EarthScope USArray Facility
Final Report

Award #
EAR-0733069

Award Title
Collaborative Research: EarthScope-Facility Operations
and Maintenance (USArray)

Award Term
October 1, 2008 – September 30, 2013

Report Prepared on
December 30, 2014

Report Prepared for
National Science Foundation
4201 Wilson Boulevard
Arlington, VA 22230

Report Prepared by
Incorporated Research Institutions for Seismology
1200 New York Avenue, NW, Suite 400
Washington, DC 20005

Introduction

The USArray component of the National Science Foundation's EarthScope program facility consists of four major observatory components: (1) a Reference Network of permanent seismic stations; (2) a Transportable Array (TA) of ~400 seismic stations; (3) a Flexible Array (FA) pool of seismic instruments available to Principal Investigators (PIs); and (4) a Magnetotelluric (MT) observatory with permanently and temporarily deployable instruments. USArray also includes comprehensive data management and siting outreach efforts.

USArray efforts during FY09–FY13 continue and expand facility activities established under the previous MREFC and O&M awards (EAR-0323309 and EAR-0323311, respectively) and continued under the "Seismological Facilities for the Advancement of Geoscience and EarthScope" award (EAR-1261681). Quarterly and annual reports submitted to the National Science Foundation throughout the award document USArray progress and accomplishments. This present report provides an overview of programmatic activities conducted under EAR-0733069.

Facility Information

The Incorporated Research Institutions for Seismology (IRIS) operates USArray. Under the governance structure in place during the O&M award, USArray management received community input via the IRIS Board of Directors, the USArray Advisory Committee, and the Transportable Array and Electromagnetic Working Groups (Figure 1). The organizational structure of the USArray has been designed to leverage the experience and facilities that already exist within IRIS. USArray activities are performed at several primary locations (Table 1), and experienced personnel (Table 2) manage all components.

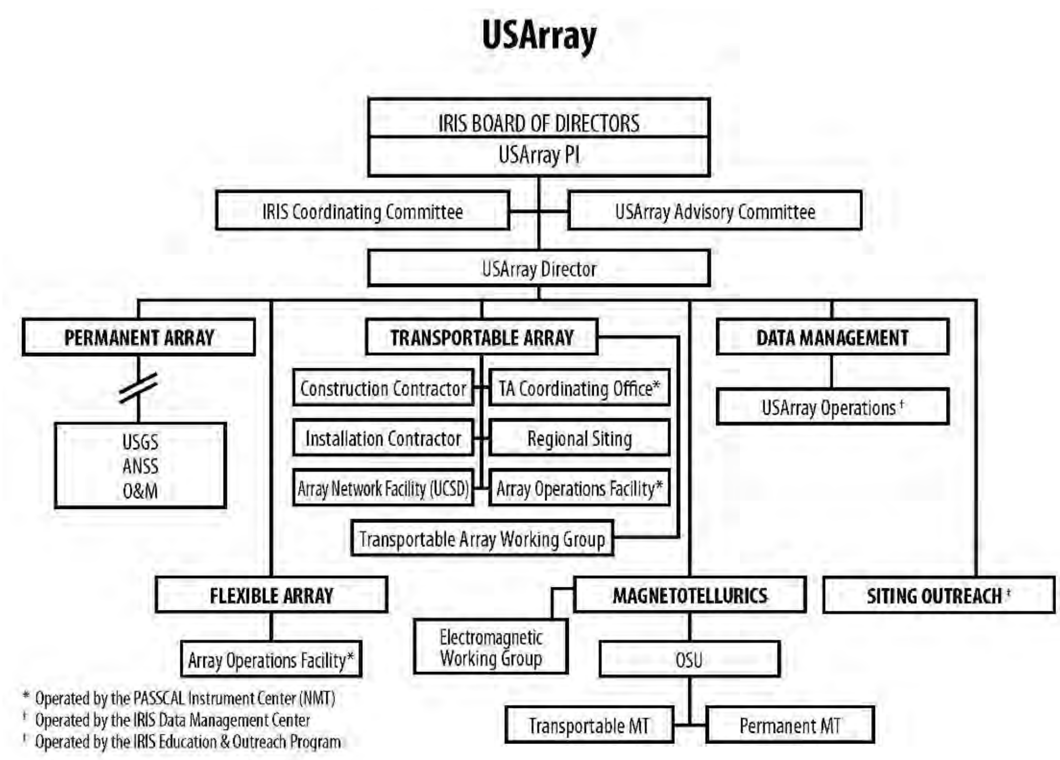


Figure 1. Organizational structure of USArray, including major subawards and advisory bodies

Table 1. Key USArray locations

USArray Facility	Activity	Location
Headquarters	Overall project management and Siting Outreach activities	IRIS Headquarters, Washington, DC
Data Management Center	Archive and distribution of all EarthScope seismic and magnetotelluric data	IRIS Data Management Center, Seattle, Washington
Array Operations Facility	Field operations support for both TA and FA, including sensor testing and repair, warehousing, etc.	Operated by New Mexico Institute of Mining and Technology (Rick Aster, PI)
Array Network Facility	Provides real-time data collection and data management for TA	Operated by the University of California, San Diego, Scripps Institution of Oceanography (Frank Vernon, PI)
Transportable Array Coordinating Office	Provides coordination activities for TA site reconnaissance, permitting, and related logistics	Operated by New Mexico Institute of Mining and Technology (Rick Aster, PI)
Magnetotelluric Depot	Provides field operations depot and support for both MT backbone and MT transportable activities	Operated by Oregon State University (Adam Schultz, PI)

Table 2. Primary USArray personnel

Name	USArray Role	Contact
David Simpson	Principal Investigator	simpson@iris.edu
Bob Woodward	USArray Director, Director of IRIS Instrumentation Services, co-PI	woodward@iris.edu
Bob Busby	Transportable Array Manager	busby@iris.edu
Marcos Alvarez/James Gridley	Flexible Array Manager	N/A
Tim Ahern	Data Management Manager	tim@iris.washington.edu
John Taber	Siting Outreach Manager	taber@iris.edu
Adam Schultz	Magnetotellurics (PI on IRIS subaward to Oregon State University)	adam@coas.oregonstate.edu

Subawards

To complete its charge, the USArray facility utilized 54 subawards spanning a wide range of tasks, scope, and cost. Some of these were a continuation of subawards established during the initial O&M award. Major operational subawards are described below. Appendix A presents a complete listing of subawards.

Coastal Technical Services, Inc.: TA Station Construction
Teams from Coastal Tech. oversaw the construction of nearly all TA stations during the award period. Activities included use of heavy machinery to emplace a water-resistant vault and solar panel mast. Coastal Tech. performed similar operations under a separate subaward related to construction of the Cascadia stations.

Honeywell Technology Solutions Inc.: TA Station Operation and Maintenance and Alaska Logistical Consultation
Engineers from Honeywell were contracted throughout the award to install, remove, and service TA station instruments and hardware. Similar operations were performed under a separate subaward related to operation of the Cascadia TA redeployment stations. Honeywell also provided logistical consultation and initial engineering support to the development of TA operations in Alaska.

New Mexico Tech: Transportable Array Coordinating Office (TACO)
The NMT TACO provides logistical and technical support for permitting, construction, and servicing of TA stations. This group performed similar operations under a separate subaward related to the installation of the Cascadia TA redeployment stations.

New Mexico Tech: Array Operations Facility (AOF)
The NMT AOF provides fundamental support for the two portable components of USArray, the TA and FA. For the TA, the AOF provides system integration, maintenance, and depot facility services. Equipment is staged at the AOF and delivered to the field installation teams. The AOF provides depot maintenance and repair of equipment that cannot be repaired in the field. The FA is operated in much the same way as the IRIS PASCCAL program, in that the FA instrumentation pool is housed at NMT and borrowed by NSF-funded PIs, with the AOF providing planning, training, field, and technical support.

University of California, San Diego: Array Network Facility (ANF)
The UCSD ANF manages the real-time data flow from the USArray TA and delivery of these data to the IRIS Data Management Center (DMC) for permanent archiving as well as distribution to the user community. The ANF provides quality control for all data and ensures that the proper hardware calibration and station metadata are up-to-date and available. The ANF performed similar operations under a separate subaward related to operation of the Cascadia TA redeployment stations.

Oregon State University: Operations and Management of EarthScope Magnetotelluric (MT) Program
OSU provides managerial oversight of the EarthScope MT program, consisting of Backbone (MT-BB) and Transportable Array (MT-TA) stations. OSU also provides technical management to ensure the scientific goals are met, and provides data processing and hardware support for PIs using reallocated MT-TA instruments for short-term Flexible Array (MT-FA) deployments (MT-FA). In addition, OSU operates and maintains the seven MT-BB stations, and plans and manages the yearly MT-TA field campaigns consisting of ~80 stations.

Cascadia Archaeology: Site Assessment on Public Land
Cascadia Archaeology provided archaeological assessment for Cascadia TA redeployment stations installed on public land.

Institute for the Application of Geospatial Technology (IAGT): Geospatial Technology Support
IAGT prepared tools and materials and provided on-site staff support for the 2009 TA siting workshop. As part of their workshop support, they performed site suitability analyses to determine the most likely areas for instrument installation. IAGT downloads GIS and related data, processes and integrates the data, runs the suitability analyses, makes and prints maps for each site, and exports maps to GeoPDF digital format before making their assessment of site suitability.

University of Alaska-Fairbanks: Support EarthScope TA in Alaska
UAF coordinates permitting, assists community outreach efforts, participates in the development and execution of fieldwork and logistics, and collaborates with USArray management relating to TA deployment efforts in Alaska.

RECON, LLC: Alaska Reconnaissance Support
RECON scouted and provided reports on 78 potential EarthScope TA stations in north-central Alaska. RECON created local and regional maps for use during fieldwork, and completed site visits to identify primary and alternate locations for each site installation.

University of Quebec: Station Deployment Support
The University of Quebec provided a translator and local expertise to the TA deployment team as it installed stations in predominantly French-speaking parts of Canada.

Moravian College: jAmaSeis
Moravian College developed jAmaSeis, an improved Java software interface for the AS-1 seismometer used by the IRIS Seismographs in Schools program.

Northwestern University: USArray Data Processing Short Course
Northwestern hosted a data processing short course that provided training in the foundations of seismic data processing to the next generation of seismologists. The short course promoted the usage and development of more effective ways to handle data from large seismic data sets, such as the USArray.

South Carolina Research Foundation: USArray Station Monitor
The South Carolina Research Foundation developed the USArray Station Monitor, a web-browser tool that quickly renders a single day of the vertical-channel seismogram at a specified TA station.

Data Products (see Appendix A for more detail)
Over three years, Data Management awarded $189,940 through eight subawards.

Siting Outreach (see Appendix A for more detail)
For four summers, Siting Outreach subawarded $937,170.30 to 28 institutions, supporting the siting of 697 TA stations by 63 students.

No-Cost Extension

A no-cost extension was granted for the period spanning October 1, 2013 to September 30, 2014. The purpose of this extension was primarily to begin converting and reinstalling TA stations to the new Central and Eastern United States Network (CEUSN), for which supplemental funding was received in FY13. Additionally, savings due to under spending in certain activities and hardware and operational efficiencies gained during the award period allowed USArray to use the positive surplus to acquire equipment spares and enhance the scope of specific tasks. This includes addition of two USArray short courses in 2013 and one in 2014, acquisition of additional interactive Kiosks for use in public outreach, procurement of additional instrumentation and hardware and data storage to increase capacity of the MT program, and expanded reconnaissance and permitting operations in Alaska.

Status of Property

All Government-owned equipment for which IRIS had accountability under EAR-0733069 was transferred to the new Cooperative Agreement EAR-1261681, which was effective October 1, 2013.

Science Highlights

The amount of significant, peer-reviewed science produced from the USArray facility has grown considerably over the period of the O&M award. From a sampling of 11 peer-reviewed journals, 293 publications used USArray data during the period from 2009–2013 (Appendix B). The rate of USArray-centric publications grew from 32 in 2009 to 76 in 2013. A similar number of AGU abstracts (268) were presented during this same period, in addition and often related to scientific results presented at the EarthScope (2009, 2011, 2013) and IRIS Consortium workshops (2010, 2012). Below we highlight some scientific results in which USArray data were key to the analysis.

Development and Application of Ambient Noise Tomography
Using ambient noise recorded by TA stations in the western United States, *Moschetti et al.* [2010] developed tomographic images that (Figure 2) reveal strong deep (middle to lower) crustal radial anisotropy. This anisotropy is confined mainly to the geological provinces that have undergone significant extension during the Cenozoic Era (since ~65 Myr ago). These observations suggest that anisotropic crustal minerals were reoriented by the extensional deformation. These data also support the hypothesis that the deep crust within these regions has undergone widespread and relatively uniform strain in response to crustal thinning and extension.

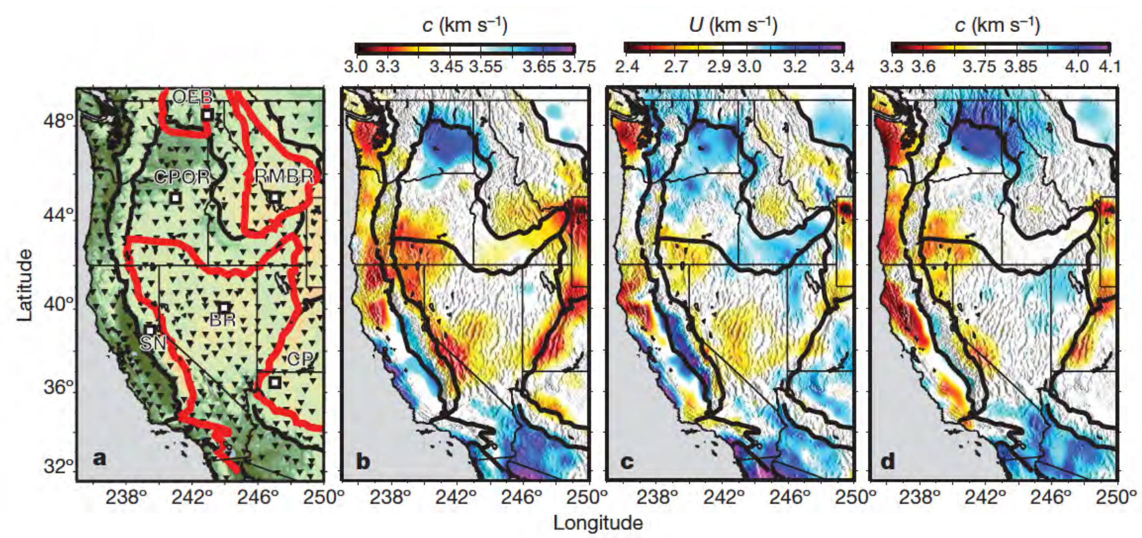


Figure 2. *Moschetti et al.* [2010] use cross-correlations between long time series (of lengths of up to several years) of ambient noise recorded at pairs of TA stations to explore surface-wave dispersion in the western United States. (a) TA stations (black triangles), major tectonic boundaries (thick black lines), and boundaries of the predominant extensional provinces (thick red lines). Maps of (b) Rayleigh wave phase speed, (c) Rayleigh-wave group speed, and (d) Love wave phase speed, at a period of 20 s are shown. From *Moschetti et al.* [2010].

Citation: Moschetti, M.P., M.H. Ritzwoller, F. Lin, and Y. Yang (2009), Seismic evidence for widespread western-US deep-crustal deformation caused by extension, *Nature*, v. 464, no. 7290, p.885, doi: 10.1038/nature08951.

Deep Earth Interferometry with Ambient Noise Cross-Correlations
Seismic body waves that travel through Earth's core are indispensable for studying remote inner regions of our planet. Traditional core phase studies rely on well-defined earthquake signals, which are spatially and temporally limited. *Lin et al.* [2013], using data from pairs of TA stations, show that by stacking the more common, but lower amplitude ambient noise signals (a technique called interferometry), body wave phases reflected off the outer core (ScS) and twice refracted through the inner core ($PKIKP^2$) can be clearly extracted. Temporal correlation between the amplitude of these core phases and global seismicity suggests that the signals originate from distant earthquakes. Similar results from a seismic array in New Zealand demonstrate that the approach is applicable in other regions and with fewer station pairs. Extraction of core phases by interferometry can significantly improve the spatial sampling of the deep Earth because the technique can be applied anywhere broadband seismic arrays exist.

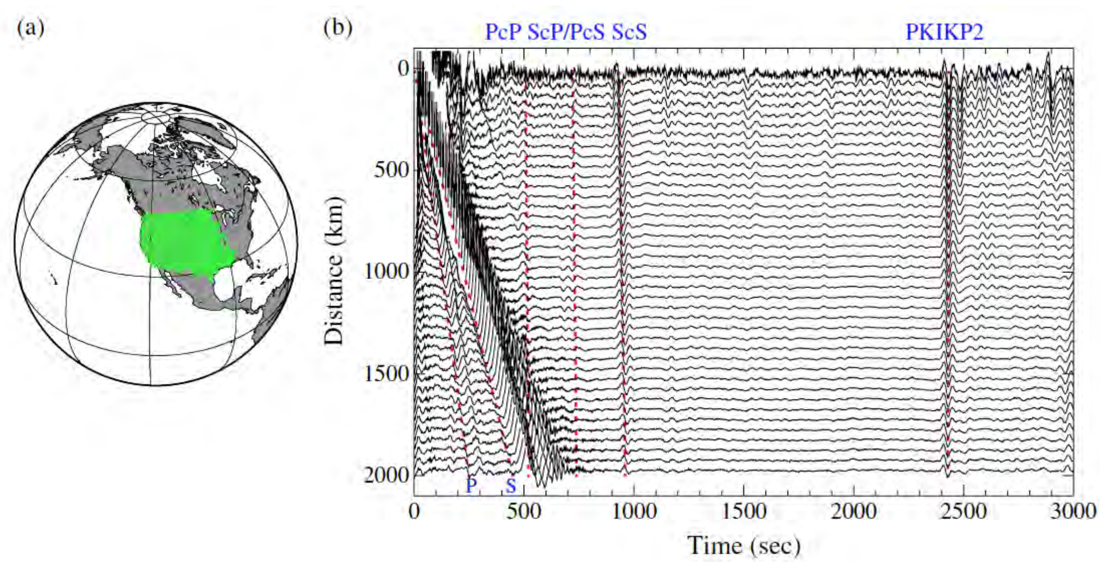


Figure 3. Stacked cross-correlations across USArray. (a) The USArray Transportable Array coverage used in this study. Station locations are marked by green dots. (b) The observed broadband stacked cross-correlations sorted by distance. The red dashed lines mark the ray-predicted arrival times for core phases based on the iasp91 Earth model. Several observed body wave phases are indicated. From *Lin et al.* [2013].

Citation: Lin, F.-C., V.C. Tsai, B. Schmandt, Z. Duputel, and Z. Zhan (2013), Extracting seismic core phases with array interferometry, *Geophysical Research Letters*, v. 40, no. 6, p.1049-1053   doi: 10.1002/grl.50237.

