The Facilities Vision ([Section 2](#)) describes *Centers of Excellence* with capabilities that need to be sustained and advanced to address fundamental research in Earth science. To address our Grand Challenges, the community identified augmentation and recapitalization of current facilities in the near future and support for technological developments as requirements.

Specific facility capabilities are categorized here as **Existing Foundational**, **Emergent Foundational**, and **Frontier Foundational** capabilities are fundamental and essential to near-term science directions, including the continuation of currently funded projects during 2018–2023. We subdivide these facilities into **Existing**, some in need of recapitalization, and **Emergent**, which are desired facilities based on proven technologies that would allow progress on major science challenges. **Frontier** capabilities are those that are of, to varying degrees, nascent, but are of significant interest to the community now for their potential to enable transformative science. The sense of **Emergent** and **Frontier** in this context may have science, technological, geographic, and/or observing environment implications.

Many of the community facilities' existing capabilities (e.g., those developed within SAGE, GAGE, EarthScope, and Polar Programs) should be maintained. Sustaining their ability to support projects at short to long experimental time scales, across a wide range of environments, and for individual PIs through community-scale projects, is assumed to be **Foundational**. We note that a number of substantial discussions are currently taking place regarding emergent community-

wide efforts that will require a responsive facility environment to advance. Projects range from multidisciplinary/international subduction zone observatories to crustal-scale studies on the scale and ambition of EarthScope. We also strongly emphasize the overarching importance of tight professionally managed coordination between data management, instrumentation, education, and outreach components to ensure efficient, effective, and responsive facility operation. Within each category, we itemize capabilities that are focused on long-term networks, are associated with temporary deployments, and are essential to supporting the geophysical workforce and research community from education, outreach, mentoring, and workforce training perspectives.

5.1. EXISTING FOUNDATIONAL CAPABILITIES

Capabilities that exist today at a significant level are essential to ongoing science. It would be disruptive if they were degraded. Ongoing recapitalization and re-engineering of seismic, geodetic, and other instrumentation for improved quality, cost/benefit, robustness,



size and weight, and ease of deployment is considered a foundational capability. The present facility components responsible for each capability are indicated in parentheses.

Maintained Permanent Seismic, Strainmeter, and Geodetic Networks

The ability to answer many fundamental geophysical questions depends on the acquisition of high-quality, long-term geophysical records. These data enable comparisons of significant events and provide stable reference frames for temporary deployments. Permanent networks are built and maintained through a wide assortment of national and international collaborations and remain as essential geophysical infrastructure for the community. Key permanent networks include:

- **A GLOBAL VERY BROADBAND SEISMOGRAPHIC NETWORK (SAGE).** This telemetered, continuous, high-quality global network with approximately 20° average station spacing (approximately 10° on land) should be sustained and operated in partnership with the USGS, CTBTO, NOAA, and international organizations. This long-term global seismographic network is essential for research on Earth structure, earthquakes, and other topics, for nuclear treaty verification, and for monitoring, rapid event characterization, and warning systems for earthquakes, tsunamis, and other seismic events. These permanent stations have additional value as elements of and platforms for long-term telemetered environmental sensing networks and should be useful to discovery mode science and as platforms for additional types of instrumentation. Current design goals are met on land by the existing Global Seismographic Network and its national and international partner networks, however, placing stations in oceanic environments remains elusive.
- **PERMANENT AND CONTINUOUSLY RECORDING GPS NETWORKS (GAGE).** A dense, stable, and robust GPS network must provide data with very low latency (<1 s) and at a high sampling rate (1 Hz or better). The network should be sufficiently dense and extensive to resolve interseismic, coseismic, and postseismic deformation parameters near major plate boundary faults of the western United States and other established focused areas of interest. High-rate and real-time geodetic data streams near plate boundaries help constrain large magnitude

events for earthquake and tsunami early warning systems. Long-term time series are needed to assess transient behavior and to constrain stable reference frames. The current GPS network in parts of western North America, with significant coverage at 20–40 km spacing, satisfies much of this goal within a limited region, but major U.S. (e.g., Alaska) and other gaps remain. The rest of the actively deforming portion of the plate boundary has a far greater area and number of faults, but lower strain rates, so should be covered with lower station density (~100 km), with more attention given to regions with active faults. On the tectonically stable part of the North American plate, a permanent set of stations with 500–1,000 km spacing is needed to provide a reference frame and to constrain the very low strain rates in the continental interior. The network should continue to include densely spaced, continuously recording, telemetered GPS and strainmeter instruments on major active volcanic systems in the western United States and in Alaska. The data would permit study and monitoring of magmatic deformation and would provide early warning of volcanic events. The facility should enable collection of GPS/GNSS data for use in reflectometry.

