EarthScope is an ambitious, multifaceted initiative to explore the structure, history and dynamics of the North American continent, and is the world’s first interdisciplinary continent-scale geophysical observatory. A broad and growing population of scientists utilize data collected by the EarthScope Facility to investigate processes that shape the Earth’s geological architecture and landscape, affect natural resources or relate to natural hazards. EarthScope science bears on processes that operate from the sub-second to billion-year timescales, from individual earthquakes to stresses driving lithospheric plate deformation. EarthScope’s target, the North American continent, provides a diverse range of geologic processes, yielding fundamental new insights into this dynamic planet.

Three interlinking components compose EarthScope: (1) the EarthScope Observatories (PBO, SAFOD, and USArray) jointly operated by the UNAVCO and IRIS consortia, (2) a scientific research program that supports PI-led investigations, and (3) an investigator community, coordinated by an academic EarthScope National Office (ESNO), which actively participates in science planning, research, and facility governance. The EarthScope stakeholder community, broadly defined, also includes formal educators (e.g., K-12 teachers and university faculty) and informal educators (e.g., interpretive Park Rangers, museum educators) who make use of the education and outreach resources and programs provided by IRIS, UNAVCO, and ESNO, including online science content, published brochures, teacher professional-development workshops, and interpretive workshops for park and museum educators. These education and outreach activities are intended to maximize the broader impact of EarthScope science.

The EarthScope Facility acquires, delivers, and archives data, develops data analysis protocols and products, provides engineering services for field instrument deployment, and organizes community forums. The EarthScope Science program at the NSF sponsors a broad range of PI-driven research and workshops, with a particular focus on multidisciplinary efforts that make use of EarthScope data sets. The EarthScope research community is a growing, broad, and diverse body, conducting innovative research, informal and formal education, and governance of EarthScope facilities.

The continued vibrancy and success of EarthScope depends on the GAGE Facility for stability of geodetic operations and standards, on the research program for financial support, and on the science community as the energy source of innovation, discovery and communication.

### 2.4.1 EarthScope Observatories

The EarthScope Facility’s three components include USArray, the Plate Boundary Observatory (PBO), and the San Andreas Fault Observatory at Depth (SAFOD). These components began construction and operation in 2003, and have evolved into an integrated system of mature and robust observing systems, providing fundamentally important datasets that have thrust researchers into new realms of data analysis and discovery as documented in the published literature and highlighted elsewhere in this proposal.

**USArray** has multiple observatory components: a Transportable Array (TA), a gridded network of 400 seismometers, barometers and infrasound sensors rolling across the lower 48 states and parts of southern Canada deployed for ~2 years per site, a Flexible Array (FA), which includes more than 2,000 seismic systems available for PI-driven field experiments, and 20 magnetotelluric systems used for campaign deployments on discrete targets.

**PBO** includes more than 1,100 continuous Global Positioning System (GPS) stations distributed across the United States, and concentrated on the active plate boundaries in the western contiguous US and southern Alaska (Figure 2.4-1). PBO also includes 75 borehole strainmeters and 78 borehole seismometers deployed along the San Andreas Fault and above the Cascadia subduction zone and volcanic arc. Tiltmeters (26) and pore pressure sensors (22) are also collocated with the other borehole instruments. The integrated nature of EarthScope observations has been especially important in Cascadia, where broadband seismic observations from over 70 stations (27 of them established through EarthScope) and high-rate, low-latency real-time GPS geodetic observations at 372 PBO stations are being supplemented with offshore observations at over 60 ocean bottom seismic stations and a number of temporary USArray FA deployments. Geogetic imagery and geochronology services supported under GeoEarthScope extend fault histories to millennial timescales.

**SAFOD** is a 3.1-km deep borehole penetrating the San Andreas Fault system near Parkfield, CA. Rock core was recovered during deep drilling sampled across the seismogenic zone, and is the focus of a variety of rock mechanics and related studies. At present a high-frequency seismometer is deployed and is maintained downhole by the USGS at SAFOD, recording a unique seismic dataset at a depth of ~660m below the surface. Under the current
NSF-Cooperative Agreement for PBO, UNAVCO manages both PBO and SAFOD. SAFOD management will transition to a newly established SAFOD Management Office (SMO) in coordination with NSF in the near future.