Teleseismic Imaging of Lithospheric Structure
Using a method called travel time tomography, *Burdick et al.* [2008, 2010, 2012, 2014] create images that reveal heterogeneities in the geologic structure of the mantle beneath North America. Travel time tomography uses global inversions of P-wave travel time residuals from regional and teleseismic earthquakes to model Earth structure. In their latest update, *Burdick et al. [2014]* use more than 2.5 million TA travel-time residuals picked by the ANF to refine the mantle images even further. Over time, TA data will continue to help define Earth structure beneath the center of the continent. These data have already shown it to be more uniform than in the West.

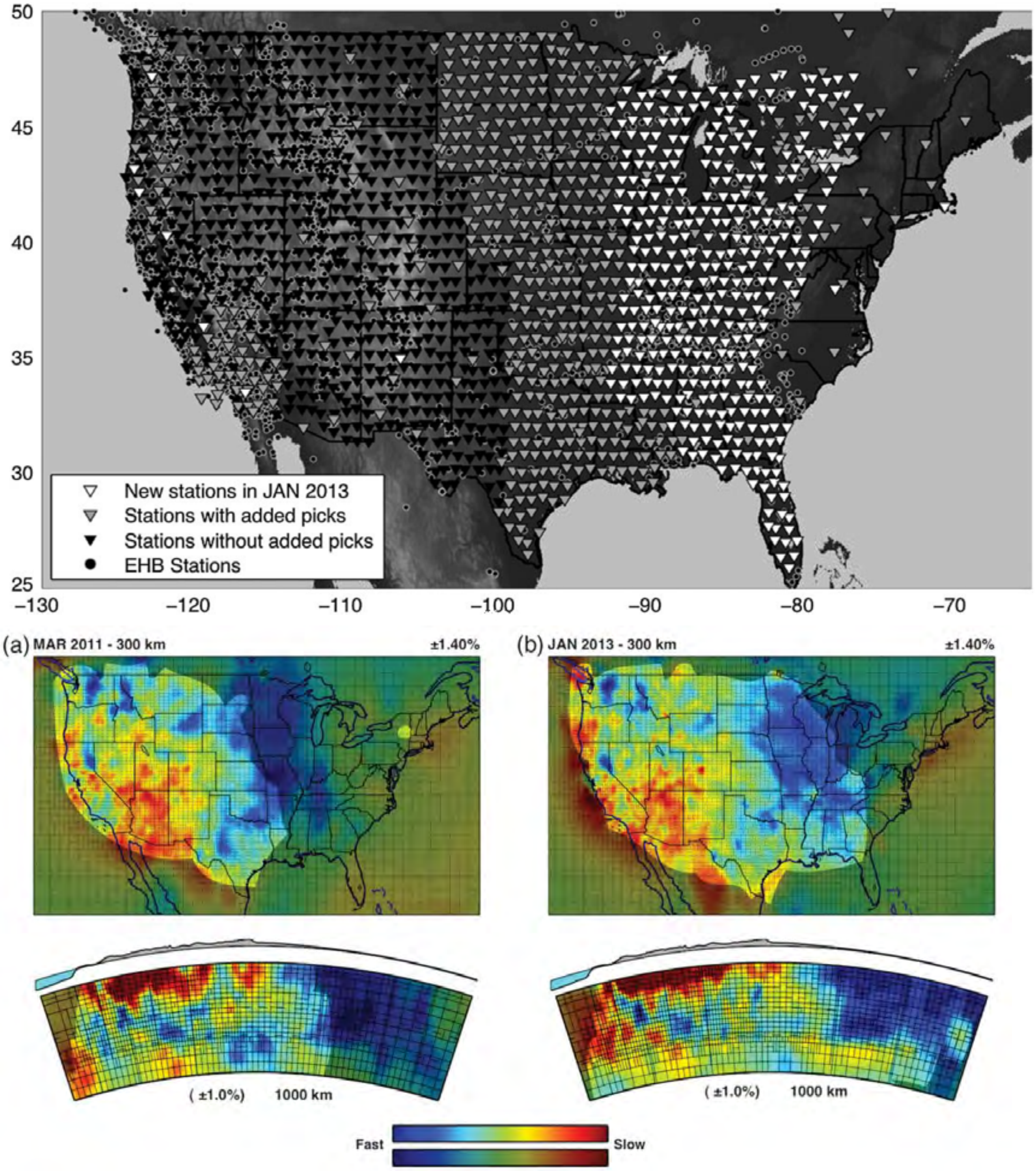


Figure 4. (Map, top) The geographical distribution of seismograph stations in and around the United States from which data are used. Black and gray triangles represent TA station locations from the previous model update for data through March 2011 [*Burdick et al.,* 2012]. Gray stations have additional picks made after the previous update while black stations do not. White triangles represent the new TA stations included in the data set. (Model, bottom) Illustration of grid refinement made over time with the TA. The map views at 200 km depth and mantle cross sections illustrating the grids used for the parameterization of the (a) 2011 and (b) 2013 models (on the left and right, respectively). Cross sections run at 40°N from 82° to 128°W. Grid spacing is representative of the adequate ray-path density within each cell. The unshaded areas show where we are able to resolve structures on the order of 1.5° as determined by checkerboard resolution tests. From *Burdick et al.* [2014].

Citation: Burdick, S., R. D. van der Hilst, F. L. Vernon, V. Martynov, T. Cox, J. Eakins, G. H. Karasu, J. Tylell, L. Astiz, and G. L. Pavlis (2014), Model Update January 2013: Upper Mantle Heterogeneity beneath North America from Travel-Time Tomography with Global and USArray Transportable Array Data, *Seismol. Res. Lett.,* v. 85, no. 1, doi: 10.1785/0220130098.

Detection and Tracking of Atmospheric Infrasound Sources
Walker et al. [2011] use reverse time migration to detect and locate 901 sources of atmospheric infrasound recorded by TA from 2007–2008 and to define the Western United States Infrasonic Catalog (WUSIC). The event locations illuminate repeating sources of infrasound, or "infrasonic hot spots," in Nevada, Utah, and Idaho that are spatially located within active military areas. The results of this study show that relatively dense seismic networks like USArray fill in the gaps between sparsely located infrasound arrays and provide valuable information for regional infrasonic source location and propagation studies. The WUSIC catalog can be used to statistically validate and improve propagation models, especially above the middle stratosphere where ground-based weather stations or meteorological satellites do not directly measure winds.

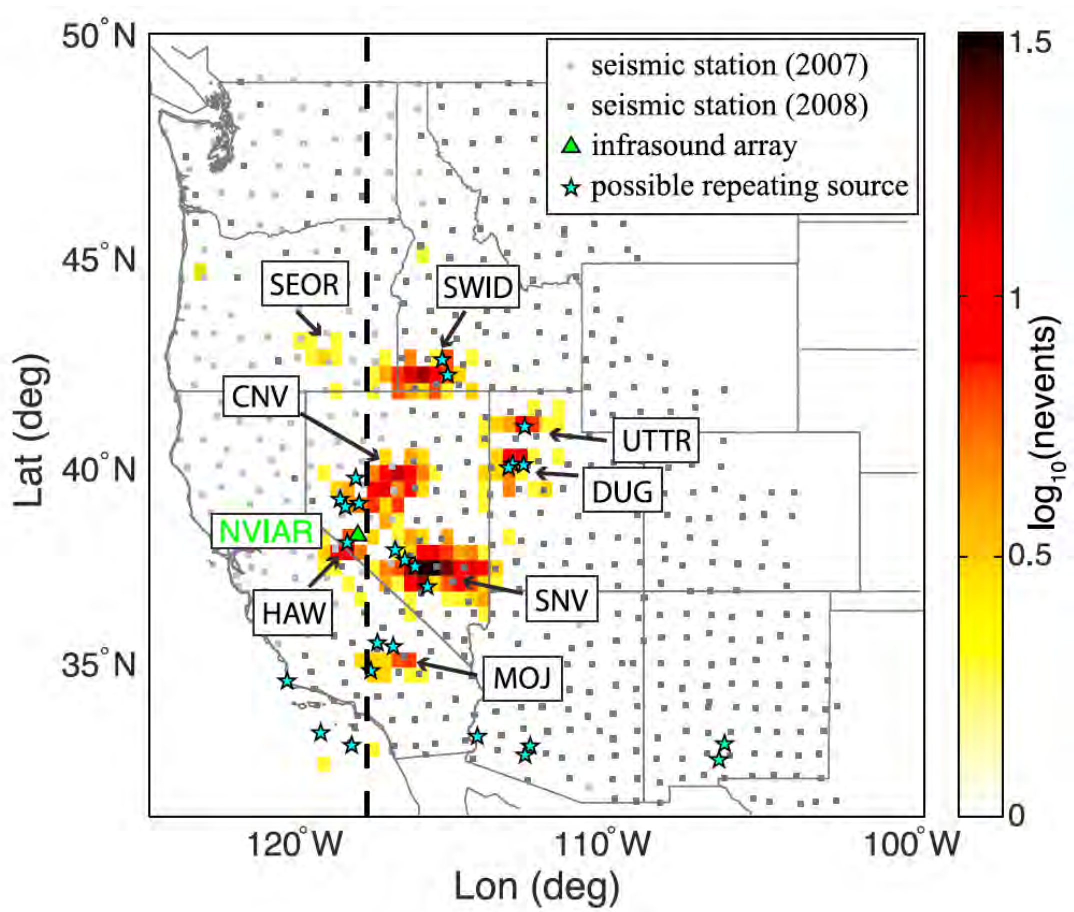


Figure 5. *Walker et al.* [2011] show these two-dimensional histograms of imaged source locations for events in 2007–2008 detected by USArray, which define "hot spots" of activity (labels). Stars indicate military areas of potential infrasonic emissions that spatially correlate with hot spots. From *Walker et al.* [2011].

Citation: Walker, K. T., R. Shelby, M. A. H. Hedlin, C. de Groot-Hedlin, and F. L. Vernon (2011), Western U.S. Infrasonic Catalog: Illuminating infrasonic hot spots with the USArray, *J. Geophys. Res.*, v. 116, no. B12305, p.15, doi: 10.1029/2011JB008579.

Development and Application of Teleseismic Backprojection Imaging
Meng et al. [2011] examine the 2011 Mw9 Tohoku-Oki earthquake, which was recorded by over 1000 near-field stations and multiple large-aperture arrays such as USArray. These arrays reveal rupture complexity with unprecedented resolution. They show that the earthquake ruptured in phases at diverse speeds, including intermittent high-frequency bursts within slow speed phases, suggesting spatially heterogeneous material properties.

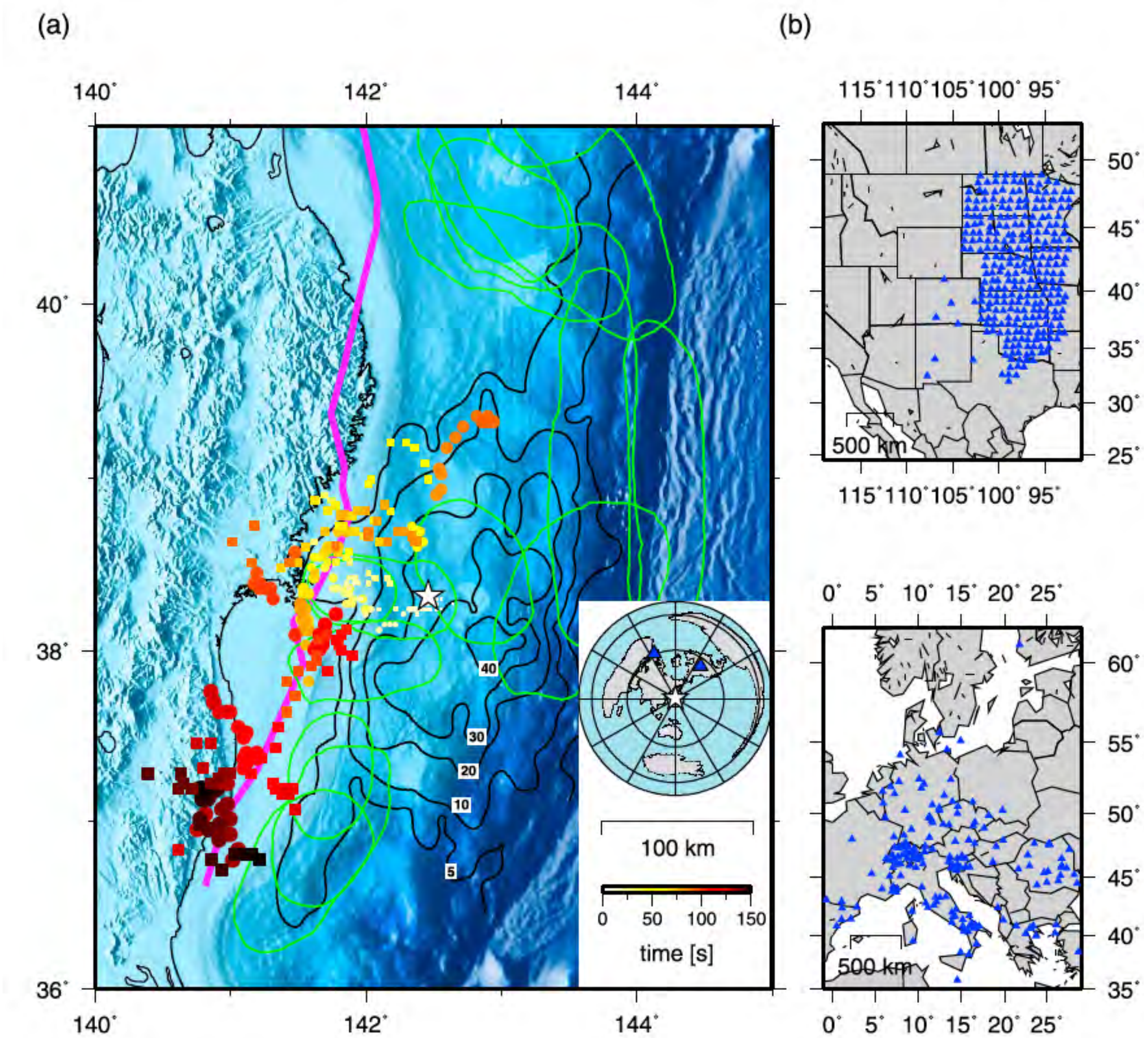


Figure 6. The 2011 Mw9.0 Tohoku-Oki earthquake imaged by the USArray and European networks. (a) The location of the strongest high-frequency radiators of the Tohoku‐Oki earthquake, seen by the USArray (squares) and by the European network (circles). The color denotes the timing with respect to the origin time. The size of the symbols denotes the relative amplitude of the radiators. The green ellipses represent the approximate rupture zone of the historical earthquakes. The pink line near the coast indicates the down‐dip limit of the megathrust seismicity [*Igarashi et al.,* 2001]. (b) Location of the 291 USArray and 181 European stations selected for the backprojection analysis. From *Meng et al.* [2011].

Citation: Meng, L., A. Inbal, and J.P. Ampuero (2011), A window into the complexity of the dynamic rupture of the 2011 Mw 9 Tohoku-Oki earthquake, *Geophys. Res. Lett.*, v. 38, no. L00G07, p.6, doi: 10.1029/2011GL048118.

Imaging of North America's Conductivity Structure Using Magnetotelluric Data
Kelbert et al. [2013] develop a regional three-dimensional electrical resistivity model for the Snake River Plain and Yellowstone areas (Idaho and Wyoming) by combining long-period magnetotelluric (MT) data from 91 USArray MT sites and previously collected MT profiles along and across the eastern Snake River Plain. This model provides new constraints on the large-scale distribution of melt and fluids beneath the Yellowstone hotspot track. The electromagnetic data, which are highly sensitive to the presence of melt and volatiles, suggest that there is little or no melt in the lower crust and upper mantle directly beneath Yellowstone caldera. Instead, low mantle resistivities (10 **Ω**m and below) are found 40–80 km beneath the eastern Snake River Plain, extending at least 200 km southwest of the caldera, beneath the area of modern basaltic magmatism. The reduced resistivities extend upward into the mid-crust primarily around the edges of the Snake River Plain, suggesting upward migration of melt and/or fluid is concentrated in these areas. The anomaly also shallows toward Yellowstone, where higher temperatures enhance permeability and allow melts to ascend into the crust. The top of the conductive layer is at its shallowest in the upper crust, directly beneath the modern Yellowstone supervolcano.

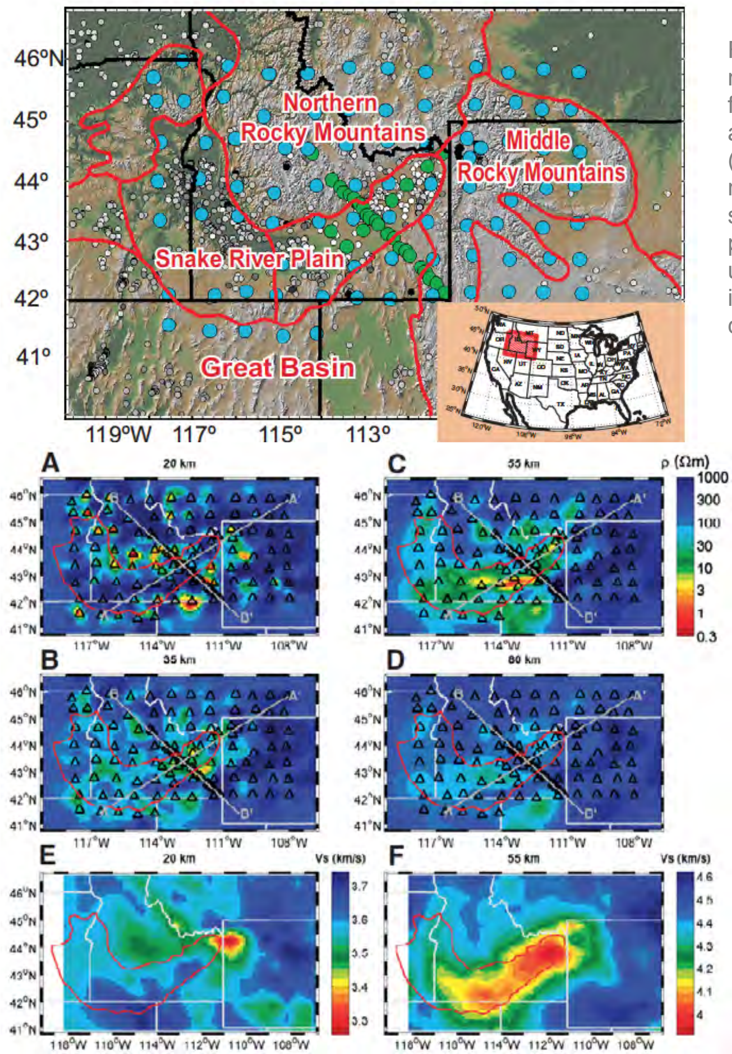


Figure 7. (map left) The USArray magnetotelluric (MT) site locations used for this study are marked with blue dots and the MT profiles with green dots. (below) (A-D) the preferred inverse model at depth, while (E-F) shows a seismic surface-wave velocity model plotted at mid-crustal (20 km) and uppermost mantle (55 km) depths and interpolated to our grid for easier comparison. From *Kelbert et al.* [2012].