- **A NETWORK OF BOREHOLE STRAINMETERS (GAGE).** Borehole strainmeters capture a part of the deformation spectrum between seismic and GPS instruments with unique sensitivity. Instrumentation exists at clusters that are selectively distributed in the active plate boundary fault zones and volcanic systems of the western United States. These instruments provide distinctive observations of aseismic slip transients on, for example, fault systems, co- and postseismic deformation, magmatic movements, Earth's normal modes, episodic tremor and slip in Cascadia, seiche-induced deformation at Yellowstone, and tsunami-generated deformation. Review of station stability and value for regional detection of deformation processes should guide prioritization of maintenance of existing stations. The geodetic community review of future evolution of the PBO facilities does not recommend new deployments at this time.

Deployable Seismographic Systems

Equipment, field support, and training are required to collect high-quality seismic data over a range of bandwidths and for a wide variety of users and user institutions. The

number of available systems should be sufficient to meet peer-reviewed community needs without disruptive waiting periods. The systems should include a clearinghouse for the collection and dissemination of community best practices that are well coordinated with data services. Specific elements are:

- **PORTABLE BROADBAND SEISMOGRAPHS FOR LOCAL TO SUB-CONTINENTAL NETWORKS AND ARRAYS (SAGE).** The facilities should give the community access to approximately 1,000 telemetry-capable and field robust seismographs and ancillary equipment for temporary installations that are integrated within an expert managed facility for storage, maintenance, and shipping. Surveys ranging from a few to a few hundred instruments employed for durations ranging from a few months to some number of years would need to be supported. Projects using the instrument pool are expected to range from PI-driven to community-driven larger-scale, and potentially long-duration efforts. A component of this pool must be capable of supporting significant deployments in polar/glaciological environments.
- **CONTROLLED-SOURCE SEISMOGRAPH SYSTEMS (SAGE).** The community requires access to approximately 3,000 stand-alone seismograph systems for crustal-scale studies and approximately 500 recording channels in cabled systems for studies at the critical zone and geotechnical scales. Both systems enable PI-driven research and have been widely used in geophysics field courses. The use of these systems overlaps with (but is not identical to) energy and geotechnical industry scientific interests. University class offerings that use these systems directly serve industry workforce needs.
- **SEISMIC SOURCE FACILITIES.** Future facilities should provide community access to resources for both land and marine data acquisition (onshore: *SAGE*; marine: *UNOLS*). Controlled, active sources provide the highest-resolution images of subsurface structure and composition from the meters scale up to many tens of kilometers.
- **OCEAN BOTTOM SEISMOGRAPHS (SAGE-OBSIP/UNIVERSITY).** Facilities should include seismographic packages for shallow and deepwater settings that incorporate approximately 160 broadband and 100 short-period systems, the latter of which will commonly be

used in active-source refraction studies. These packages should incorporate differential and absolute pressure gauges. A subset of OBS instrument packages should have accelerometers for use in areas with potential for strong ground motions.

Deployable Geodetic Observation Systems

While the permanent geodetic infrastructure provides key spatial and temporal reference information, the only way to get sufficiently dense observations in many places is through repeated temporary deployments and more comprehensive use of InSAR data. Numbers of available GNSS systems should be sufficient to meet peer-reviewed community needs without disruptive waiting periods. In addition, a wide range of geodetic instrumentation (e.g., terrestrial laser scanning, or TLS) is currently only used in temporary deployments. In all cases, the availability of instrumentation needs to be accompanied by the necessary expertise supporting field deployment, hardware and software troubleshooting, maintenance, and repairs. The facility should also provide leadership and expertise on the latest commercial off-the-shelf instruments and on the application of emerging technologies, such as ground-based radar and structure from motion photogrammetry collected using drones. Some airborne and mobile lidar needs are met by the National Center for Airborne Laser Mapping. There are several other needed elements.

- **DEPLOYABLE GNSS INSTRUMENTATION (GAGE).** The future facilities should have approximately 150 field-ready up-to-date GPS receivers for temporary deployments to globally distributed locations (we assume all receivers will have GNSS capabilities by 2018 under current GAGE planning). Such an instrument pool would be used to capture transient deformation following large earthquakes as well as many other diverse PI-targeted investigations. A component of this pool must be configurable for deployment in polar and other extreme environments. This pool of receivers may also support mobile continuous reoccupation of network(s) of permanent monumentation but without permanent receivers.
- **CAMPAIGN-MODE SEAFLOOR GEODESY (University).** Through a combined effort of our future facilities and university partners, we should continue installation of seafloor geodetic monuments allowing for campaign

and semi-continuous observations. Underlying technology allowing for reductions in cost and increases in spatial and temporal sampling should continue to be supported. Such campaigns should continue to provide baseline measurements in case of large events as well as to enable the search for aseismic transients.