Ongoing PBO O&M, the upgrade of GPS-only systems to those with full GNSS capability, and RT-GPS data stream enhancements will be significant activities under the GAGE Facility. The details are outlined below in Section 3 The GAGE Facility.

2.4.2 EarthScope Achievements

EarthScope has become an international community platform for Earth science investigations. Data collected by the EarthScope Facility have supported groundbreaking science, including new discoveries in Earth's atmosphere, surface, crust, mantle, and core. Hundreds of published papers have used EarthScope data, and new results enabled by EarthScope are published weekly. EarthScope has enabled new data processing techniques as well as innovative visualization tools. EarthScope has enabled new discoveries that already mandate rewriting key portions of Earth science textbooks.

While many of the fundamentally new results that rely on EarthScope data are discipline-based, some of the more exciting discoveries have emerged from EarthScope’s goal of encouraging interdisciplinary studies that integrate geology, geodesy, seismology, geochemistry, geodynamics, and geophysics. EarthScope has encouraged a new generation of young scientists to start their careers in an interdisciplinary framework, and some of these scientists are now entering leadership positions within the scientific community. These efforts continue to challenge the community to maintain a broad scope of research activities. Ongoing EarthScope research support strengthens these research directions.

Some examples of the breadth of EarthScope discovery and transformative science include:

- Tracking, imaging and elucidating ETS along the Cascadia and the San Andreas fault systems, characterizing this recently recognized mechanism that operates within the earthquake cycle.
- More precise constraints on surface deformation driven by slip along the San Andreas fault.
- Clear evidence for extremely low friction coefficients on fault rocks sampled by SAFOD, confirming that the fault slips under very low shear stresses.
- Integration of accelerometer records with GPS data for characterizing earthquakes, advancing GPS-seismology and early warning systems.
- Direct three-dimensional mapping of crustal deformation patterns and mountain uplift in the western US.
- Unprecedented seismic imagery of the structure of the crust and mantle that underlies the western US, revealing the fate of more than 100 million years of Farallon plate subduction.
- New seismic images of the lithosphere-asthenosphere boundary, mantle transition zone and structures that provide a record of western US tectonomagmatic history.
- New constraints on the location and geometry of lithospheric instabilities that influence the dynamics of western US deformation.
- Insights into mechanisms of Great Basin deformation that accommodate gravitational collapse of the continental interior.
- New seismic constraints on deep mantle dynamics, core-mantle structure, and internal core structure.

2.4.3 Building on EarthScope Success: 2013 – 2018

In October 2009 the EarthScope community met in Snowbird, Utah to discuss science goals, to plan for the future of the program, and to clearly articulate its underlying scientific priorities. The report from that meeting, Unlocking the Secrets of the North American Continent: An EarthScope Science Plan for 2010–2020 [Williams et al., 2010] charts the state and direction for EarthScope science.

This GAGE Facility proposal describes the status and direction of EarthScope science, providing an update to topics in the Science Plan, and includes additional topics that have come to the fore since 2009. Because of the breadth of disciplines and development of technologies that compose EarthScope research, sustained efforts and unique opportunities continue to advance the sciences of Earth observation, modeling, integration, interpretation and dissemination of results.

Over the next 5 years, the EarthScope facilities, operated jointly by the GAGE and SAGE (Seismology Advancing Geosciences and EarthScope – see companion NSF proposal) Facilities, will continue to support and advance this community science plan. Specific tasks outlined in this proposal include:

- Growing the EarthScope community. Support for workshops, institutes, community involvement, education and outreach efforts, and governance will be essential to maintain this element.
- Expanding EarthScope’s geographic focus. Completion of observations by the TA to the Eastern margin of North America, the expansion of the TA to Alaska and the continuation and augmentation of Plate Boundary Observatory observations will focus regional activities.

Alaska: A Geoscience Frontier

During 2013-2018, the collective observing power of EarthScope in Alaska will yield an extraordinary scientific impact. Some 132 PBO GPS stations in Alaska have been operating for over five years, yielding precise time series, and thus useful constraints on regional surface deformation. Beginning in 2013 the USArray Transportable Array (TA) will deploy a grid of ~290 stations across Alaska and into parts of Canada—each site equipped with broadband seismometers, infrasonic sensors, and (at some sites) strong motion accelerometers. Alaska promises to produce a rich dataset given that it has a seismicity rate five times higher than the lower 48 states combined; a complex crustal history; continental-scale fault systems; and significant surface motion everywhere relative to stable North America. Further, there is a high likelihood of recording a magnitude 7 or larger earthquake during any five-year time window and any major volcanic activity has a reasonable chance of being captured simultaneously by the PBO GPS network and the TA seismic and infrasound network.