Citation: Kelbert, A., G.D. Egbert, and C. de Groot-Hedlin (2012), Crust and upper mantle electrical conductivity beneath the Yellowstone Hotspot Track, *Geology*, v. 40, no. 5, p.447-450 doi: 10.1130/G32655.1.

USArray Leads to Improved Earthquake Catalogs
A detailed record of earthquake frequency and distribution is essential to understanding regional tectonic strain and seismic hazard, particularly in regions of low, but significant, seismicity levels. Comprehensive analyses of seismicity within Arizona have not been previously possible due to a lack of seismic stations in many regions, contributing to the perception that earthquakes within Arizona are rare and generally limited to the north-central and northwestern portions of the state. The TA deployment within Arizona from April 2006 to March 2009 provided the opportunity to examine seismicity on a statewide scale. In this study, *Lockridge et al.* [2012] developed a streamlined workflow for producing a comprehensive earthquake catalog using TA data, and combined their catalog with historical earthquake catalogs to produce the first comprehensive earthquake catalog for the state of Arizona. The TA-derived catalog is complete to local magnitude $M_L \sim 1.2$, contains crustal events as small as M_L 0.0, and includes events located within several previously unidentified areas of seismic activity in Arizona. Identified earthquake swarms and clusters, such as those documented in this study, may represent important regions of small-scale tectonic strain release within intraplate regions that otherwise have apparently low seismicity levels.

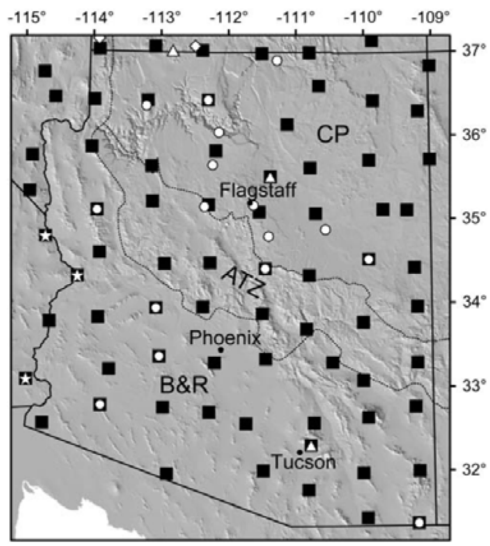
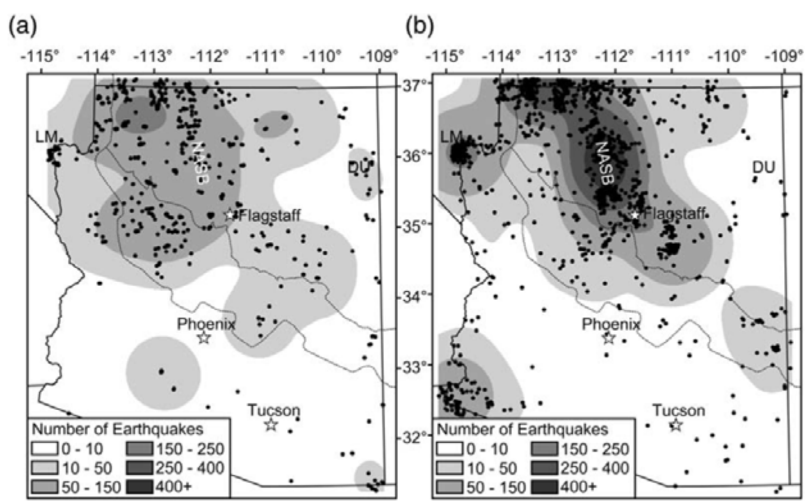


Figure 8. (left) Seismic stations within Arizona used in this study. Solid black squares represent stations associated with the USArray TA. (below) Density (shaded areas) and distribution of earthquakes (black dots) from modern and historical catalogs. In both (a) and (b), density is calculated as the cumulative events within a 100 km radius. (a) Earthquakes from this study recorded by TA stations from April 2006 to March 2009. (b) Total historical events documented within Arizona from 1830 to 2011. From *Lockridge et al.* [2012].



Citation: Lockridge, J. S., M. J. Fouch, and J. R. Arrowsmith (2012), Seismicity within Arizona during the Deployment of the EarthScope USArray Transportable Array, Bull. Seismol. Soc. Amer., v. 102, no. 4, p. 1850-1863, doi: 10.17845/0120110297.

Seismic Wave Gradiometry: Novel Techniques Developed with TA Data
Poppeliers [2011] uses a new technique called the multiwavelet transform to derive uncertainty estimates for wave parameters obtained by seismic wave gradiometry. Wave gradiometry uses spatial gradients as measured by a small-scale seismic array to estimate wave parameters, including propagation azimuth, slowness, geometrical spreading, and radiation pattern. The advantage of wave gradiometry is that the wave parameters are estimated on a point-by-point basis for the entire seismogram. *Poppeliers* [2011] uses the multiwavelet transform to decompose the wave field into a series of mutually orthogonal wavelet coefficients, which can then be analyzed by wave gradiometry. They used TA data to demonstrate that the method accurately and robustly determines the wave parameters of large teleseismic earthquakes.

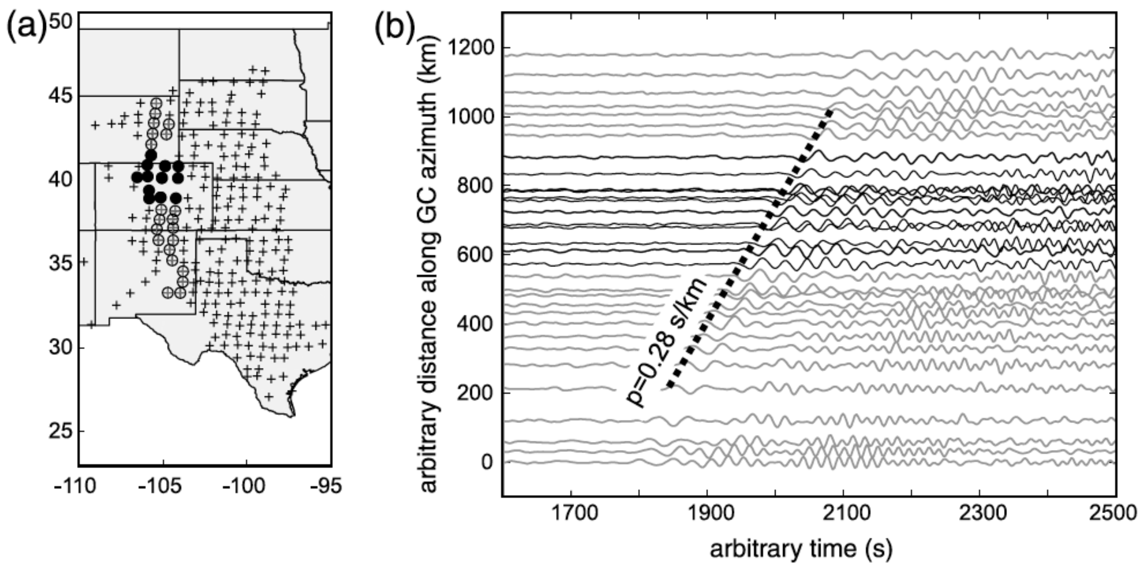
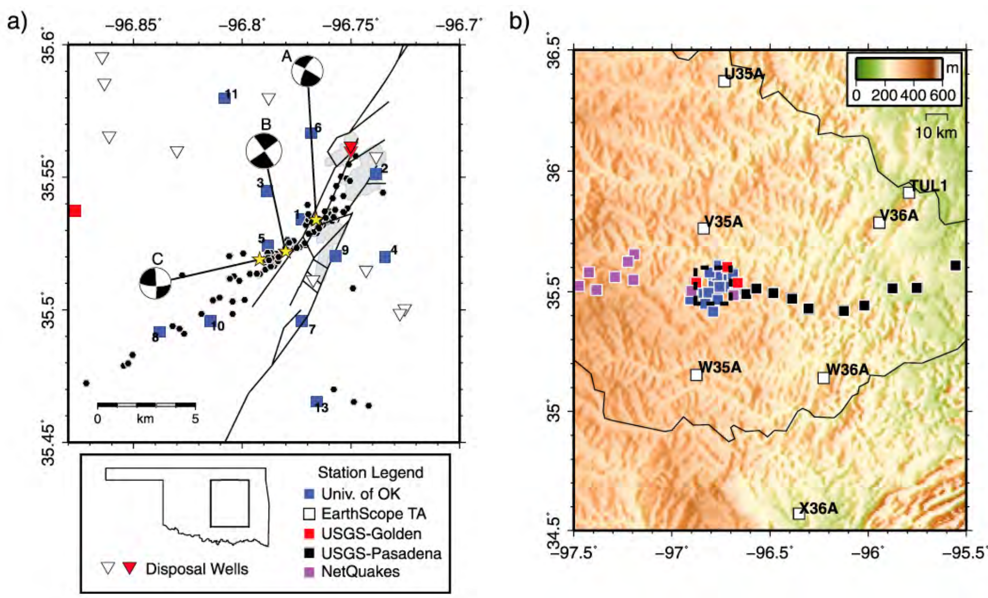


Figure 9. Rayleigh waves for a line of USArray TA stations. (a) TA stations deployed in February 2010. Circled crosses are stations within two degrees of the great circle backazimuth of the analyzed event. Solid circles are the stations used to form the gradiometer. (b) Data collected from the circled stations, as well as the gradiometer, filtered to 20–50 s passband. The seismograms are displayed such that their relative distance from the earthquake origin is preserved. The prominent arrival is the Rayleigh wave, which has a magnitude slowness of 0.28 s/km. Black lines are seismograms recorded by the gradiometer. Gray lines are seismograms recorded by the stations that are not part of the gradiometer. From *Poppeliers* [2011].

Citation: Poppeliers, C. (2011), Multiwavelet Seismic-Wave Gradiometry, *Bull. Seismol. Soc. Amer.*, v. 101, no. 5, p.2108-2121 doi: 10.1785/0120100226.

Induced Seismicity in Oklahoma
In November 2011, a M5.0 earthquake occurred less than a day before a M5.7 earthquake near Prague, Oklahoma. *Sumy et al.* [2014] detect and locate earthquakes using data from an IRIS PASSCAL RAMP (Rapid Array Mobilization Program) experiment and the USArray TA to examine the role that coseismic Coulomb stress transfer plays in generating earthquakes that follow the M5.0 foreshock. They find that the foreshock promoted failure on the Wilzetta fault rupture plane, resulting in the M5.7 mainshock and thousands of aftershocks, including one of M5.0. They argue that fluid injection induced the M5.0 foreshock, and possibly triggered cascading failure along the complex Wilzetta fault system.



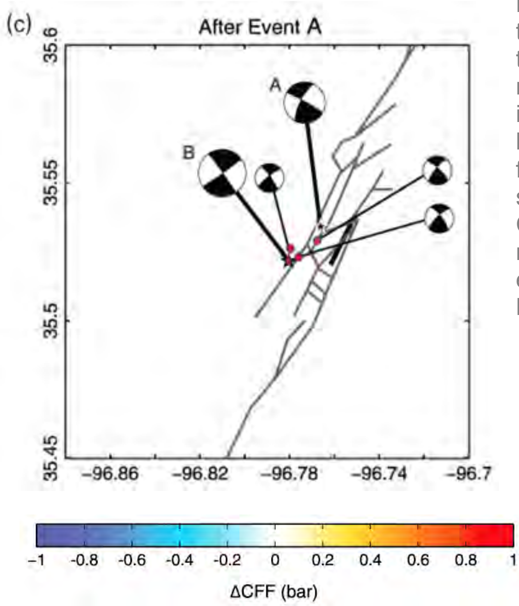


Figure 10. (a) The three M≥5.0 events (yellow stars) from the November 2011 Oklahoma sequence. Black dots show the earthquake locations with the best quality focal mechanism solutions determined in this study. Active injection wells close to Event A (red inverted triangles) may be responsible for triggering earthquakes along these faults. (b) The map shows the 47 stations used in this study, including the TA stations (white squares). (c) Coulomb fault failure modeling shown for the focal mechanism solutions for earthquakes after Event A. The earthquake epicenters are color-coded by its **Δ**CFF, in bar. Modified from *Sumy et al.* [2014].

Citation: Sumy, D. F., E. S. Cochran, K. M. Keranen, M. Wei, and G. A. Abers (2014), Observations of static Coulomb stress triggering of the November 2011 **M**5.7 Oklahoma earthquake sequence, *J. Geophys. Res. Solid Earth, 119*, doi:10.1002/2013JB010612.

Lithospheric Structure in the Eastern United States

Hotspot tracks are thought to be the surface expressions of tectonic plates moving over upwelling mantle plumes, and are characterized by volcanic activity that is age progressive. At present, most hotspot tracks are observed on oceanic or thin continental lithosphere. For old, thick continental lithosphere, such as the eastern United States, hotspot tracks are mainly inferred from sporadic diamondiferous kimberlites putatively sourced from the deep mantle. *Chu et al.* [2013] use seismic waveforms initiated by the 2011 Mw 5.6 Virginia earthquake, recorded by USArray TA, to analyze the structure of the continental lithosphere in the eastern United States. They identify an unexpected linear seismic anomaly in the lower lithosphere that has both a reduced P-wave velocity and high attenuation, and which they interpret as a hotspot track. The anomaly extends eastward, from Missouri to Virginia, cross-cutting the New Madrid rift system, and then bends northwards. It has no clear relationship with the surface geology, but crosses a 75-million-year-old kimberlite in Kentucky. They suggest that the hotspot track could be responsible for late Mesozoic reactivation of the New Madrid rift system and seismicity of the eastern United States.

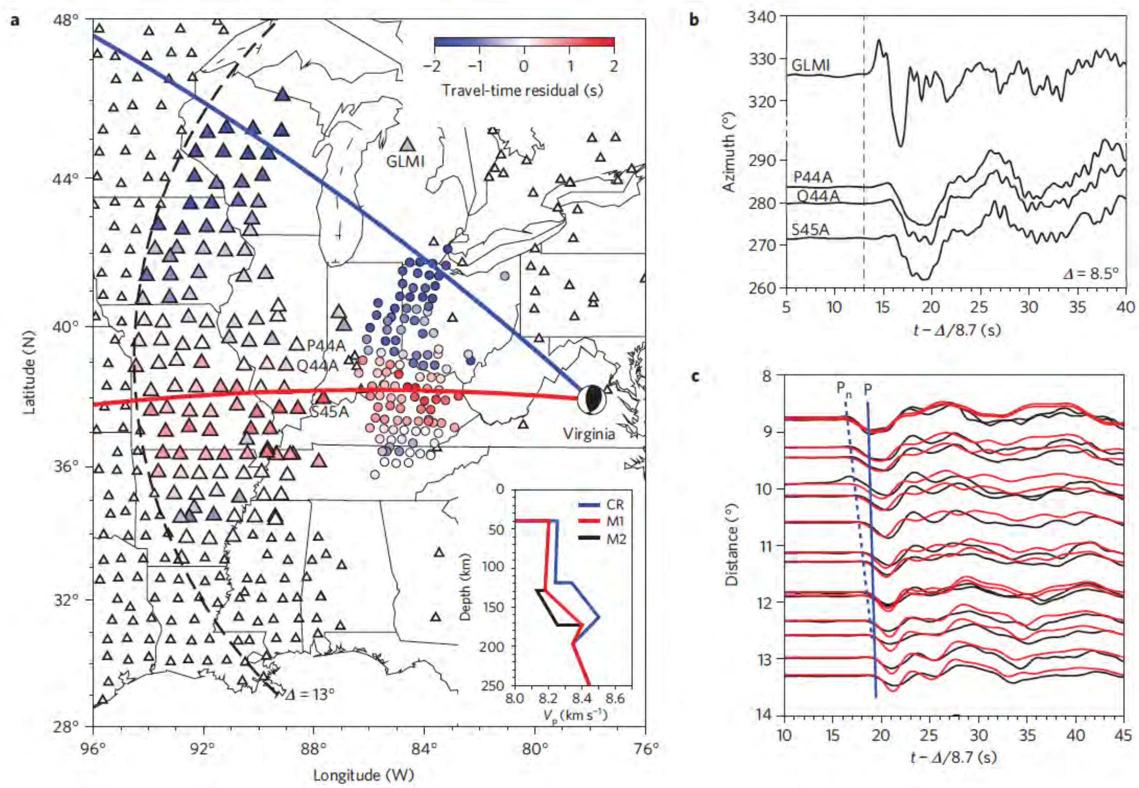


Figure 11. Summary of seismic observations of the Virginia earthquake (black beach ball) recorded by the Transportable Array stations (triangles). (a) Travel-time residuals (color triangles) and the ratio of long-period and short-period amplitudes multiplied by the travel-time residuals (colored circles at the midpoints) delineate an east–west corridor. (b) The recordings along the red profile are broad and late with deficient short-period energy, compared with those along the blue profile (e.g., Q44A versus GLMI). The model M1 (red lines in a,) predicts good waveform fits for the corridor (c). (c) The synthetics (red) show the interferences between Pn, travelling in the upper lithosphere, and delayed P in the lower lithosphere. From *Chu et al.* [2013].

Citation: Chu, R., W. Leng, D.V. Helmberger, and M. Gurnis (2013), Hidden hotspot track beneath the eastern United States, *Nature Geoscience*, v. 6, p.963-966 doi: 10.1038/ngeo1949.

Unbiased View of United States Seismicity from the Array Network Facility
The USArray Array Network Facility (ANF) recently published an overview of its network event bulletin (http://www.iris.edu/spud/eventbulletin), generated from USArray TA recordings between April 2004 and November 2013. During this period as the TA migrated eastward, 53% of the events listed in the ANF bulletin were unique (not listed in any other catalog). East of Washington, Oregon, and California between 60% and 80% of the ANF listings were unique, demonstrating the vastly improved detection threshold provided by the TA (Figure 12). The study also helps to discriminate anthropogenic seismic sources, such as daytime mine blasts. The ANF bulletins provide a much more comprehensive picture of seismic sources across the United States during TA deployment than previously available.