▪ **TERRESTRIAL LIDAR INSTRUMENTATION (GAGE).**

The needs include hardware, field engineers, and software expertise for a shared pool of terrestrial lidar instrumentation. These capabilities support a variety of research in geology, geomorphology, and polar sciences by providing access to expensive, high-precision instrumentation and the expertise to run them.

Land and Marine Magnetotellurics (SAGE/University)

The future facilities should include centralized and maintained access to ~100 long-period and wideband MT systems to support PI-led campaigns. Facilities should have the capacity to support two to four simultaneous campaigns.

Data Archiving, Quality Control, and Distribution (GAGE/SAGE/WInSAR)

Facilities are needed that provide modern cyberinfrastructure and professional support for ingestion and quality control of high-capacity seismic, MT, InSAR, GPS/GNSS, strainmeter, and TLS data and open access to these data. Support must include the archiving and efficient distribution of both raw and processed data forms and their associated metadata. In many cases (e.g., processed InSAR or GPS data), the information of interest may be a data product (e.g., an interferogram or displacement time series) that must be highly processed, documented, and distributed to meet the needs of the broad research, agency, public, and other user communities. A curated archive of high-resolution topographic data produced via terrestrial lidar, TLS, and other approaches should be openly accessible. This facility element also should include the archiving and visualization of derived models and other research results of general interest to the community, and hierarchical levels of community-guided data products. Data archives must also provide access points that support both expert users with high-volume demands as well as entry-level, classroom, and non-specialist users.

Hosting of Community-Provided Products and Services (GAGE/SAGE)

The future facilities need to be able to host community products and services such as seismic, interferometric, and geodetic time series and results generated in response to special events (e.g., earthquakes); community models; software; and teaching and workshop materials. The balance between facility-coordinated versus PI- or other NSF-supported data products and services should be subject to community programmatic and quality evaluation and oversight.

High-Level Computational Modeling Tools (CIG/University)

Infrastructure should be aimed at accelerating the understanding of Earth and Earth-like systems. This infrastructure would provide community access to innovative computational methods, resources, and technologies, including access to HPC resources and cyberinfrastructure for supporting a variety of multidisciplinary Earth science research.

Professional Staff Support (SAGE/GAGE)

It is essential to have professional staff supporting the facilities. Staff should have a variety of expertise, including in research, development, and implementation of new technologies; training others in instrument use and data collection; implementation of best practices; field logistics; data handling; and the responsible, efficient, and effective caretaking and utilization of facility resources. Expert guidance from embedded professional staff in these areas significantly enhances the overall success of NSF-supported projects and their broader impacts.

Workforce Development (SAGE/GAGE)

Facility staff often play important educational, experiential, and mentorship roles, in collaboration with academic partners, in the training of the next generation of geoscientists. Facilities, through their links to consortium members, provide a level of long-term professional logistical support and a quality and variety of research mentoring that often cannot be equaled by stand-alone research experiences at a

single institution. At the undergraduate level, students are provided with access to research opportunities through formal or informal trainee/intern programs and via more varied research project participation. At the graduate level, students are trained via dedicated workshops in specialized data use methodologies that mesh with facility capabilities and community resources and standards. At the academic professional level, early career support and mentorship efforts that incorporate facilities training should be continued. Such community training through broadly accessible facility-supported workshops, webinars, internship programs, and focused short courses have been successful in providing valuable and effective contributions to standard graduate and undergraduate educational opportunities and should be continued.

Professionally Staffed Nationwide Education and Public Outreach Programs (SAGE/GAGE)

Our facilities need to provide a broad array of resources that have the potential to impact informal education, public outreach, and K–16 education, including videos, animations, apps, sensors designed for education, and informal learning documentation. Social media will continue to play an important role in reaching younger audiences. Informal education can serve as a recruiting tool to bring a new and diverse worker pool into the Earth sciences by reaching out to groups that may not typically be exposed to seismology and Earth sciences. This outreach can be accomplished through, for example, distinguished lecture series and museum exhibits, and through activities targeted at underrepresented groups. Data, data access tools, and data products should be available for instruction at all levels, including the popular “Recent Teachable Moments” that are disseminated after large geophysical events. Facility-supported research internships play a critical role in attracting/retaining undergraduates to Earth sciences and in illuminating career pathways. This strategy is particularly critical for removing barriers for participation so as to attract students from underrepresented groups. Facilities should continue to support training workshops and classroom activities that enable teachers to more effectively engage students on current geoscience topics and careers, and provide opportunities for educators to interact more directly with scientists.