The 2011 EarthScope workshop report ‘Opportunities for EarthScope Science in Alaska In Anticipation of USAArray’ highlighted the EarthScope science opportunities in Alaska. As the report notes, “In many ways Alaska is a geoscience frontier with enormous area never having been studied beyond reconnaissance level.” The report highlights a number of globally relevant science topics that will be addressed by EarthScope in Alaska, including subduction processes, mantle flow, terrane accretion, far-field deformation, and glacial unloading. That the Alaskan subduction zone is capable of producing great earthquakes and devastating tsunamis heightens the societal relevance of the research. Taken together the scale and scientific opportunities in Alaska make it an ideal target for EarthScope and more than justify the great operational challenges associated with deploying and maintaining stations there.
and opportunities for partnerships with other communities and programs such as GeoPRISMS.

- **Strengthening** data analysis, integration, and interpretation. Continued development of data products and cyberinfrastructure will be guided by the recent report “A Preliminary Strategic Plan for EarthScope Cyberinfrastructure” [Gurnis et al., 2012]. Open access to higher-level data products that build on the expertise of community members will provide information that is easily accessible to an increased number of users.

### 2.4.4 EarthScope Beyond 2018

EarthScope has become the global standard for a broad-based, community-driven, integrative research facility that provides a nexus for interdisciplinary science. The Earth system processes of relevance to the EarthScope scientific community operate on timescales longer than the originally planned 15-year lifespan of the facility, and we expect that a legacy of EarthScope observing systems (for example, PBO as a nucleus for the Network of Geodetic Networks) will continue to sample time-varying phenomena beyond the 2018 horizon. Tectonic deformation is a slow process, and commonly does not occur in a steady state. Earthquake cycle deformations, which are both subject to and offer insight into the rheology of the Earth, can vary over decades to centuries. Just as new and unexpected mechanisms of plate boundary deformation such as ETS were discovered when precise geodetic observations became available at interannual periods, and were better understood in light of high resolution seismic mapping, additional new, interesting, and important modes of deformation related to hydrogeodesy are revealed as interdecadal records become available. In addition, managing, mining, visualizing, and integrating very large, disparate datasets are now coming of age with enhanced cyberinfrastructure, driven by such new initiatives as EarthCube at NSF and COOPEUS in Europe. These efforts are integral to the Geodetic Data Services program within GAGE and are discussed in more detail in Section 3.2.

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**Beyond 2018: A Subduction Zone Observatory?**

The success, knowledge, and experience gained during EarthScope provide an unprecedented launching point for IRIS and UNAVCO to collaborate on the creation of a planetary-scale Subduction Zone Observatory (SZO). This observatory, stretching 18,000 km along the eastern Pacific Ocean, from the Aleutians in the north, to the tip of Tierra del Fuego in the south, will provide an integrated, interdisciplinary approach to understanding the entire subduction zone as a system. SZO research will have enormous societal relevance, given the population centers all along the coast that are subject to earthquake-, tsunami-, and volcano-related hazards.

Existing geophysical networks and observatories will provide the SZO’s starting backbone. The Plate Boundary Observatory (PBO) core—the set of GNSS sites that will form the post-EarthScope backbone in North America—will be one of an anticipated federation of geodetic networks that overlap with new SZO. Current NSF-funded IRIS and UNAVCO activities, such as the GRO-Chile seismic network, the COCONet GPS network, and the onshore and offshore stations of the Cascadia Initiative will provide key infrastructure. The SZO will grow through infill with strategic deployments of broadband seismometers and high-sample-rate GPS. Small, flexible PI-led projects can be designed and performed within this larger framework.

SZO will be a major international initiative, and IRIS and UNAVCO propose to collaborate now on bringing together the necessary geographic, organizational, and disciplinary representation to develop the SZO concept and articulate the science benefits.