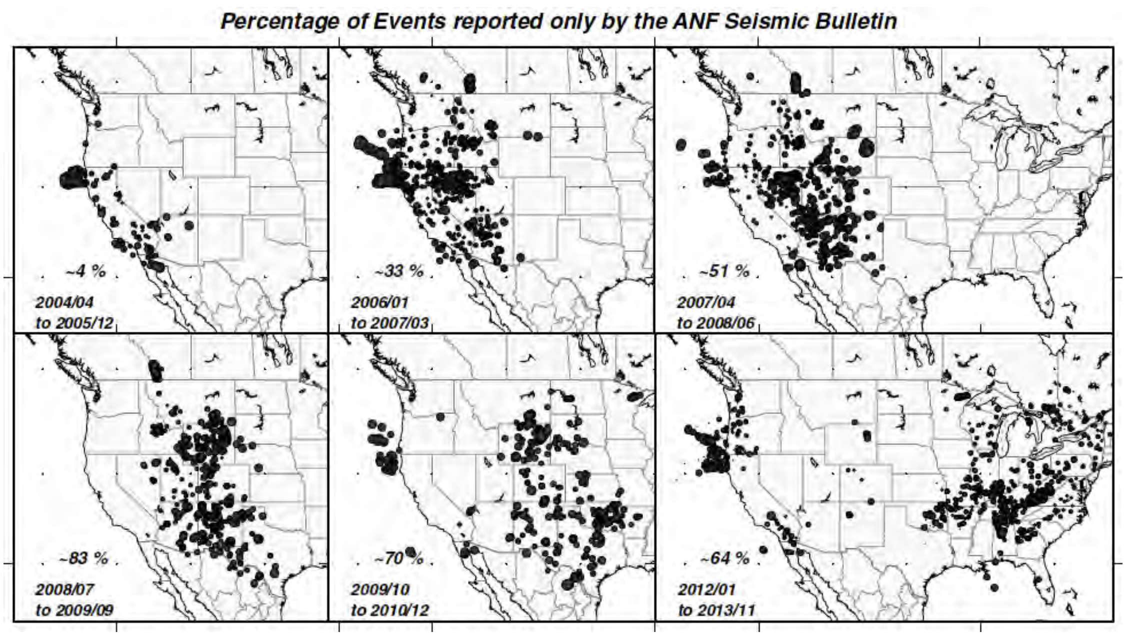


Figure 12. Locations of events reported only in the ANF Seismic Bulletin, ~53% of all events between April 2004 and November 2013. The percentage of events reported only by the ANF during each time period with respect to the total number of events reported is indicated in
each panel. From *Astiz et al*. [2014].

Citation: Astiz, L., J. A. Eakins, V. G. Martynov, T. A. Cox, J. Tytell, J. C. Reyes, R. L. Newman, G. H. Karasu, T. Mulder, M. White, G. A. Davis, R. W. Busby, K. Hafner, J. C. Meyer, and F. L. Vernon (2014), The Array Network Facility Seismic Bulletin: Products and an Unbiased View of United States Seismicity, Seismol. Res. Lett., v. 85, no. 3, doi: 10.1785/0220130141.

Cumulative Award CSSR Report

Table 3. Summary of cumulative planned and spent award budgets divided between WBS elements and supplemental items. The USArray award has spent nearly 100% of its designated funds, with a $27K remaining variance prior to final closeout on 12/31/2014.

EarthScope USArray O&M CSSR Report: October 2008 – September 2014
Revised Accruals Thru O&M Yr 6 Qtr 4 (September 2014)

Yr 6 (Oct 2008 - Sep 2014)		December 2008 Rev. Baseline	Planned Value	Spent (with Accruals)	Variance	Variance (%)
WBS Element						
2.4 USArray						
2.4.1	USArray Management	2,716,907	2,450,042	2,388,605	61,437	2.5%
2.4.3	Transportable Array	49,044,613	48,331,976	48,371,424	39,448	-0.1%
2.4.4	Flexible Array	7,499,647	7,069,036	7,009,313	59,723	0.8%
2.4.5	Data Management System	8,417,013	8,239,776	8,194,254	45,522	0.6%
2.4.6	Siting Outreach	1,546,945	1,628,275	1,670,592	(42,317)	-2.6%
2.4.7	Magnetotellurics	2,684,003	2,894,167	2,950,362	(56,195)	-1.9%
	Management Fees	125,000	125,000	125,000	0	0.0%
Subtotal		72,034,128	70,738,272	70,709,551	28,721	0.0%
	CEUSN Supplement		2,452,048	2,461,955	(9,907)	-0.4%
	ESSP Supplement		113,983	113,983	0	0.0%
	ESNM Supplement		436,590	420,771	15,819	3.6%
	Foreign Travel Supplement		3,300	3,241	59	1.8%
	Cascadia Supplement		2,500,000	2,507,406	(7,406)	-0.3%
USArray Total		72,034,128	76,244,193	76,216,907	27,286	0.0%

Other Supplements

Supplements to the award include support to organize logistics for the EarthScope National Meetings in Boise, Idaho (2009); Austin, Texas (2011); and Raleigh, North Carolina (2013) and the “Workshop for an EarthScope Science Plan” in Snowbird, Utah (2009).

WBS Task 2.4.1 Management

Management includes salaries of principal management and support staff overseeing the execution of award activities. Several managers worked exclusively on USArray (e.g., USArray Director, TA Manager) and others were split across multiple IRIS activities (Director of Data Services, Director of Education and Public Outreach). Support staff (e.g., webmaster, graphics support, etc.) were shared with other IRIS activities.

WBS Task 2.4.2 Reference Network

The Reference Network (RefNet), a virtual network of dispersed permanent stations, provides a long-term reference frame for comparison of observations made with the denser, but transient, Transportable Array. It was developed in close collaboration with the USGS as an augmentation, with other station upgrades, to the backbone component of the USGS Advanced National Seismic System (ANSS). EarthScope contributed the installation and upgrading of 39 stations to the ANSS Backbone; these stations were referred to as the Permanent Array component of USArray and installation was completed September 30, 2006. Throughout this award, the Transportable Array operated 20 stations to improve the uniformity of the Reference Network coverage (Figure 13)

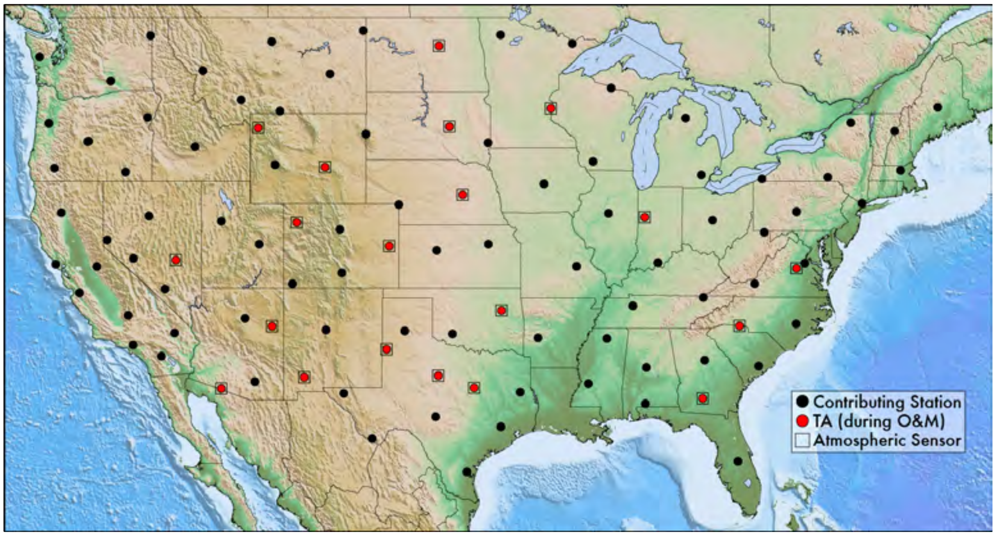


Figure 13. Transportable Array stations supplement the coverage of the backbone of the RefNet's contributing stations.

WBS Task 2.4.3 Transportable Array

Nearly all Transportable Array (TA) activities performed under this award are characterized as ongoing activities, meaning that they will continue throughout the lifetime of the TA. Siting, permitting, construction, and installation activities all took place during this award. During the award period, the TA installed, removed, and operated 1510 sites, from the intermountain west to the Atlantic seaboard (Figure 14). At any given time, there were approximately 400 TA stations operating for approximately two years each. During the eastward movement of the TA, NSF approved deployment of 56 TA stations into Ontario and Quebec, Canada, in the area south of the 48th parallel between Michigan's Upper Peninsula and the eastern border of Maine. These stations allowed more suitable coverage of several key geologic features of North America.

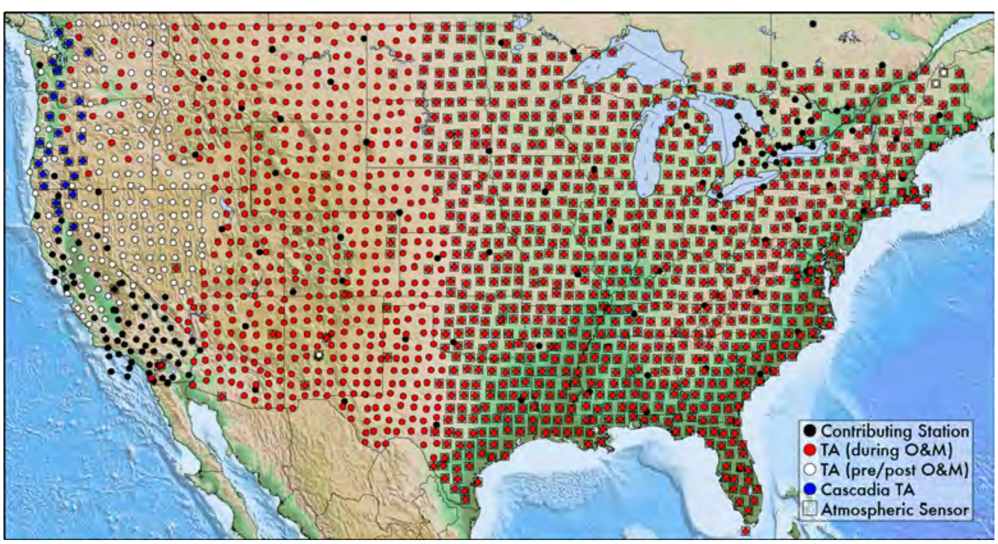


Figure 14. Map of Transportable Array station locations since 2004. Other contributing stations are selected from regional networks, USGS-operated Advanced National Seismic System, the IRIS Global Seismographic Network, and Polaris. The map also includes TA stations installed and operated as part of the Cascadia Initiative supplement. Stations eastward of the Great Plains show the addition of atmospheric sensors.

As the TA progressed, a number of organizations chose to adopt one or more of its stations. These organizations reimburse NSF for the cost of the equipment and agree to openly share the data collected by their station(s). During the award period, 55 stations were adopted, creating a legacy of permanent stations in the wake of the TA (Figure 15).

Adoptions and Continued Usage - EARN
Groups are encouraged to subscribe to EducAtion and Research Network (EARN) support, a paid service by which the USArray facility, through IRIS, operates and maintains adopted TA stations. EARN aids operators who lack the network management experience to directly maintain their adopted stations. These services include data telemetry, validation, processing, and archiving, as well as station state-of-health monitoring and necessary major maintenance to the station. During the award, EARN operated 25 adopted TA stations. Depending on telemetry costs, EARN services cost between $4,058-$6,850 per station per year.

Adoptions and Continued Usage – Non-EARN
Established operators and other groups (Arizona Broadband Seismic Network, New Mexico Tech Seismic Network, Oklahoma Seismic Network, Pacific Northwest Regional Seismic Network, Purdue University, University of Utah Regional Network) chose to integrate the stations into their networks immediately or used EARN as a bridging service. Following adoption or the end of EARN support, full control of the station and land-use permit shifted to the operator. In 17 additional cases, groups only requested to adopt the TA vault and assume control of the permit.

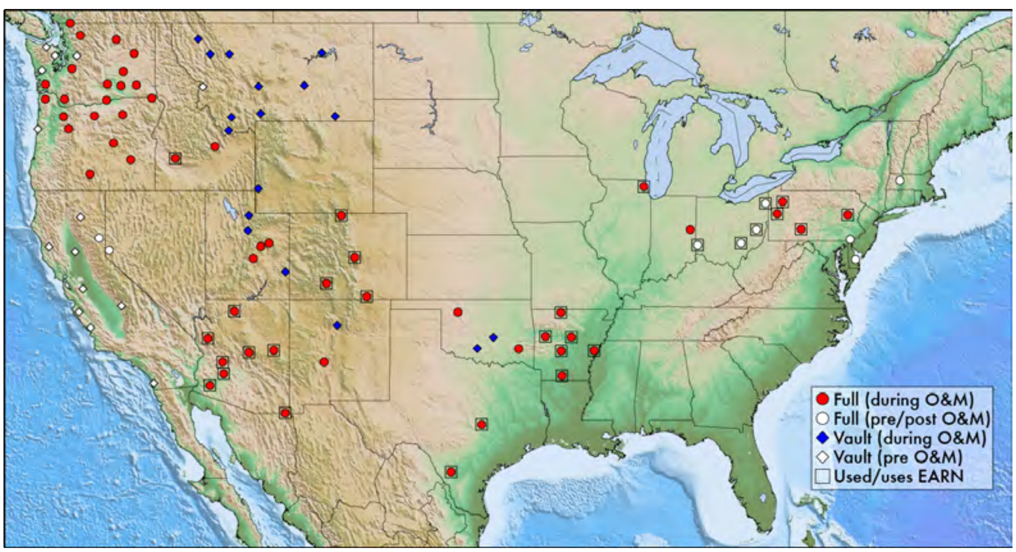


Figure 15. Adopted TA stations and vaults are distributed across most of the North American TA footprint.

Technology Upgrades and Enhanced Capabilities
During this award, the TA grew in its capacity and robustness. Early lessons learned in station operation were incorporated, including the distribution of advanced electronics boxes (vault interface enclosures) at all newly installed TA stations. These boxes provide a protective case for station electronics and connections (Figure 16). In addition, observations of water seepage in the original vault design led to a proactive redesign of TA tank vaults, using a single-piece, custom-molded unit that was easier to deploy and is designed for the precise housing of TA hardware. MEMS state-of-health sensors providing data on temperature, humidity, and pressure within the TA vault were added during 2009, and with an MRI-R2 award #0960275 from the National Science Foundation to the University of California, San Diego, sophisticated barometric and infrasound sensors were subsequently installed at all new stations, fundamentally adding to its capabilities as an atmospheric observatory. As with the TA seismic records, all of these data are available in real time and are used in broad applications such as streaming by MesoWest, a repository for weather data operated by the University of Utah.

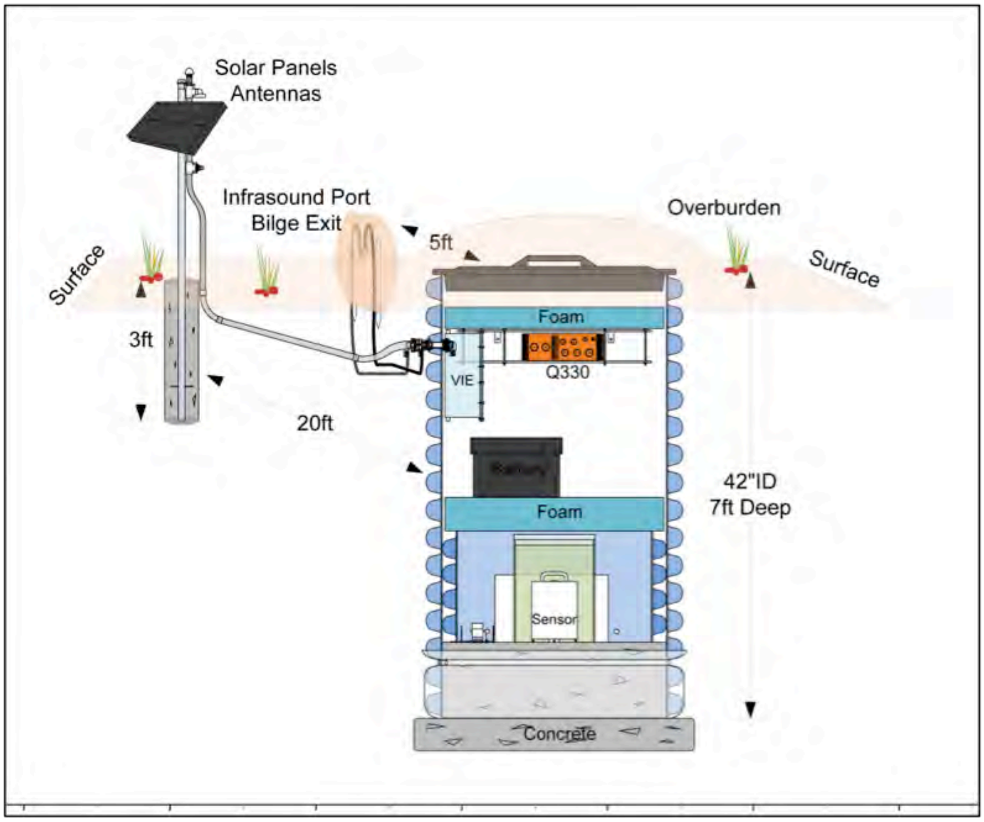


Figure 16. TA station design, incorporating advancements such as the custom VIE and atmospheric sensor configuration.

During the final two years of the award, several additional TA seismometers were deployed both in Alaska, California, and New Mexico. These test stations explored new methods of emplacing posthole-style sensors using augers, downhole hammers, and rock coring drills. These efforts acknowledge the inherent challenges in redeploying the TA to Alaska during EarthScope's final five-years. Results of these studies demonstrated that these new methods are not only logistically feasible and economically viable, but in many cases produce superior data. This award provided the foundation to explore these new practices in a manner that is likely to benefit many future field seismologists.

Cascadia Transportable Array

The American Recovery and Reinvestment Act funded a major seismic and geodetic investigation of the Pacific Northwest known as the Cascadia Initiative. The funds permitted development of an onshore-offshore Amphibious Array Facility focused on studying the Cascadia subduction zone. The onshore portion consists of 27 new TA stations deployed to complement the initial post-TA backbone of broadband seismometers in Cascadia (Figure 17). A supplement (Table 3) to this award supported the purchase of all hardware and the siting, permitting, installation, and operation of the on-land stations. Where possible and appropriate, some original TA sites were reoccupied, and new installations were completed during the summer of 2010. All 27 stations include a broadband seismometer and strong-motion accelerometer, atmospheric sensors, and real-time telemetry. These stations will continue to operate until at least September 2015.

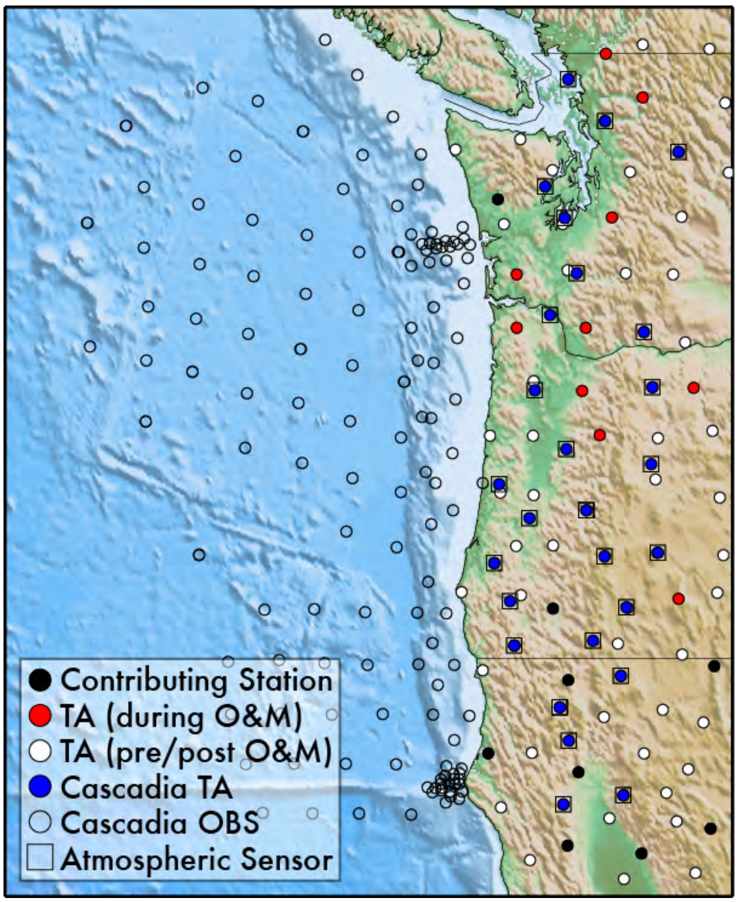


Figure 17. The 27 reinstalled TA stations complement deployments of ocean bottom seismometers supported by NSF Ocean Sciences as part of the Cascadia Initiative.