5.2. EMERGENT FOUNDATIONAL CAPABILITIES (HIGH PRIORITY FOR 2018–2023)

Facility capabilities that do not currently exist but that are tractable next steps in new or augmented geophysical infrastructure with high relevance to Grand Challenges.

Large-N Intermediate- to High-Frequency Arrays

We should have available to the community on the order 10,000 three-component, rapidly deployable, robust, and unobtrusive intermediate- to short-period (tens of seconds to thousands of Hertz seismometers, plus some longer-period accelerometer capability) seismographic systems for both rapid response (see below) and scheduled deployments in support of earthquake, volcano, glaciological, and other topics in both PI- and community-scale initiatives. The scale of this element should be sufficient to enable the transformational change from recording sparsely sampled seismic waveforms to recording the full seismic wavefield with greatly reduced spatial aliasing at a variety of scales. Instruments should be both exceptionally easy to deploy in large numbers and capable of sustained, long-term, autonomous operation (up to at least months, if not years).

Rapid Response Instrumentation

The facilities should have the capability to support and deploy (leveraging large-N, next generation GNSS, and other general emerging facility technologies) small (tens) to large (hundreds to thousands) networks of appropriate instrumentation within hours to days of significant geophysical developments, such as volcano unrest, earthquake swarm or aftershock sequences, glacial surges or floods, or landslides. For earthquake aftershock studies, a mix of weak- and strong-motion functionality is needed. Some rapid response capability exists in the present facilities. However, to be fully effective, rapid response capabilities must be sufficiently supported within a policy and procedures context with NSF and/or other sources of rapid scientist/technical support funding available in a suitably rapid time frame. To facilitate timely deployments, pre-crisis strategic partnerships with federal and state agencies and with university and other partners should be

coordinated by and with the facilities. Rapid response activities may also incorporate structure from motion, lidar, or other rapid mapping capabilities as appropriate. For large subduction zone or other offshore events, an OBS and seafloor geodetic component may be incorporated. Rapid response instrumentation and associated data handling should be capable of augmenting the real-time monitoring and response efforts of local, regional, and national partners.

Access to Large Volumes of InSAR Data and Products

The facilities should provide routine, automated, and rapid access to large volumes of satellite InSAR products, including those from the upcoming U.S.-India NISAR mission, such as individual unwrapped interferograms in radar and geocoded coordinates, epoch-by-epoch time series, and geophysical parameterized products (e.g., secular velocities and coseismic displacements), all with comprehensive metadata and processing provenance. Products should be available from observations made by the rapidly expanding international constellation of radar satellites that, taken together, provide global coverage, greater temporal resolution, and lower latency. Ideally, the facility should also provide access to customized, on-demand, project-specific reprocessing. Such a facility should be a joint effort of multiple agencies and multiple centers of expertise.

Operational GNSS Processing

The facilities should play a leadership role in moving from using only GPS signals to using the full GNSS constellation. There should be operational processing of GNSS data at daily and near-real time higher rates (>1 Hz) either directly or through partnership with university groups. Processed data should include both near-real-time products for monitoring and disaster response as well as lower-latency, higher-quality products for less-time-critical science use. Operational processing should be coordinated by the facilities in partnership with academic developers and service providers to support continued innovation for better methodologies, models, and new data products as well as to ensure training of the next generation of scientists. The scope of coverage should include all data available in open access archives around the world. The system should keep pace with the growth in the number of stations. The

facilities should maintain leadership in GNSS reflectometry techniques by supporting software development and distributing GNSS environmental products and supporting relevant short courses.

Enhanced Capabilities to Explore, Develop, and Apply Next Generation and Emerging Instrumentation

Facilities provide key community expertise, experience, and resources that enable new technologies to be more quickly adopted by the community. For instance, optical fiber-based strain measurements have the potential to provide higher-resolution observations of strain and temperature. Similarly, consumer drones (fixed wing and N-copter) are currently being utilized for a variety of applications, including high-resolution digital elevation models for geomorphology and coseismic fault offset detection, ice stream kinematics, civil environment applications, and volcano monitoring. It is critical that facilities have the capacity to continually investigate and integrate such new technologies as they become available. Seafloor geodesy is another area with multiple scientific motivations where recent technological advances indicate important advances can be made in the near future.