Central and Eastern United States Network (CEUSN)

Supplemental funds (Table 3) allowed reinstallation of 37 stations as part of the CEUSN initiative. CEUSN will serve as a long-term subarray of 159 seismometers (Figure 18) selected from the TA footprint. The mission of the CEUSN is to enable researchers and federal agency scientists to better address basic geologic questions, background earthquake rates and distribution, seismic hazard potential, and associated societal risks in this region. TA stations were selected for conversion to CEUSN based on their proximity to regions of elevated seismic hazard and/or critical facilities, such as nuclear power plants, and also for their ability to enhance areal station coverage. The long-term deployment of seismometers will produce a more complete set of observations than achievable during the originally planned two-year duration of the TA. Some CEUSN stations have added strong motion accelerometers and have sampling rates increased to 100 samples per second.

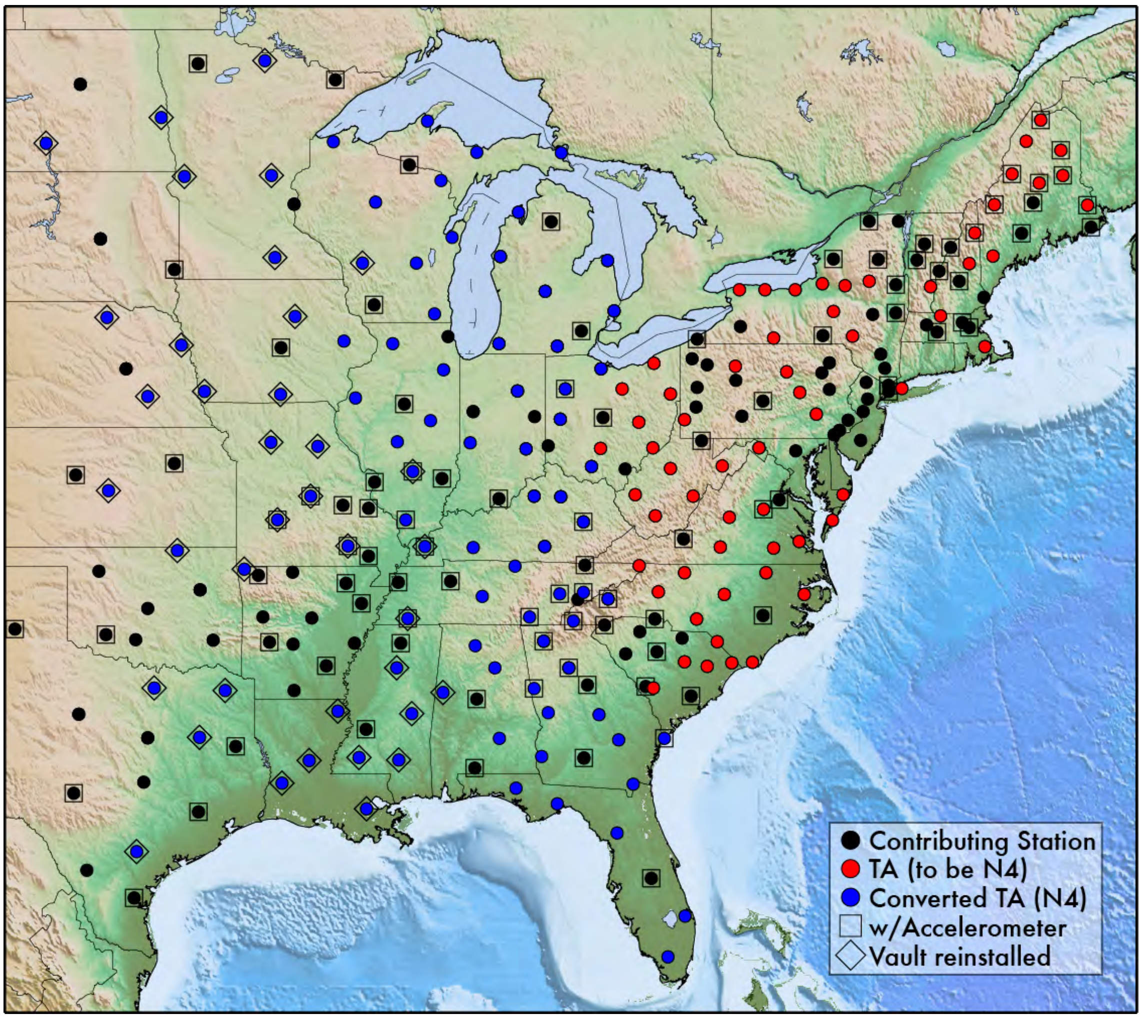


Figure 18. CEUSN status map showing stations completed through 9/30/14 as part of the FY13 supplement and no-cost extension. By the end of FY15, all planned CEUSN stations will be transitioned from the TA.

WBS Task 2.4.4 Flexible Array

The Flexible Array (FA) operates an instrument pool consisting of 326 broadband, 120 short-period, and 1700 active-source seismic systems. The FA instrument pool includes all equipment necessary to make complete stations, including solar panels, enclosures, cables, and communications gear (with the exception of batteries). The three primary FA O&M activities are to: (1) provide training and (limited) field support for PIs and students who use FA instruments, (2) provide all depot support operations for FA equipment and experiments (e.g., shipping, maintenance, storage), and (3) provide data services to organize and deliver the collected data and metadata to the IRIS DMC.

All FA equipment used in PI-driven experiments address EarthScope program scientific goals. The quality of data collected in FA experiments has been high, as have the data return rates. The USArray Array Operations Facility staff have streamlined the process of getting data from temporary deployments collated and delivered to the DMC; this service has become very popular with PIs. During the award period, 21 passive and three active source data sets were archived using equipment specifically utilized for PI-led FA deployments (Figure 19, Table 4). Some of these data sets, such as COLZA and Bighorns, represent multiple facets of the same experiment.

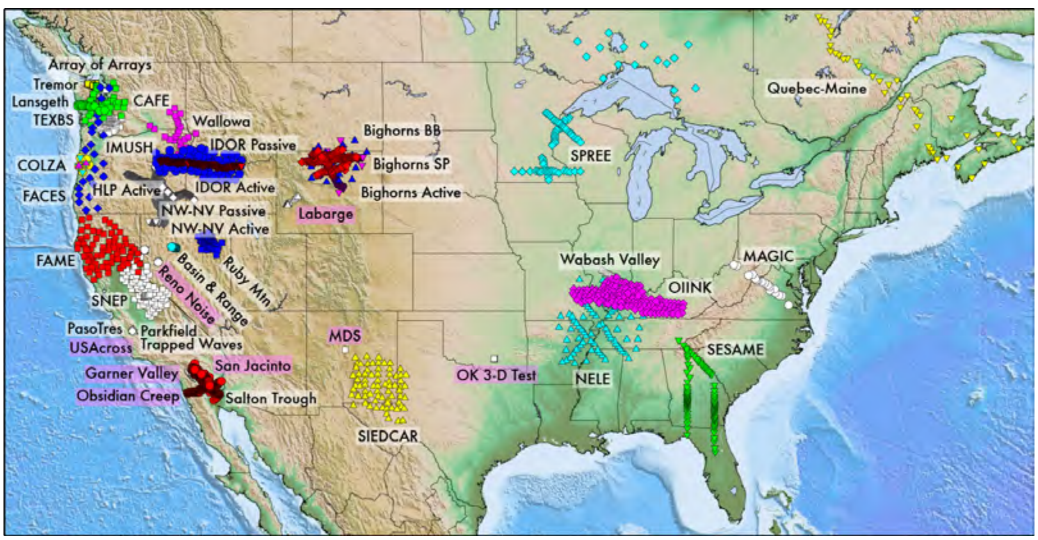


Figure 19. Colored symbols indicate Flexible Array deployments facilitated during the award period.

Table 4. Flexible Array data sets collected during the award period.

EarthScope Funded					Number of Stations			Data	
PASSCAL Short Name	Network Code or Assembled ID	BB	HF	SP	Q330/RT130	Texan	Start	End	Available %
Active									
Bighorns Active	10-017		2936			2936	7/19/10	8/6/10	345 Gb
Salton Trough	11-012		4915		272	4643	2/28/11	3/18/11	1300 Gb
IDOR Active	13-002		2700			2700	7/15/12	9/1/12	372 Gb
Passive									
Langseth (onshore stations)	ZZ.2012-2012		15		15	2596	6/5/12	7/25/12	100.0
Quebec-Maine	X8.2012-2015	3		6	9		5/25/12	8/24/13	97.2
NELE	ZL.2011-2015	14			14		9/8/2011	10/9/12	100.0
OIINK	XO.2011-2015	58		14	72		7/19/11	9/30/13	96.2
SPREE	XI.2011-2013	82			82		4/17/11	5/28/13	96.4
IDOR Passive	XT.2011-2013	87			87		5/21/11	6/28/13	97.1
SESAME	Z9.2010-2013	86			86		7/17/10	5/20/13	97.4
Basin and Range	5A.2010-2012	34			34		11/7/10	4/24/11	97.7
Bighorns Active	ZI.2010-2010		2211			2211	7/19/10	8/7/10	100.0
Bighorns SP	ZH.2010-2010			172	172		4/14/10	11/22/10	94.8
Bighorns BB	XV.2009-2010	38			38		7/1/09	10/25/10	95.9
Ruby Mountains	YX.2010-2012	55			55		6/15/10	6/16/12	98.6
Array of Arrays	XG.2009-2011			165	188	84	6/16/09	9/8/11	83.2
SIEDCAR	XR.2008-2011	71			71		7/1/08	3/17/11	92.7
FAME	XQ.2007-2009	76			76		7/19/07	7/8/09	91.1
FACES	YW.2007-2010	23			23		11/2/07	7/11/10	89.6
COLZA	XA.2008-2009	7			7		1/22/08	12/31/09	97.7
COLZA	XN.2010-2010	4			4		1/1/10	12/31/10	87.5
COLZA	ZH.2011-2012	2			2		1/1/11	7/20/12	78.8
Wallowa	ZG.2006-2009	30			30		10/3/06	8/6/09	89.7
CAFE	XU.2006-2012	50		22	72		7/9/06	5/8/12	92.5

Facility Highlight

In 2010, the Array Operations Facility in Socorro completed fabrication of nearly 200 "Quick Deploy" boxes, which were developed for initial use in the Bighorn Arch Seismic Experiment (BASE). Nicknamed “biho” boxes in honor of BASE, each compact box contains a data logger, battery, power regulator, seismometer, solar panel, and GPS antenna and is essentially ready to deploy upon arrival in the field. These biho boxes enable a field team to install a large number of stations quickly. In fact, the BASE team completed their deployment of 170 short period instruments a week ahead of schedule because the team was able to deploy as many as 14 stations in a day.

left) Assembled “biho” boxes ready to be shipped for BASE. (right) The first Bighorns short period station was installed in April 2010 using a biho box.

WBS Task 2.4.5 Data Management

The IRIS Data Management Center performs the data management functions for USArray. The IRIS Data Management System (DMS) is responsible for receiving, archiving, and distributing all data collected by USArray, including all data from the Reference Network, Flexible Array, Transportable Array, and Magnetotelluric stations. The DMS is also responsible for quality control of these data and development of associated data products. The data management portion of the award supports the staff, equipment, travel, materials and supplies, subawards, and other direct costs associated with USArray data management. In addition, the DMS manages time series data from Plate Boundary Observatory (PBO)- and San Andreas Fault Observatory at Depth (SAFOD)-operated seismic and strain instruments.

EarthScope data are received in real time and via batch shipments and are made freely available to the community as quickly as possible. During the award period, 44.1 Terabytes (Tb) of USArray data have been archived (Figure 20) and 211.36 Tb of data have been shipped (Figure 21). Adopted (EARN) or supplemental (Cascadia) TA stations operated by IRIS contributed an additional 0.25 and 2.38 Tb of archived data and 1.18 and 4.27 Tb of data shipped, respectively. Since 2009, the DMC has tracked the second-level domains that have requested USArray data, showing potentially 12,438 requests from unique sources (Appendix C). The EarthScope data are served out via all of the DMC's request-based and streaming-data access tools. The data are also served out via the EarthScope data portal.

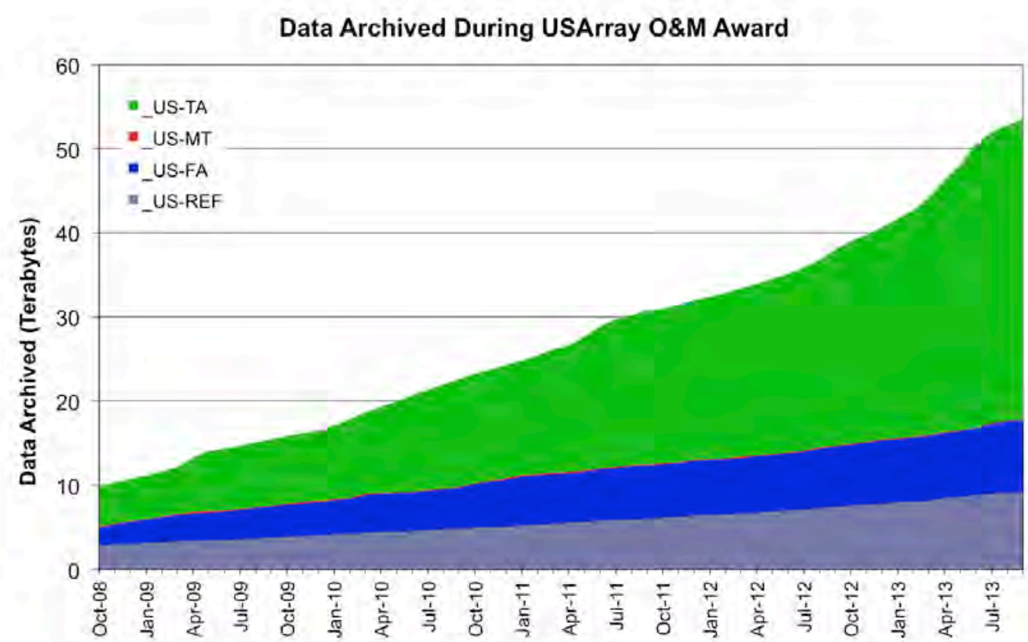


Figure 20. Cumulative data archived, divided by virtual network (Transportable Array, Magnetotelluric, Flexible Array, and Reference Network), shows the growth in TA data return over time due to the addition of Cascadia TA stations and continued operation of adopted TA stations.

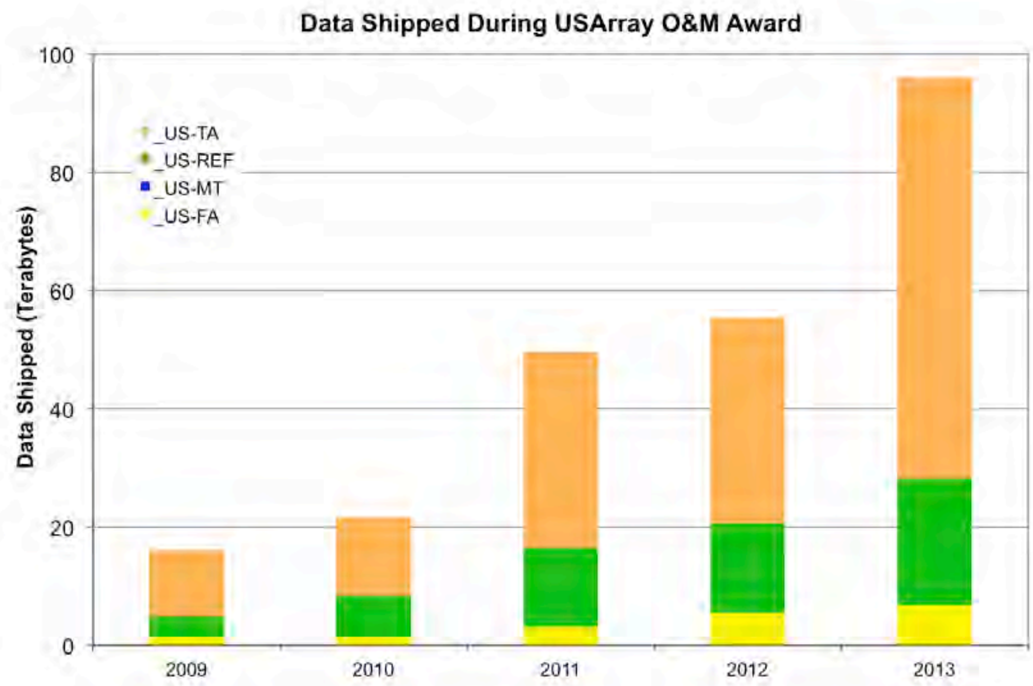
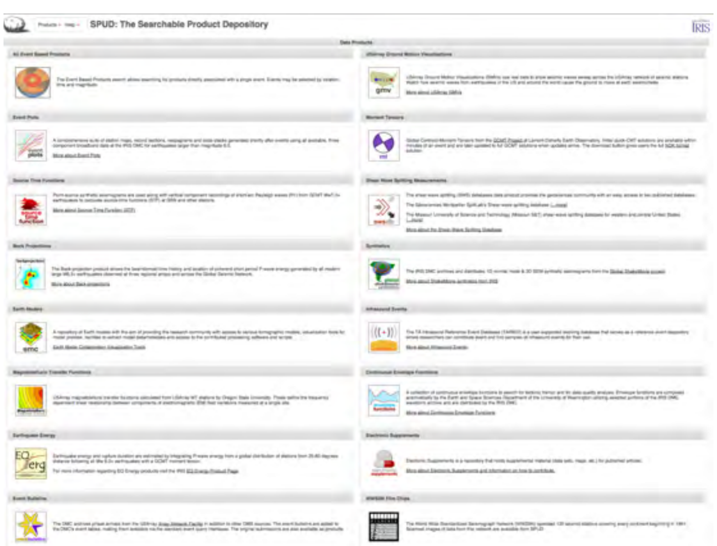


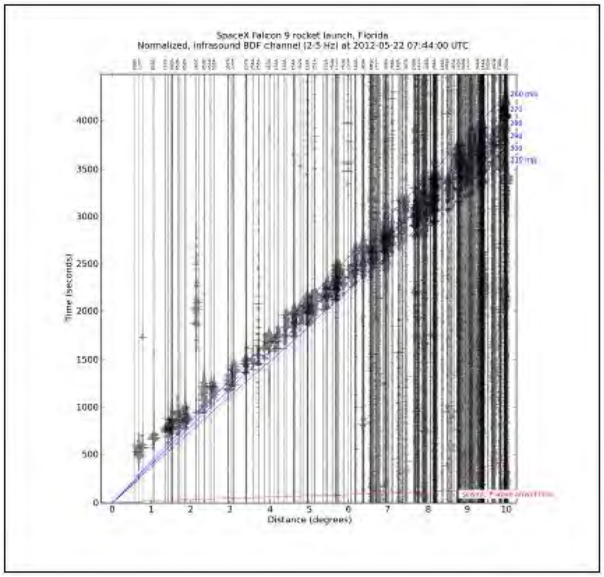
Figure 21. Data shipped by year, split by virtual network (Transportable Array, Magnetotelluric, Flexible Array, and Reference Network), shows the heavy usage of the USArray data set.

The DMS has also produced a variety of data products designed to visualize USArray data and provide reference research products and novel ways to facilitate research. These products include motion visualizations, infrasound event catalogs, teleseismic back projections, and ambient noise cross-correlations.

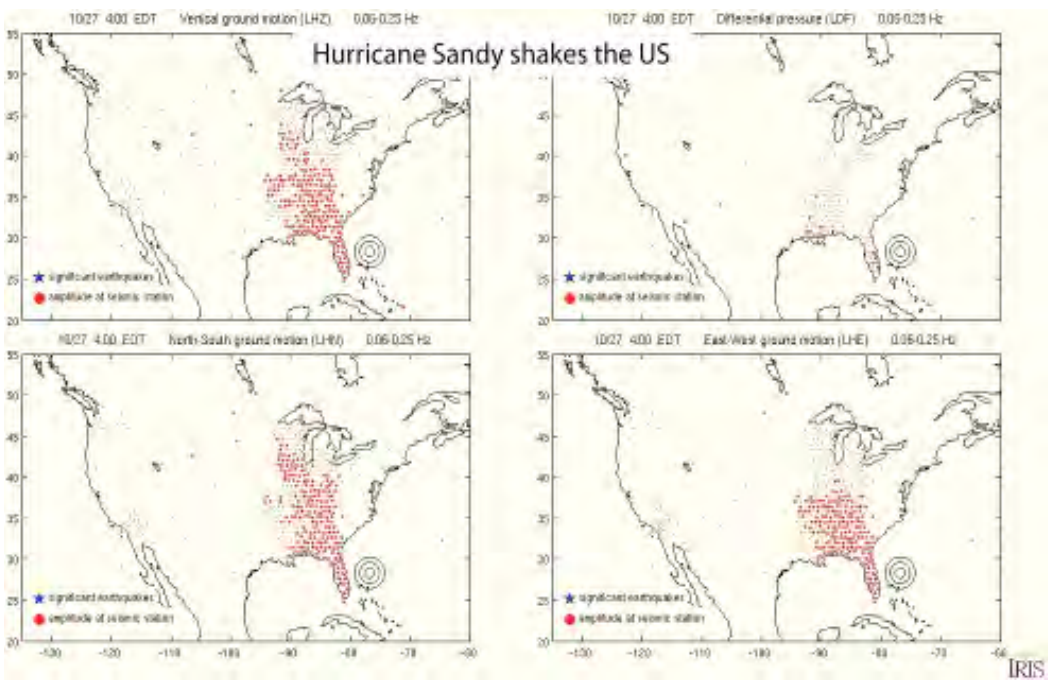
Facility Highlights



SPUD: The Searchable Product Depository (SPUD) is the IRIS DMC's primary data product management system. The SPUD system mainly contains derivative data products of other types (e.g., images, movies) created either at the DMC or by members of the community. For users, SPUD is the query and access point for these products. The Web interfaces allow users to search for products using customized queries across product and event details. Users can search across all product types at once or within specific product types. SPUD also has Web service interfaces for programmatic discovery and access to the data products.



Data Management Center Releases the Transportable Array Infrasound Reference Event Database (TAIRED): TAIRED is a user-supported database that serves as a reference event depository where researchers can contribute new events, provide a new solution for an existing event, and find sample infrasound events for their use. Initially populated with observations from infrasound sensors installed at TA stations, this database also includes event bulletins, news on meteorological phenomena, and data from explosions and rocket launches.



Transportable Array Detects Hurricane Sandy: The Data Management Center created and released an animation of seismic and atmospheric pressure data for TA and other stations on the east coast of the United States showing the effect of Hurricane Sandy: http://www.iris.edu/dms/newsletter/vol14/no3/effects-of-hurricane-sandy-visualized-across-the-usarray/.

WBS Task 2.4.6 Siting Outreach

Siting Outreach supports Transportable Array siting and deployment by promoting the value of hosting a site to local communities, assisting in finding potential sites, and providing a legacy following the relocation of the TA. Siting Outreach is designed to precede and be integrated with the permitting process, creating community awareness and interest before the TA arrives and while it is in place. A large part of Siting Outreach, summer student siting activities, has been completed for the remainder of USArray activities (Figure 22). Following the completion of the main award activities, science writer Maia ten Brink documented many siting-related stories (Appendix D). Station reconnaissance and siting will be conducted on a professional basis in Alaska due to the vastly different field conditions. Also, Siting Outreach formally supported, either via subaward or directly, management the 2011, 2013, and 2014 USArray Short Courses hosted at Northwestern University and attended by 103 students and postdoctoral researchers. These courses were intended to orient young seismologists with the best practices for processing and analyzing the unusually large USArray data sets.

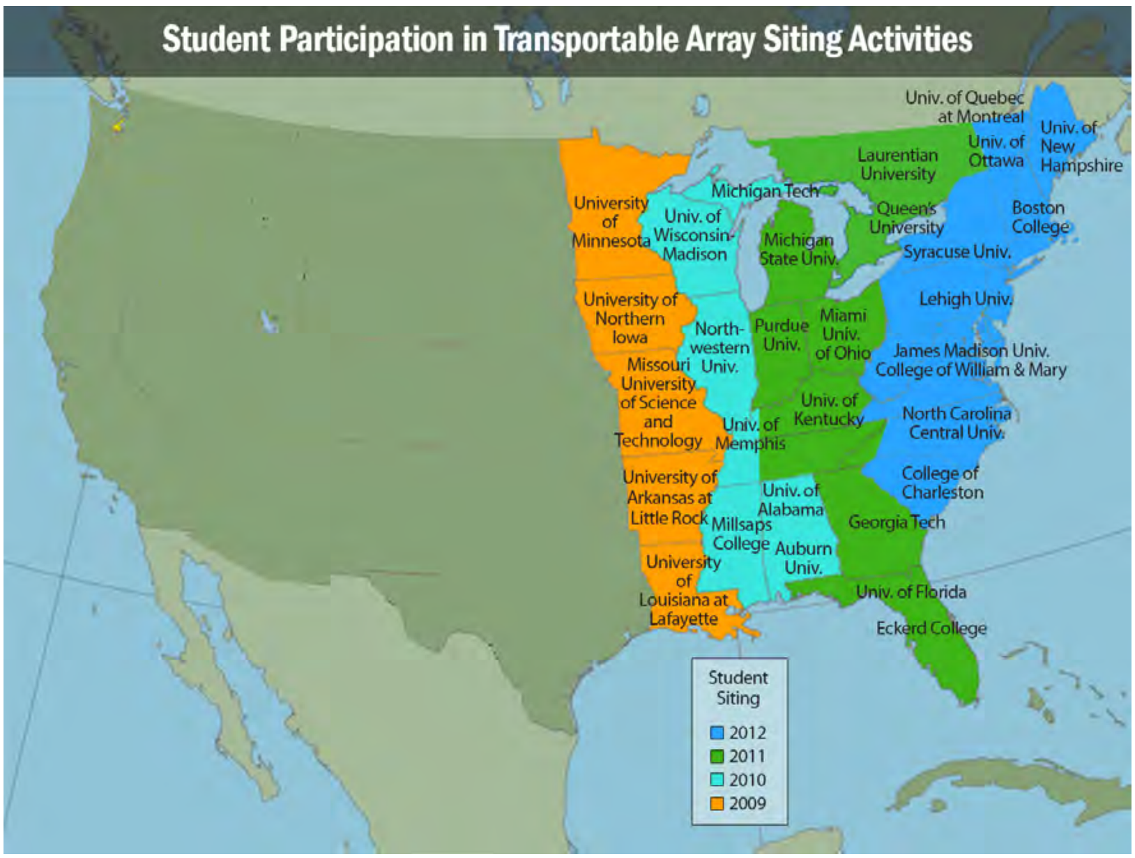


Figure 22. Participating schools in the USArray student siting program and the portions of the footprint identified, by year, for the reporting period spanned by this report.

Siting Outreach supported the development and distribution of Active Earth Monitor kiosks. These interactive consoles contain IRIS-produced content related to EarthScope and USArray. Following a competitive application process, Active Earth Monitor kiosks were awarded to educational facilities in the states where USArray is currently deployed. Kiosks are loaned to various educational institutions (Table 5) such as museums and schools for one year with the opportunity for a recipient to purchase the kiosk for use as a permanent display. These kiosks help to increase awareness of USArray and EarthScope within the USArray footprint. Kiosks have been loaned to 43 locations; four have been purchased by venues for more permanent placement.

Table 5. Location of loaned Active Earth Monitor kiosks.

Loan Period	City	State	Location
2011	Rolla	MO	State Geologists Office
2011	St Paul	MN	State Geologists Office
2011	Waco	TX	Baylor University
2011-present (purchased)	Omaha	NE	University of Nebraska-Omaha
2012-present (purchased)	Nashville	TN	Adventure Science Center
2012	Carmel	IN	Carmel Clay Schools-Planetarium
2012	Memphis	TN	Pink Palace Museum and Sharp Planetarium
2012	Flint	MI	Sloan Mueum/Longway Planetarium
2012	Springfield	IL	Illinois State Museum
2012	Bloomfield Hills	MI	Cranbrook Institute of Science
2012-present (purchased)	Tuscaloosa	AL	UA/Alabama Museum of Natural History
2012	Riverwoods	IL	Ryerson Woods
2013	Charlotte	NC	McDowell Nature Center
2013	Tampa	FL	MOSI (Museum of Science & Industry)
2013	Canton	OH	McKinley Presidential Library and Museum
2013-present (purchased)	Atlanta	GA	Fernbank Science Center
2013	Charleston	WV	Clay Center for Art and Sciences of WV
2013	Newport News	VA	Virginia Living Museum
2013	Columbia	SC	South Carolina State Museum
2013	Jacksonville	FL	MOSH, Museum of Science & History
2013	Abington	PA	Penn State Abington, Science and Engineering
2013	Wilmington	DE	Delaware Museum of Natural History
2013	Raleigh	NC	North Carolina Museum of Natural Sciences
2014	Charleston	WV	Clay Center for Art and Sciences of WV
2014	Danville	VA	Danville Science Center
2014	Roanoke	VA	Science Museum of Western Virginia
2014	Cape Cod	MA	Cape Cod National Seashore
2014	Jacksonville	FL	MOSH, Museum of Science and History
2014	Newark	NJ	Newark Museum/Dreyfuss Planetarium
2014	Charlotte	NC	Discovery Place
2014	Greenville	NC	GO-Science
2014	Buffalo	NY	Buffalo Museum of Science
2014	Schenectady	NY	MiSci (Museum of Innovation and Science)

Facility Highlights
In May 2011, a new Welcome Center near New Madrid, Missouri, opened with a focus on the region's historic 1811/1812 earthquakes. The display includes two Active Earth Monitor kiosks connected to the Internet and signage about EarthScope, the Transportable Array, and the region's earthquake history. IRIS provided all information.

WBS Task 2.4.7 Magnetotellurics

USArray operated seven magnetotelluric backbone stations and 431 MT-Transportable Array (MT-TA) stations during this award. MT-TA stations were deployed in seasonal field campaigns, occupying sites on a 70 km grid (similar to the seismic TA) in the Pacific Northwest and Midwestern United States. A small number of the 431 MT-TA stations were reoccupied the following field season to provide better data, yielding a total of 406 delivered stations (Figure 23). All time-series data from the summer MT-TA field campaigns are been delivered to the IRIS DMC in mini-SEED format. In addition, magnetotelluric transfer functions have been computed; they are available via the DMC's SPUD interface as well as via traditional FTP.

The EarthScope MT depot established at Oregon State University provides O&M support for all MT activities, including the maintenance of the backbone stations and staging for the MT transportable campaigns. Additionally, the OSU staff provides equipment preparation and data handling for PIs using EarthScope MT instrumentation for temporary (flexible array) deployments (MT-FA). For instance, OSU provided personnel and support for MOCHA (Magnetotelluric Observations of Cascadia using a Huge Array), the first MT-FA experiment. This high-resolution onshore-offshore MT experiment imaged details of convergent margin segmentation and the distribution of fluids associated with the subducting slab in the Cascadia convergent margin.

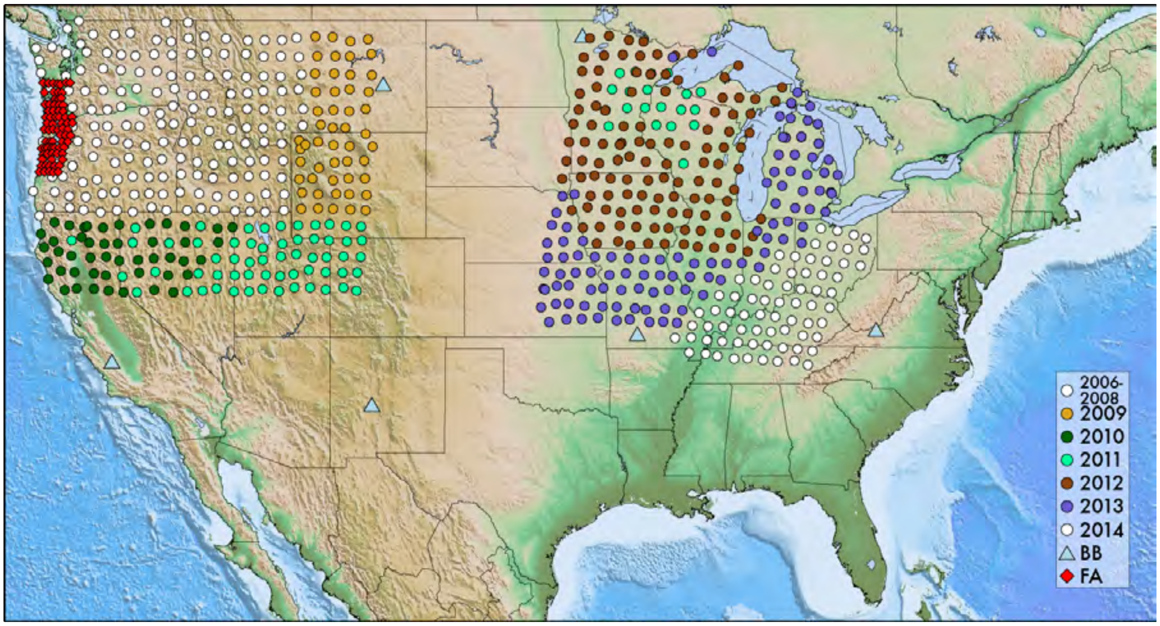


Figure 23. The USArray Magnetotelluric program consists of seven permanent backbone stations and temporary Transportable Array stations, including 406 archived from the 2009–2013 summer field campaigns.

Media and Outreach Activities

There was considerable media exposure for USArray during the award period (Appendix E). We highlight a number of the most prominent media events as well as other events that highlighted programs run under the award.

National Geographic Channel Highlights EarthScope and the Transportable Array
The Transportable Array was prominently featured in "X-Ray Earth," a two-hour special produced for the National Geographic Channel. The segment included footage filmed during the installation of TA station J32A near Parkston, South Dakota. The program premiered on Sunday, May 15, 2011, and has aired several other times since then.

Screen shot of National Geographic Channel's website for "X-Ray Earth."

Filming of Transportable Array segment of "X-Ray Earth."

Filming of Transportable Array segment of "X-Ray Earth."

EarthScope Ranks #1 in *Popular Science*'s List of Amazing Big Science Projects
In July 2011, *Popular Science* named EarthScope the universe's top "big science" project in operation today. Ranking factors included construction costs, operating budget, the size of the staff and the physical size of the project itself. Additional consideration was given to the project's scientific utility, its utility to the average person ("what will it do for me") and the "wow" factor. See the article at http://www.popsci.com/science/article/2011-07/supersized-10-most-awe-inspiring-projects-universe.

The Weather Channel Airs a Story About EarthScope's Transportable Array (April 26, 2013)
(http://www.youtube.com/watch?v=TJKYXPlzYI4). About two weeks prior to the broadcast, a Weather Channel reporter and crew filmed the installation of Station S59A near Mechanicsville, Virginia. Also at the site was Professor Steve Whitmeyer of James Madison University who provided the scientific context for the story.

USArray Conducts Tours of TA Station Closest to the Nation's Capital
USArray hosted events on May 2, 2013, and October 14, 2014, at TA station Q59A near Harwood, MD, 40 km from downtown Washington, DC. Representatives from numerous federal agencies and other organizations, including NSF, USGS, DOE, State Department, NRC, the US Naval Academy, EarthScope National Office, Carnegie Institution of Washington, and congressional staff attended the event, which provided participants with an opportunity to view an installed station and its components and to learn how EarthScope and the TA are contributing to our understanding of the earth.




First TA Station in Virginia Installed Near Epicenter of August 23, 2011, Mineral Earthquake
TA station R58B was installed in Mineral, Virginia, on August 8, 2012, ahead of schedule, to provide continuity of aftershock data collection upon removal of the temporary aftershock deployment instrumentation. IRIS organized a field trip to allow others observe the installation. Visitors included the Virginia State Geologist, EarthScope scientists from James Madison University, a freelance reporter, and several staff from IRIS Headquarters.

Visitors observe the installation of Transportable Array station R58B in Mineral, Virginia.

European Filmmaker Features the TA
Gruppe 5, a German documentary company, filmed the installation of a TA station in July 2012 near Ann Arbor, Michigan, for a three-part series on earthquakes, volcanoes, and hurricanes. The production aired on German TV in May 2013.

Installation of Transportable Array station L49A near Ann Arbor, Michigan, was filmed for a documentary produced by the German filmmaker Gruppe 5.

USArray Hosts Delegation from the China Earthquake Administration
In December 2012, representatives from the China Earthquake Administration met with USArray staff at IRIS Headquarters and then traveled to Ligonier, Pennsylvania, to visit a TA station. Members of the Chinese delegation are affiliated with the ChinArray, a project deploying a large number of seismometers in a grid, with some similarities to the TA. The visit provided an opportunity for each group to exchange information about the station configurations and activities of their respective projects.