Geophysical Instrumentation Capabilities for Geomorphological, Glaciological, Surface, Near-Surface, and Critical Zone Geophysics

While existing facilities supply some portable seismic instrumentation for shallow imaging, the community presently lacks access to more comprehensive instrumentation, technical support, and user training for glaciology and surface/near-surface geophysics. Required instrumentation includes portable hardware for campaign-style deployments; downhole geophysical logging equipment; and a small drilling/coring rig that can access the upper 50–100 m of the subsurface. Specific imaging tools include ground-penetrating radar, seismic refraction and reflection, magnetotelluric, electrical resistivity, nuclear magnetic resonance, microgravity, magnetic gradiometry, and time and frequency domain EM systems. Widely used downhole logging instrumentation capabilities should include caliper, sonic, resistivity, natural gamma, fluid temperature/conductivity, flowmeters, and borehole televiewers (acoustic and optical). Access to slimline wireline

tools is also necessary. Imaging of surface features and topography is rapidly evolving. Examples include drone-hosted structure from motion and other rapidly developing photogrammetry technologies and ground-mounted radars. Both of these technologies are currently emerging into broader use and can augment or supplant lidar and other present methods. The community requires these capabilities to work in a variety of extreme environments, particularly polar.

Onshore Seismic Source Capabilities

Controlled, active seismic sources are essential for imaging the crust at the highest resolution. At present, the expense of these sources impedes PI-led proposals such that very few projects are funded larger than at the kilometer scale, and onshore multichannel seismic reflection has not been funded since the 1990s. At the same time, academia and industry have embraced 3-D (and 4-D) reflection seismology, illustrating the continuing value of the method. While sources are ephemeral (vibrators, or drilling and explosives), a facility of managed contracts with industrial providers could be built.

Land and Marine EM Capabilities

Wideband MT with crustal-scale capabilities (to 1000 s period) should be expanded and recapitalized to enable simultaneous deployment of six to 10 instruments. Support for higher-frequency shallower research for near-surface and critical zone studies (e.g., modern multichannel controlled source electromagnetics) should also be included.

Expanded Ocean Bottom Seismographic and Geodetic Capabilities

The facilities need to be capable of deploying tens of instruments or more in shallow water for longer periods of time. The instruments must routinely record both weak and strong broadband ground motions. The facilities also need to be able to deploy seafloor geodetic instrumentation, develop and operate seafloor geodetic arrays at community-targeted sites, effectively and efficiently colocate oceanographic and other instrumentation within OBS experiments, and develop and deploy long-term very broadband seafloor geophysical observatories.

High-Bandwidth and Real-Time Global Telemetry

The facilities should provide geographically ubiquitous access to affordable, robust, high-bandwidth, and real-time telemetry for seismic and geodetic instrumentation that can be deployed in both long-term and short-term situations and in small to very large numbers.

Development of Instrumentation and Telemetry Systems Capable of Supporting Multidisciplinary Environmental Observatories

Power, data, and communications systems should be capable of supporting broader geophysical observatories that can capture a wide variety of ancillary Earth observations from diverse analog and digital sensors.

Ubiquitous Access to HPC Resources

The facilities should provide software and tools that enable data reduction, forward modeling, visualization, and model inference on massive scales. A new generation of observational capabilities and inverse methodologies drive the need for routine access to HPC hardware with a particular emphasis on Tier V mid-level compute resources. Applications range from generating and interpreting large point cloud data sets from lidar and structure-from-motion imagery, to the routine calculation of data synthetics from complex 3-D Earth models, to structural model inference using seismic, geodetic, MT, or other data. In all cases, access to consulting computational scientists is essential to advance efficiently the transition of tools from desktops to HPC resources. This staff is comparable to experts in observational deployments that are presently integral to facility operations.

National-Scale Engagement with K–12 Education

The high-quality, professional, curated, and openly distributed data managed by the geophysical facilities offer a unique resource in support of the Next Generation Science Standards (NGSS). These standards have the potential to significantly improve the science education of U.S. students by providing an experiential understanding of science methodologies. Many NGSS practices focus on obtaining,

analyzing, mathematically manipulating, interpreting, evaluating, and communicating real data. There is currently an overwhelming demand from teachers, curriculum developers, and textbook companies for real high-quality geoscience data sets that can be used in K–12 classrooms. This need is particularly acute in high schools, for which the NGSS requires a full year of geoscience education (in addition to a year in middle school). As of July 2015, more than 70% of American school districts were in the process of aligning their school curricula either in full or in part with the NGSS. The potential return on educational geoscience data sets created and distributed by geophysical research community facilities is thus enormous.

5.3. FRONTIER CAPABILITIES

Future facility capabilities with the promise of transformative science.

Seafloor and Free-Floating Geophysical Networks

The facilities should have the capacity and resources to install, maintain, and exploit dense seafloor geophysical observatories, providing in some cases continuous records in near-real time. A subset of targeted sites should be able to collect long-term seismic observations in remote ocean basins to achieve the global design criteria for the GSN, as well as broadband geodetic observations. Quasi-permanent networks should be augmented with deployable networks that can serve as short-term large-aperture arrays. Automated communication vehicles and data link technologies are needed to communicate with and retrieve data globally from geophysical seafloor instrumentation while engaging little or no ship time. Submarine drifting hydrophone systems may also offer unique and highly cost-effective opportunities for retrieving acoustic and other data from vast expanses of the ocean.

Next-Generation Magnetotelluric and Controlled-Source Electromagnetic Capabilities

Wideband (and controlled source) MT facilities should be expanded to permit long deployments for 4-D imaging. The facility of the future should support and help to

accelerate the development of cheaper and more capable instruments as well as new sampling strategies (e.g., high-density electric field measurements, drone-based airborne EM) to allow denser sampling and improved and cheaper EM imaging. Magnetic sensors installed at selected GSN sites on ocean islands (not true observatories with absolute baseline control) could fill the largest gaps in the global distribution of geomagnetic observatories and enable significantly improved imaging of mantle conductivity. These data would also be valuable to the space physics and the geomagnetism communities. Development of a true multi-user marine EM facility (analogous to OBSIP) should also be a priority for the facility of the future.

Deep Borehole Access and Instrumentation

The facilities should have the capacity to support drilling and instrumentation of deep (i.e., >1 km) terrestrial and marine boreholes for in situ studies of active fault systems. Representative instrumentation may include temperature, hydrological, seismic, strain, and geochemical sensors.

Instrumentation for High-Risk/High-Benefit Experiments

The facilities should include temporary, quick, or autonomously deployed, and potentially disposable, telemetered instruments for high-risk science with human safety concerns such as near volcanic vents, in areas of extreme topography, and flood-prone or unstable glacial environments. Such instruments are needed to make observations that cannot be made remotely and where the instrument may be non-recoverable or destroyed. Deployment may be coupled with drone or other automated deployment/recovery/instrumentation systems that incorporate structure from motion photogrammetric, sensor, or other capabilities.

Programs to Communicate Broad Understanding of Earth System Science

To enhance community engagement, the facilities should exploit new forms of communication (social media, apps, crowd sourcing); improve visualizations of data and concepts; provide opportunities that bring together scientists, educators, and journalists; and develop programs that maximize research experiences for students and articulate career pathways. The facilities have been important

communication hubs for the science community, but they need to use a range of methods to broaden their audience. One example is to provide opportunities for student-collected and crowd-sourced data and models to be accessible via mobile apps and other evolving platforms.

Workforce Diversity

Recent graduates with a BS/BA geoscience degree are 77% Caucasian and just 7% minority populations (Wilson, 2014), although the proportion of minorities in the U.S. population is currently 27% and growing. The geosciences lag behind many STEM fields in academic and professional workforce diversity. Effective and evidence-based strategies must be widely employed to engage a diverse student population for the nation to remain a leader in the geosciences (Velasco and Jaurrieta de Velasco, 2010). Furthermore, general interest in the geosciences continues to grow (6% long-term increase) since its low in 1990 (AGI, 2014), providing additional opportunities to diversify the workforce with the changing face of the nation.

Improving the current situation requires that the facilities and their partners establish increasing diversity as a central and supported component to their mission and develop multifaceted and professionally managed programs that reach across both traditional and non-traditional audiences. Engaging undergraduates early in their academic careers improves educational accomplishments, especially for underrepresented groups in STEM. Such efforts can be formally coordinated via MOU's with societies and universities with strong emphases in reaching underserved and underrepresented communities.

6. Summary and Perspectives

This report represents the outcome of a wide range of community activities carried out during 2014 and 2015 to define the geophysical observing facilities required to meet the needs and ambitions of the geoscience community over the next decade. The last several decades have taught us the benefits of community facilities that are effectively *Centers of Excellence*. These facilities, and the professionals within them, maintain critical pools of instruments; manage, enable, and promote free and open access to vast high-quality archives of heterogeneous data; support design, maintenance, and construction of quasi-permanent as well as temporary field deployments; and through community governance, maintain the essential agility to address rapidly evolving challenges and opportunities. They provide access to critical instrumentation and data and catalyze research and broader impacts participation across a diversity of academic institutions. Facilities play crucial roles in supporting the education of next generation

Earth scientists. Thus, they contribute critically to future scientific advancement and U.S. science leadership, to mitigating natural and artificial hazards, and to sustaining essential workforce elements of the energy, technology, natural resources, and other sectors of the economy.