American Museum of Natural History Films Transportable Array Station Installations
A crew from the American Museum of Natural History filmed the installation of two TA stations near Syracuse, New York, in August 2013. The museum is producing a short documentary highlighting the TA and the contributions made to our knowledge of the earth. When the production is complete, the video will be shown in the museum and posted on the museum’s website.

Facility Metrics and Targets

Station uptime is the primary benchmark for performance of the USArray facilities, with a targeted minimum uptime of 85% during the award period. This target was exceeded considerably in all cases. The Reference Network (Figure 24), Transportable Array (Figure 25), Flexible Array (Table 4), and Magnetotelluric Transportable Array (Figure 26) facilities recorded 94.4%, 98.5%, 94.0%, and 95.7% uptime during their deployments, respectively.

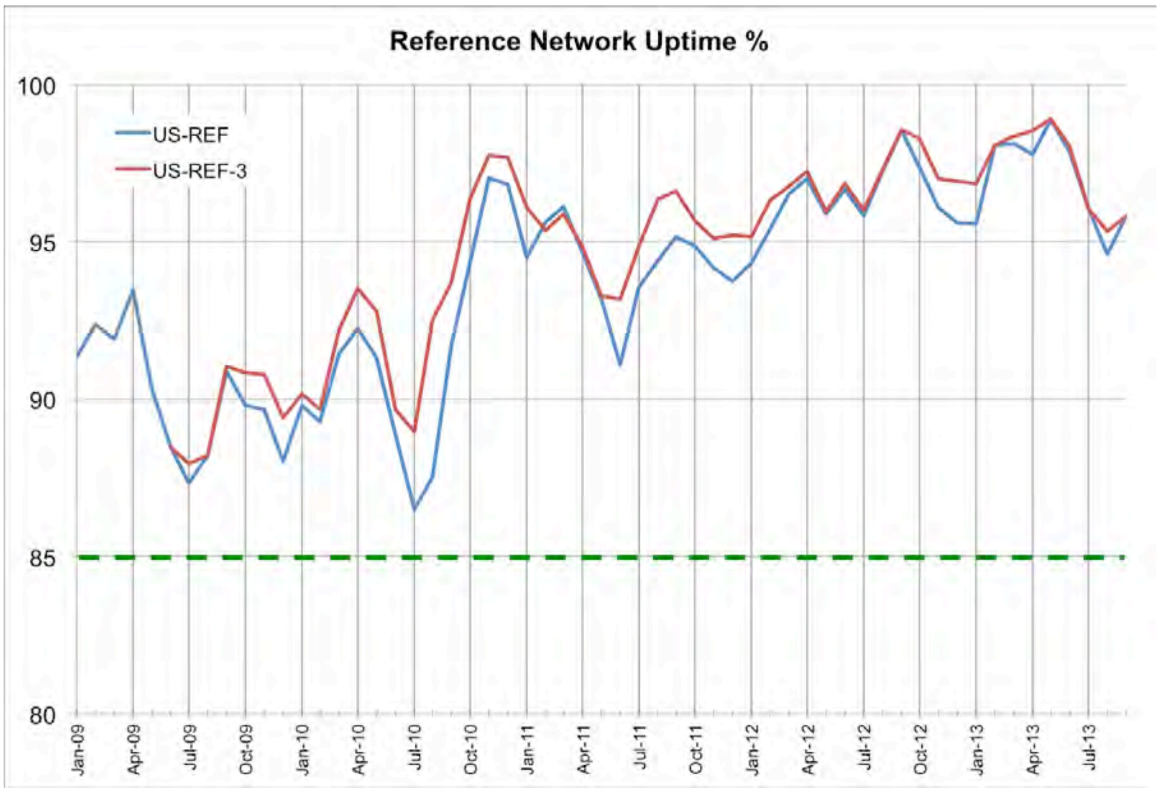


Figure 24. Reference Network uptime data shows that data return rates from stations increase within three months of initial real-time return as gaps in telemetry are back-filled. The first eight months of track are incomplete.

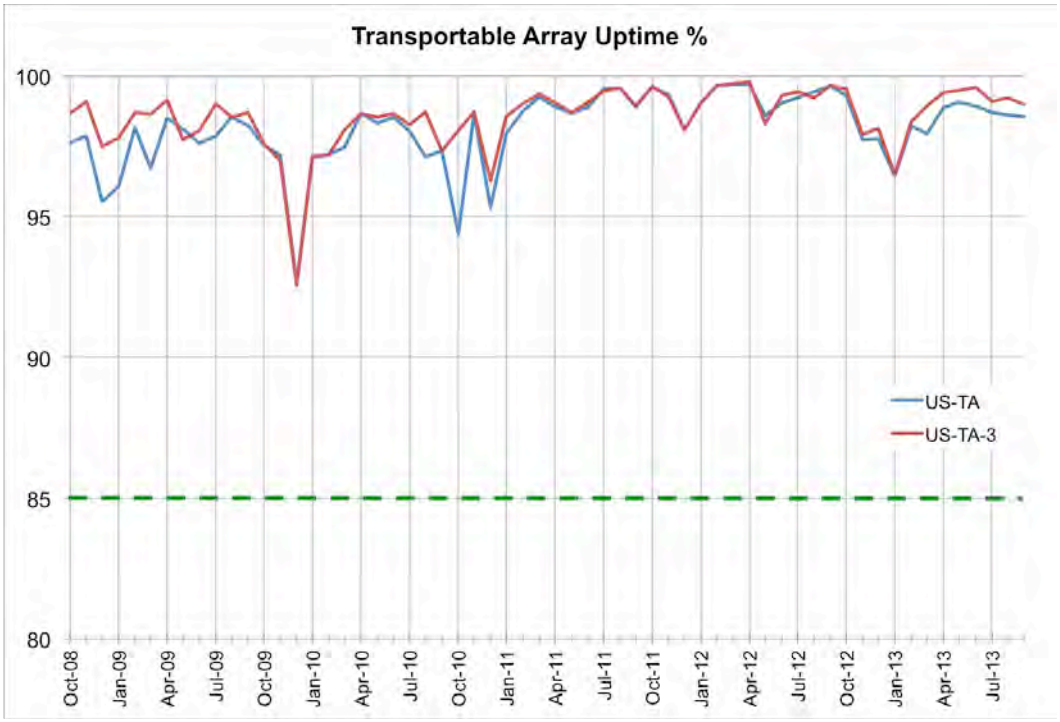


Figure 25. Transportable Array uptime data shows that data return rates from stations increase within three months of initial real-time return as gaps in telemetry are back-filled.

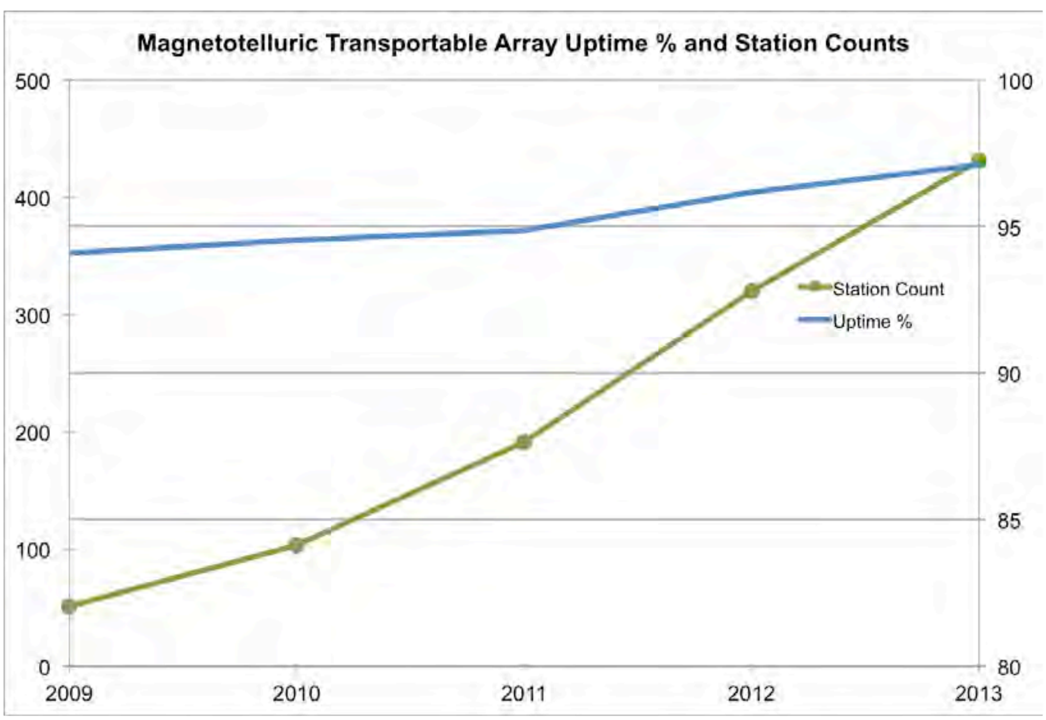


Figure 26. Magnetotelluric Transportable Array uptime data shows consistently high data return during a large increase in data collection.

Summary of Status of Cooperative Agreement Deliverables

This section summarizes the deliverables under the USArray O&M award, and the final status of each of these deliverable items.

A. The rolling deployment of an array of 400 transportable broadband seismic stations at an average spacing of about 70 km.
All Transportable Array activities were carried out per plan and schedule. As the above section documents, the Transportable Array rolled across the lower 48 states throughout the five-year award period. There were never fewer than 400 instruments installed, and the spacing was maintained at 70 km (with a 15 km radius buffer around each site). The Transportable Array stations continued to roll eastward through FY14 and are scheduled to complete the planned deployment at the end of FY15 (FY14 and FY15 funding provided under a separate NSF award).

B. 20 semi-permanent transportable broadband stations deployed in gaps in coverage of the ANSS that serve as fixed reference points for calibration of the Transportable Array.
These 20 stations were operated as planned. As the section above documents, the 20 TA stations that contributed to the Reference Network were operated throughout the five-year award period and continue to operate through to the present, under a separate NSF award.

C. A pool of 2,146 seismic stations that will be available for earthquake studies and short-term experiments through proposals funded by the National Science Foundation and other agencies.
This pool of 2,146 instruments was supported as planned. These instruments, which comprise the Flexible Array, were made available throughout the five-year award period. These instruments continue to be available to experiments under a separate NSF award.

D. 27 magnetotelluric field systems, seven permanent stations that will serve as fixed reference points for the calibration of the Transportable Magnetotelluric Array and 20 temporary stations that will be available for short-term experiments.
These 27 MT systems were supported and operated as planned. As the section above documents, the 20 temporary stations were deployed as planned each field season over the course of the award. The seven permanent (backbone) stations were operated through FY13, at which point USArray Change Order 37 (USArray CO 0037) documented the plan to decommission the backbone sites and transition the instruments into use in the portable (temporary) station pool. MT efforts have continued through to the present, under a separate NSF award.

Appendix A. Table of Subawards

Appendix B. Bibliography of USArray Publications

Appendix C. List of USArray Data Users

Appendix D. USArray Stories from the Field

Appendix E. List of USArray Media Exposure

Appendix A. Table of Subawards

Institution	Program	Title of Effort	Award Amt	P.I.	Start	End
Honeywell Technology Solutions	TA	TA Station Construction, Installation, Removal and Servicing	$9,996,494	D. Ford	10/01/2008	04/30/2014
New Mexico Institute of Mining and Technology	TA & FA	USArray Operations Facility (AOF) and Transportable Array Coordinating Office (TACO)	$9,396,430	R. Aster, B. Beaudoin	10/01/2008	04/30/2014
University of California, San Diego	TA	USArray Network Facility (ANF)	$6,667,030	F. Vernon	10/01/2008	04/30/2014
Coastal Technical Services	TA	Excavation & Construction of Seismic Vaults	$4,382,500	R. Stout	10/01/2008	09/30/2013
Oregon State University	MT	Operations and Management of EarthScope Magnetotelluric Programs	$2,861,588	A. Schultz	10/01/2008	09/30/2014
University of California, San Diego	TA	TA Station Metadata	$1,691,808	F. Vernon	10/01/2008	10/31/2013
Honeywell Technology Solutions	TA	Cascadia Station Construction, Installation, and Servicing	$401,809	B. Pierce, D. Ford	10/01/2009	09/30/2013
University of Alaska	TA	Technology Assistance with Implementation & Operation of the TA in Alaska	$259,599	M. West	04/15/2013	02/28/2014
RECON, LLC	TA	Alaska Reconnaissance Support	$238,457	I. Rowland	04/01/2014	09/30/2014
University of California, San Diego	TA	Cascadia Station Data Quality	$203,738	F. Vernon	10/01/2009	09/30/2013
Coastal Technical Services	TA	Cascadia Station Construction	$138,550	R. Stout	09/01/2009	09/30/2013
New Mexico Institute of Mining and Technology	TA	Cascadia Permitting and Operations	$64,886	R. Aster, B. Beaudoin	08/01/2009	09/30/2013
Cascadia Archaeology	TA	Cascadia Archeological Assessment in Western, Washington	$16,880	J. Boersema	01/01/2010	09/30/2010
South Carolina Research Foundation	TA/Mana-gement	REV & USArray Monitor Maintenance	$46,000	T. Owens	01/01/2011	09/30/2013
TA Summer Student Siting Assistance						
Boston College	TA	Technology Assistance with Implementation & Operation of the TA	$36,418	J. Ebel	05/01/2012	09/30/2012
College of Charleston	TA	Technology Assistance with Implementation & Operation of the TA	$31,937	S. Jaume	05/01/2012	09/30/2012
James Madison University	TA	Technology Assistance with Implementation & Operation of the TA	$36,231	S. Whitmeyer, C. Bailey	05/01/2012	09/30/2012

Lehigh University	TA	Technology Assistance with Implementation & Operation of the TA	$35,891	A. Meltzer	05/01/2012	09/30/2012
North Carolina Central University	TA	Technology Assistance with Implementation & Operation of the TA	$38,416	G. Vlahovic, P. Arroucau	05/01/2012	09/30/2012
Syracuse University	TA	Technology Assistance with Implementation & Operation of the TA	$36,280	R. Moucha	05/01/2012	09/30/2012
University of New Hampshire	TA	Technology Assistance with Implementation & Operation of the TA	$36,166	M. Boettcher	05/01/2012	09/30/2012
University of Quebec, Montreal	TA	Technology Assistance with Implementation & Operation of the TA	$33,111	F. Darbyshire, P. Audet	05/01/2012	09/30/2012
Eckerd College	TA	Technology Assistance with Implementation & Operation of the TA	$34,472	L. Wetzel	05/01/2011	09/30/2011
University of Florida	TA	Technology Assistance with Implementation & Operation of the TA	$34,050	M. Panning	05/01/2011	09/30/2011
Georgia Tech	TA	Technology Assistance with Implementation & Operation of the TA	$34,488	A. Newman	05/01/2011	09/30/2011
University of Kentucky	TA	Technology Assistance with Implementation & Operation of the TA	$34,550	Z. Wang	05/01/2011	09/30/2011
Miami University of Ohio	TA	Technology Assistance with Implementation & Operation of the TA	$33,867	M. Brudzinski	05/01/2011	09/30/2011
Michigan State University	TA	Technology Assistance with Implementation & Operation of the TA	$35,680	K. Fujita	05/01/2011	09/30/2011
Purdue University	TA	Technology Assistance with Implementation & Operation of the TA	$32,397	H. Gilbert, R. Nowack	05/01/2011	09/30/2011
Laurentian University	TA	Technology Assistance with Implementation & Operation of the TA	$36,356	R. Smith	05/01/2011	09/30/2011
Queens University	TA	Technology Assistance with Implementation & Operation of the TA	$35,596	S. Dineva	05/01/2011	09/30/2011
University of Alabama	TA	Technology Assistance with Implementation & Operation of the TA	$34,636	A. Goodlife, L. Wolfe	05/01/2010	09/30/2010
University of Memphis	TA	Technology Assistance with Implementation & Operation of the TA	$30,135	J.-M. Chiu	05/01/2010	09/30/2010

Michigan Tech	TA	Technology Assistance with Implementation & Operation of the TA	$29,803	G. Waite	05/01/2010	09/30/2010
Millsaps College	TA	Technology Assistance with Implementation & Operation of the TA	$32,266	J. Harris	05/01/2010	09/30/2010
Northwestern University	TA	Technology Assistance with Implementation & Operation of the TA	$31,204	S. van der Lee	05/01/2010	09/30/2010
University of Wisconsin, Madison	TA	Technology Assistance with Implementation & Operation of the TA	$29,468	C. Thurber	05/01/2010	09/30/2010
University of Arkansas, Little Rock	TA	Technology Assistance with Implementation & Operation of the TA	$52,318	H. Mahdi	05/01/2009	09/30/2009
University of Northern Iowa	TA	Technology Assistance with Implementation & Operation of the TA	$31,087	J. Walters	05/01/2009	09/30/2009
University of Louisiana, Lafayette	TA	Technology Assistance with Implementation & Operation of the TA	$33,980	G. Kinsland	05/01/2009	09/30/2009
University of Minnesota	TA	Technology Assistance with Implementation & Operation of the TA	$61,600	J. Revenaugh	05/01/2009	09/30/2009
Missouri S&T	TA	Technology Assistance with Implementation & Operation of the TA	$60,685	S. Gao	05/01/2009	09/30/2009
Institute for the Application of Geospatial Technology	TA	Geospatial Technology Support	$27,954	F. Pieper, K. Kwasnowski	02/01/2009	09/30/2009
Moravian College	SO	Seismology Software	$22,000	B. Coleman	05/15/2009	09/30/2009
University of Quebec	TA	Technology Assistance with Construction of the TA in Ontario and Quebec	$12,689	F. Darbyshire	06/10/2013	09/30/2013
Northwestern University	SO	USArray Data Processing Short Course	$10,783	S. van der Lee	08/15/2011	12/31/2011
Data Products						
University of Colorado, Boulder	DM	Western US Ambient Noise Cross-Correlations	$24,049	M. Ritzwoller, M. Barmine	05/01/2011	04/30/2012
University of California, San Diego	DM	SeisSound: The Audio/Video Seismic Waveform Visualization	$24,238	D. Kilb	05/01/2011	04/30/2012
Carnegie, DTM	DM	EMERALD: A software framework for seismic event processing	$24,071	M. Fouch, J. West	05/01/2012	04/30/2013

Oregon State University	DM	EMTF: USArray Magnetotelluric Transfer Functions	$23,842	A. Kelbert, G. Egbert, A. Schultz	05/01/2012	09/30/2013
Georgia Tech	DM	EQEnergy: Earthquake energy and rupture duration	$24,768	A. Newman, J. Convers	05/01/2012	04/20/2013
Missouri S&T	DM	SWS-DB-MST: The Missouri S&T Western and Central United States shear-wave splitting database	$25,000	K. Liu, S. Gao	07/01/2013	06/30/2014
Columbia, LDEO	DM	ASWMS: Automated Surface Wave Phase Velocity Measuring System	$18,972	G. Jin, J. Gaherty	07/01/2013	06/30/2014
University of Rhode Island	DM	GlobalGreensTensors: Global Empirical Green’s Tensor database	$25,000	Y. Shen, H. Gao	07/01/2013	09/30/2014