The community recognizes the obstacles in addressing the very wide range of facility needs outlined in this report, which has led to a classification of specific items and activities into three broad categories. **Existing Foundational** capabilities are essential to the status quo, including ongoing projects funded by NSF. Without the sustaining of existing foundational elements, ongoing and near-future scientific discovery, and the communication and impact of results, would be drastically impeded. Our science would be cast backward, negating years of progress. **Emergent Foundational** capabilities are those that do not currently exist but that, as evidenced by nascent activities and developments, are viewed



as both realizable in the near future and essential to continued progress. Such emergent capabilities include, but are not limited to: Large-N seismic networks and arrays, dense EM deployments, operational processing of high-rate low-latency GNSS data streams, access to vast quantities of satellite InSAR data from the international satellite constellation, and targeted development and deployment of geophysical networks across the ocean. We urgently suggest infusing these emerging capabilities, which hold promise to bring profound new discoveries and perspectives into Earth structure and dynamics, into a vastly wider community than has access to them presently. Going beyond these foundations and high-priority next steps, we are already beginning to see over the horizon to identify next-generation facility capabilities. These **Frontier** capabilities and activities have great promise but will require significant investment and substantial exploration to come to fruition.

These *emergent and frontier* needs and ambitions exceed the scope of the current highly successful facilities and may require community-guided reimagining of operational structures and intra- and extra-NSF partnerships. It is abundantly clear that the range of scientific imperatives and adopted technologies imply facilities and partnerships that extend beyond NSF's Division of Earth Sciences and require comprehensive collaboration across different NSF divisions as well as with and among federal agencies (NASA, USGS, NOAA, USAID, DOE, and others), across the academic community, and with commercial instrumentation and industry partners. A subset of these activities clearly fall under the umbrella of facilities that resemble present-day structures, while others will necessarily require bold investments in approaches that disrupt conventional stovepiped structures as they integrate optimally.



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8. Appendix

Community Science Plans and Other Reports Referred to in This Document

A Strategic Vision for NSF Investments in Antarctic and Southern Ocean Research (2015)

<http://www.nap.edu/catalog/21741/a-strategic-vision-for-nsf-investments-in-antarctic-and-southern-ocean-research>

US Geoscience Enrollments and Degrees Robust in 2014 (2015)

<http://www.americangeosciences.org/workforce/currents/us-geoscience-enrollments-degrees-robust-2014>

Status of Recent Geoscience Graduates 2014 (2014)

http://www.americangeosciences.org/sites/default/files/cwilson/ExitSurvey_101614_MedResWithLinks_0.pdf

The Future of PBO in the GAGE Facility (2013-2018) and After EarthScope (2014)

http://www.unavco.org/community/meetings-events/2014/pbo-future-14/PBO_workshop_final_report_all_submitted.pdf

A Facility Plan for Polar Seismic and Geodetic Science: Meeting Community Needs Through IRIS and UNAVCO Polar Services (2012)

http://www.iris.edu/hq/files/publications/other_workshops/docs/Polar_Facility_Plan_IRIS_UNAVCO.pdf

A Foundation for Innovation: Grand Challenges in Geodesy (2012)

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A Preliminary Strategic Plan for EarthScope Cyberinfrastructure (2012)

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New Research Opportunities in the Earth Sciences (2012)

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President's Council of Advisors on Science and Technology Report to the President—Engage to Excel: Producing One Million Additional College Graduates with STEM Degrees in Science, Technology, Engineering, and Mathematics (2012)

https://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast-engage-to-excel-final_feb.pdf

Autonomous Polar Observing Systems (APOS) Workshop Report (2011)

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Unlocking the Secrets of the North American Continent: An EarthScope Science Plan for 2010-2020 (2010)

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Seismological Grand Challenges in Understanding Earth's Dynamic Systems (2009)

http://www.iris.edu/hq/lrps/seis_plan_final.pdf

Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond (2007)

http://www.nap.edu/openbook.php?record_id=11820

Living on a Restless Planet (2002)

<http://solidearth.jpl.nasa.gov/seswg.html>

9. Acronyms

CIG	Computational Infrastructure for Geodynamics
CTBTO	Comprehensive Nuclear-Test-Ban Treaty Organization
CZ	Critical zone
DOE.....	Department of Energy
DPM.....	Damage proxy maps
EAR.....	NSF Division of Earth Sciences
EEW.....	Earthquake early warning
EM	Electromagnetic
GAGE.....	Geodesy Advancing Geosciences and EarthScope
GIA	Glacial isostatic adjustment
GLISN	Greenland Ice Sheet Monitoring Network
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GRACE.....	Gravity Recovery and Climate Experiment
GSN.....	Global Seismographic Network
HPC.....	high performance computing
InSAR.....	interferometric synthetic aperture radar
IRIS	Incorporated Research Institutions for Seismology
JAXA	Japan Aerospace Exploration Agency
MOU	Memorandum of Understanding
MT	Magnetotelluric
NASA.....	National Aeronautics and Space Administration
NGSS	Next Generation Science Standards
NISAR	NASA-ISRO [Indian Space Research Organization] Synthetic Aperture Radar
NOAA	National Oceanic and Atmospheric Administration
NSF.....	National Science Foundation
OBS	Ocean bottom seismometer
OBSIP	Ocean Bottom Seismometer Instrumentation Pool
PASSCAL.....	Portable Array Seismic Studies of the Continental Lithosphere
PI.....	Principal Investigator
POLENET.....	Polar Earth Observing Network
RESESS.....	Research Experiences in Solid Earth Science for Students
REU	Research Experiences for Undergraduates
SAGE.....	Seismological Facilities for the Advancement of Geosciences and EarthScope
SAR.....	Synthetic aperture radar
STEM.....	Science, technology, engineering, and mathematics
TLS	Terrestrial laser scanning
UNOLS	University-National Oceanographic Laboratory System
USAID.....	United States Agency for International Development
USGS.....	U.S. Geological Survey
WIS.....	Whillans Ice Stream

Photo Captions

FRONT INSIDE COVER. Terrestrial Laser Scan, North Fork of the Toutle River near Mount St. Helens. *Photo credit: Jim Normandeau*

OPPOSITE PAGE 1. Installation of Transportable Array equipment at Alaska Earthquake Center's station at Knik Glacier, May 2015. *Photo courtesy of IRIS*

PAGE 2 (LEFT). New seafloor benchmark with a commercial transponder that has millimeter-level repeatability, deployed at a site offshore Oregon. *Courtesy of SIO/WHOI*

PAGE 2 (RIGHT). Wave Glider configured for GPS-acoustic operations underway at sea. *Courtesy of SIO*

PAGE 3 (LEFT). Six hundred single-component "Texans" being deployed in a dense array at the Hill Air Force Base to image a toxic waste site. *Photo courtesy of IRIS*

PAGE 3 (RIGHT). Interns Alexis Hu and Nicole Ingraham perform fieldwork in Idaho Springs, CO, under the guidance of Annie Zaino and Spencer Niebuhr, who are members of UNAVCO's Polar Group, July 2015. *Photo credit: Aisha Morris*

PAGE 4/5. Annual PBO GPS maintenance at Mount St. Helens, September 12, 2014. *Photo credit: Beth Bartel*

PAGE 7 (LEFT). Deploying PASSCAL instruments in Peru. *Photo courtesy of Lara Wagner*

PAGE 7 (RIGHT). IRIS summer research interns set up a PASSCAL Geode seismographic system during the intern orientation at New Mexico Tech. *Photo courtesy of IRIS*

PAGE 23 (LEFT). Korey Dausz upgrading the communications and electronics at site SC03 on Mt. Olympus on Sept. 8, 2010. *Photo courtesy of UNAVCO*

PAGE 23 (RIGHT). Colorado State University Student Bryce Johnson in the field with PASSCAL seismographic equipment for a 2015 fluvial seismology experiment in Rocky Mountain National Park. *Photo courtesy of Rick Aster*

PAGE 33 (LEFT). GPS site photo from Macmillan Pass on the border between the Yukon and NW Territories as part of the EarthScope Mackenzie Mountains project, August 2015. *Photo credit: Max Kaufman*

PAGE 33 (RIGHT). Ocean bottom seismometers being deployed at Cascadia. *Photo courtesy of IRIS*

PAGE 42/43. IRIS broadband seismographic systems being staged atop the Ross Ice Shelf for aircraft and snowmobile deployment as part of the NSF-supported Dynamic Ross Ice Shelf project in October 2014. *Photo credit: Rick Aster*

BACK INSIDE COVER. UNAVCO polar engineer Nicolas Bayou checking comms at new GPS site SOG1 with the help of Graham Parker, the South Georgia Government Observer. *Photo credit: Amy Westman*