Appendix B. Bibliography of USArray Publications (2009-2013)

Abercrombie, R.E. **(2013)** "Comparison of direct and coda wave stress drop measurements for the Wells, Nevada, earthquake sequence," *Journal of Geophysical Research: Solid Earth*, Vol. 118, No. 4, p.1458-1470 doi: 10.1029/2012JB009638

Afonso, J.C., J. Fullea, W L. Griffin, Y. Yang, A.G. Jones, J.A. D. Connolly, and S.Y. O'Reilly **(2013)** "3-D multiobservable probabilistic inversion for the compositional and thermal structure of the lithosphere and upper mantle. I: a priori petrological information and geophysical observables," *Journal of Geophysical Research: Solid Earth*, Vol. 118, No. 5, p.2586-2617 doi: 10.1002/jgrb.50124

Al-Shukri, H., and H. Mahdi **(2012)** "Eastern Section SSA 2011 Meeting Report," *Seismological Research Letters*, Vol. 83, No. 1, p.200-221 doi: 10.1785/gssrl.83.1.200

Allison, C.M., R.C. Porter, M.J. Fouch, and S. Semken **(2013)** "Seismic evidence for lithospheric modification beneath the Mojave Neovolcanic Province, Southern California," *Geophysical Research Letters*, Vol. 40, No. 19, p.5119-5124 doi: 10.1002/grl.50993

Babaie Mahani, A., and G.M. Atkinson **(2013)** "Regional Differences in Ground-Motion Amplitudes of Small-to-Moderate Earthquakes across North America," *Bulletin of the Seismological Society of America*, Vol. 103, No. 5, p.2604-2620 doi: 10.1785/0120120350

Baig, A.M., M. Campillo, and F. Brenguier **(2009)** "Denoising seismic noise cross correlations," *Journal of Geophysical Research*, Vol. 114, p. 10-11 - 10-12 doi: 10.1029/2008JB006085

Bailey, I.W., M.S. Miller, K. Liu, and A. Levander **(2012)** "VS and density structure beneath the Colorado Plateau constrained by gravity anomalies and joint inversions of receiver function and phase velocity data," *Journal of Geophysical Research: Solid Earth*, Vol. 117, No. B2, p.2156-2202 doi: 10.1029/2011JB008522

Balcerak, E. **(2013)** "New details on transition zone below western United States," *Eos, Transactions American Geophysical Union*, Vol. 94, No. 25, p.228-228 doi: 10.1002/2013EO250007

Balcerak, E. **(2013)** "Global fires after asteroid impact probably caused mass extinction" *Eos, Transactions American Geophysical Union*, Vol. 94, No. 20, p.188-188 doi: 10.1002/2013EO200011

Balcerak, E. **(2013)** "Monitoring subsidence and vent wall collapse on Kīlauea Volcano, Hawaii," *Eos, Transactions American Geophysical Union*, Vol. 94, No. 20, p.188-188 doi: 10.1002/2013EO200007

Baltay, A., G. Prieto, and G.C. Beroza **(2009)** "Radiated seismic energy from coda measurements and no scaling in apparent stress with seismic moment," *Journal of Geophysical Research*, Vol. 115, No. B08314, p.14-11 - 14-12 doi: 10.1029/2009JB006736

Bao, X., E. Sandvol, E. Zor, S. Sakin, R. Mohamad, R. Gok, R. Mellors, T. Godoladze, G. Yetirmishli, and Niyazi Turkelli **(2011)** "Pg Attenuation Tomography within the Northern Middle East," *Bulletin of the Seismological Society of America*, Vol. 101, No. 4, p.1496-1506 doi: 10.1785/0120100316

Barbour, A.J., and D.C. Agnew **(2012)** "Erratum to Noise Levels on Plate Boundary Observatory Borehole Strainmeters in Southern California," *Bulletin of the Seismological Society of America*, Vol. 102, No. 1, p.451-452 doi: 10.1785/0120110268

Bedle, H., and S. van der Lee **(2009)** "Velocity variations beneath North America," *Journal of Geophysical Research*, Vol. 114, p. 8-1 - 8-22 doi: 10.1029/2008JB005949

Beghein, C., J.A. Snoke, and M.J. Fouch **(2009)** "Depth constraints on azimuthal anisotropy in the Great Basin from Rayleigh-wave phase velocity maps," *Earth and Planetary Science Letters*, Vol. 289, No. 3-4, p.467 doi: 10.1016/j.epsl.2009.11.036

Berglund, H.T., A.F. Sheehan, M.H. Murray, M. Roy, A.R. Lowry, R.S. Nerem, and F. Blume **(2012)** "Distributed deformation across the Rio Grande Rift, Great Plains, and Colorado Plateau," *Geology*, Vol. 40, No. 1, p.23-26 doi: 10.1130/G32418.1

Bezada, M.J., and E.D. Humphreys **(2012)** "Contrasting rupture processes during the April 11, 2010 deep-focus earthquake beneath Granada, Spain," *Earth and Planetary Science Letters*, Vol. 353-354, No. 0, p.38-46 doi: doi.org/10.1016/j.epsl.2012.08.001

Blackburn, T.J., S.A. Bowring, J.T. Perron, K.H. Mahan, F.O. Dudas, and K.R. Barnhart **(2012)** "An Exhumation History of Continents over Billion-Year Time Scales," *Science*, Vol. 335, No. 6064, p.73-76 doi: 10.1126/science.1213496

Blewitt, G., C. Kreemer, W.C. Hammond, and J.M. Goldfarb **(2013)** "Terrestrial reference frame NA12 for crustal deformation studies in North America," *Journal of Geodynamics*, Vol. 72, No. 0, p.11-24 doi: 10.1016/j.jog.2013.08.004

Bökelmann, Götz H.R., and A. Wüstefeld **(2009)** "Comparing crustal and mantle fabric from the North American craton using magnetics and seismic anisotropy," *Earth and Planetary Science Letters*, Vol. 277, No. 3-4, p.355

Bondár, I., and D. Storchak **(2011)** "Improved location procedures at the International Seismological Centre," *Geophysical Journal International*, Vol. 186, No. 3, p.1220-1244 doi: 10.1111/j.1365-246X.2011.05107.x

Bonner, J., R. Herrmann, and H. Benz **(2009)** "Variable-Period surface-wave magnitudes: A rapid and robust estimator of seismic moments," *Bulletin of the Seismological Society of America*, Vol. 100, No. 5A, p.2301-2309 doi: 10.1785/0120090388

Bonnin, M., G. Barruol, and Götz H.R. Bökelmann **(2009)** "Upper mantle deformation beneath the North American - Pacific plate boundary in California from SKS splitting," *Journal of Geophysical Research*, Vol. 115, No. B04306, p. 17 doi: 10.1029/2009JB006438

Bonnin, M., A. Tommasi, R. Hassani, S. Chevrot, J. Wookey, and G. Barruol **(2012)** "Numerical modelling of the upper-mantle anisotropy beneath a migrating strike-slip plate boundary: the San Andreas Fault system," *Geophysical Journal International*, Vol. 191, No. 2, p.436-458 doi: 10.1111/j.1365-246X.2012.05650

Bordet, E., M.G. Mihalynuk, C.J.R. Hart, J.K. Mortensen, R.M. Friedman, and J. Gabites **(2013)** "Chronostratigraphy of Eocene volcanism, central British Columbia1," *Canadian Journal of Earth Sciences*, Vol. 51, No. 1, p.56-103 doi: 10.1139/cjes-2013-0073

Borsa, A., and J.B. Minster **(2012)** "Rapid Determination of Near-Fault Earthquake Deformation Using Differential LiDAR," *Bulletin of the Seismological Society of America*, Vol. 102, No. 4, p.1335-1347 doi: 10.1785/0120110159

Bossmann, A.B., and P.E. van Keken **(2013)** "Dynamics of plumes in a compressible mantle with phase changes: Implications for phase boundary topography," *Physics of the Earth and Planetary Interiors*, Vol. 224, No. 0, p.21-31 doi: 10.1016/j.pepi.2013.09.002

Braun, J. **(2009)** "The many surface expressions of mantle dynamics," *Nature Geosci*, Vol. 3, No. 12, p.825 doi: 10.1038/ngeo1020

Bromirski, P.D. **(2009)** "Earth Vibrations," *Science*, Vol. 324, No. 5030, p.1026-1027

Bromirski, P.D., and P. Gerstoft **(2009)** "Dominant source regions of the Earth's “hum” are coastal," *Geophysical Research Letters*, Vol. 36, No. 13, p.3-1 - 3-5 doi: 10.1029/2009GL038903

Buehler, J.S., and P.M. Shearer **(2009)** "Pn tomography of the western United States using USArray," *Journal of Geophysical Research*, Vol. 115, No B09315, p. 15-11 - 15-12 doi: 10.1029/2009JB006874

Buehler, J.S., and P.M. Shearer **(2013)** "Sn propagation in the Western United States from common midpoint stacks of USArray data," *Geophysical Research Letters*, Vol. 40, No. 23, p.6106-6111 doi: 10.1002/2013GL057680

Buehler, J.S., and P.M. Shearer **(2012)** "Localized imaging of the uppermost mantle with USArray Pn data," *Journal of Geophysical Research: Solid Earth*, Vol. 117, No. B9, p n/a doi: 10.1029/2012JB009433

Burdick, S., R.D. van der Hilst, F.L. Vernon, V. Martynov, T. Cox, J. Eakins, G.H. Karasu, J. Tylell, L. Astiz, and G.L. Pavlis **(2009)** "Model update January 2010: Upper mantle heterogeneity beneath North America from Traveltime Tomography with Global and USArray Transportable Array Data," *Seismological Research Letters*, Vol. 81, No. 5, p.689-693 doi: 10.1785/gssrl.81.5.689

Burdick, S., R.D. van der Hilst, F.L. Vernon, V. Martynov, T. Cox, J. Eakins, G.H. Karasu, J. Tylell, L. Astiz, and G.L. Pavlis **(2012)** "Model Update March 2011: Upper Mantle Heterogeneity beneath North America from Travel time Tomography with Global and USArray Transportable Array Data," *Seismological Research Letters*, Vol. 83, No. 1, p.23-28 doi: 10.1785/gssrl.83.1.23

Burdick, S., R.D. van der Hilst, F.L. Vernon, V. Martynov, T. Cox, J. Eakins, T. Mulder, L. Astiz, and G.L. Pavlis **(2009)** "Model update December 2008: Upper mantle heterogeneity beneath North America from P-wave travel time tomography with Global and USArray Transportable Array Data," *Seismological Research Letters*, Vol. 80, No. 5, p.675-679 doi: 10.1785/gssrl.80.5.675

Burkett, E., and M. Gurnis **(2013)** "Stalled slab dynamics," *Lithosphere*, Vol. 5, No. 1, p.92-97 doi: 10.1130/l249.1

Cao, A., and A. Levander **(2009)** "High-resolution transition zone structures of the Gorda Slab beneath the western United States: Implication for deep water subduction," *Journal of Geophysical Research*, Vol. 115, No B07301, p 1-1 - 1-13 doi: 10.1029/2009JB006876

Castro, R.R., P.M. Shearer, L. Astiz, M. Suter, C. Jacques-Ayala, and F.L. Vernon **(2009)** "The Long-Lasting aftershock series of the 3 May 1887 Mw 7.5 Sonora Earthquake in the Mexican Basin and Range Province," *Bulletin of the Seismological Society of America*, Vol. 100, No. 3, p.1153-1164 doi: 10.1785/0120090180

Chao, K., Z. Peng, A. Fabian, and L. Ojha **(2012)** "Comparisons of Triggered Tremor in California," *Bulletin of the Seismological Society of America*, Vol. 102, No. 2, p.900-908 doi: 10.1785/0120110151

Charléty, J., S. Voronin, G. Nolet, I. Loris, F.J. Simons, K. Sigloch, and I.C. Daubechies **(2013)** "Global seismic tomography with sparsity constraints: Comparison with smoothing and damping regularization," *Journal of Geophysical Research: Solid Earth*, Vol. 118, No. 9, p.4887-4899 doi: 10.1002/jgrb.50326

Chaves Moreno, C.A., and N. Ussami **(2013)** "Modeling 3-D density distribution in the mantle from inversion of geoid anomalies: Application to the Yellowstone Province," *Journal of Geophysical Research: Solid Earth*, Vol. 118, No. 12, p.6328-6351 doi: 10.1002/2013JB010168

Chen, C.-Wu, D.E. James, M.J. Fouch, and L.S. Wagner **(2013)** "Lithospheric structure beneath the High Lava Plains, Oregon, imaged by scattered teleseismic waves," *Geochemistry, Geophysics, Geosystems*, Vol. 14, No. 11, p.4835-4848 doi: 10.1002/ggge.20284

Chevrot, S., and V. Monteiller **(2009)** "Principles of vectorial tomography - the effects of model parametrization and regularization in tomographic imaging of seismic anisotropy," *Geophysical Journal International*, Vol. 179, No. 3, p.1726-1736

Cho, Kwang Hyun, Sang-Hyun Lee, and Ik-Bum Kang **(2011)** "Crustal Structure of the Korean Peninsula Using Surface Wave Dispersion and Numerical Modeling," *Pure and Applied Geophysics*, Vol. 168, No. 10, p.1587-1598 doi: 10.1007/s00024-011-0262-x

Chu, R., and D.V. Helmberger **(2013)** "Source Parameters of the Shallow 2012 Brawley Earthquake, Imperial Valley," *Bulletin of the Seismological Society of America*, Vol. 103, No 2A, p.1141-1147 doi: 10.1785/0120120324

Chu, R., W. Leng, D.V. Helmberger, and M. Gurnis **(2013)** "Hidden hotspot track beneath the eastern United States" *Nature Geoscience*, Vol. 6, p.963-966 doi: 10.1038/ngeo1949

Chu, R., S. Ni, Ar. Pitarka, and D.V. Helmberger **(2013)** "Inversion of Source Parameters for Moderate Earthquakes Using Short-Period Teleseismic P Waves," *Pure and Applied Geophysics*, p.1-13 doi: 10.1007/s00024-013-0719-1

Chu, R., B. Schmandt, and D.V. Helmberger **(2012)** "Juan de Fuca subduction zone from a mixture of tomography and waveform modeling," *Journal of Geophysical Research: Solid Earth*, Vol. 117, No. B3, p n/a doi: 10.1029/2012JB009146

Chu, R., S. Wei, D.V. Helmberger, Z. Zhan, L. Zhu, and H. Kanamori **(2011)** "Initiation of the great Mw 9.0 Tohoku-Oki earthquake," *Earth and Planetary Science Letters*, Vol. 308, No. 3-4, p.277-283 doi: 10.1016/j.bbr.2011.03.031

Chun, Kin-Yip, and G.A. Henderson **(2009)** "Lg Attenuation near the North Korean border with China, Part II: Model development from the 2006 Nuclear Explosion in North Korea," *Bulletin of the Seismological Society of America*, Vol. 99, No. 5, p.3030-3038 doi: 10.1785/0120080341

Claprood, M., M.W. Asten, and J. Kristek **(2011)** "Using the SPAC Microtremor Method to Identify 2D Effects and Evaluate 1D Shear-Wave Velocity Profile in Valleys," *Bulletin of the Seismological Society of America*, Vol. 101, No. 2, p.826-847 doi: 10.1785/0120090232

Claprood, M., M.W. Asten, and J. Kristek **(2012)** "Combining HVSR microtremor observations with the SPAC method for site resonance study of the Tamar Valley in Launceston (Tasmania, Australia)," *Geophysical Journal International*, Vol. 191, No. 2, p.765-780 doi: 10.1111/j.1365-246X.2012.05654.x

Cottaar, S., and B. Romanowicz **(2012)** "An unusually large ULVZ at the base of the mantle near Hawaii," *Earth and Planetary Science Letters*, Vol. 355-356, No. 0, p.213-222 doi: 10.1016/j.epsl.2012.09.005

Cox, R.T., J.L. Hall, and C.S. Gardner **(2013)** "Tectonic history and setting of a seismogenic intraplate fault system that lacks microseismicity: The Saline River fault system, southern United States," *Tectonophysics*, Vol. 608, No. 0, p.252-266 doi: 10.1016/j.tecto.201309.031

Crow, R., K. Karlstrom, Y. Asmerom, B. Schmandt, V. Polyak, and S.A. DuFrane **(2011)** "Shrinking of the Colorado Plateau via lithospheric mantle erosion: Evidence from Nd and Sr isotopes and geochronology of Neogene basalts," *Geology*, Vol. 39, No. 1, p.27-30 doi: 10.1130/G31611.1

Curtis, A., H. Nicolson, D. Halliday, J. Trampert, and B. Baptie **(2009)** "Virtual seismometers in the subsurface of the Earth from seismic interferometry" *Nature Geoscience*, Vol. 2, p.700-704

Darold, A., and E. Humphreys **(2013)** "Upper mantle seismic structure beneath the Pacific Northwest: A plume-triggered delamination origin for the Columbia River flood basalt eruptions," *Earth and Planetary Science Letters*, Vol. 365, No. 0, p.232-242 doi: 10.1016/j.epsl.2013.01.024

De Angelis, S., and P. Bodin **(2012)** "Watching the Wind: Seismic Data Contamination at Long Periods due to Atmospheric Pressure-Field-Induced Tilting," *Bulletin of the Seismological Society of America*, Vol. 102, No. 3, p.1255-1265 doi: 10.1785/0120110186

De Angelis, Silvio, David Fee, Matthew Haney, and David Schneider **(2012)** "Detecting hidden volcanic explosions from Mt. Cleveland Volcano, Alaska with infrasound and ground-coupled airwaves," *Geophysical Research Letters*, Vol. 39, No. 21, p n/a

De Groot-Hedlin, C., MA.H. Hedlin, and K. Walker **(2011)** "Finite difference synthesis of infrasound propagation through a windy, viscous atmosphere: application to a bolide explosion detected by seismic networks," *Geophysical Journal International*, Vol. 185, No. 1, p. 305 doi: 10.1111/j.1365-246X.2010.04925.x

Debayle, E., and Y. Ricard **(2012)** "A global shear velocity model of the upper mantle from fundamental and higher Rayleigh mode measurements," *Journal of Geophysical Research: Solid Earth*, Vol. 117, No B10, p n/a doi: 10.1029/2012JB009288

Di Giacomo, D., D. Bindi, S. Parolai, and A. Oth **(2011)** "Residual analysis of teleseismic P-wave energy magnitude estimates: inter- and intrastation variability," *Geophysical Journal International*, Vol. 185, No. 3, p.1444-1454 doi: 10.1111/j.1365-246X.2011.05019.x

Diaz, J., A. Villaseñor, J. Morales, A. Pazos, D. Cordoba, J. Pulgar, J.L. Garcia-Lobon, M. Harnafi, R. Carbonell, J. Gallart, and Group TopoIberia Seismic Working **(2009)** "Background Noise Characteristics at the IberArray Broadband Seismic Network," *Bulletin of the Seismological Society of America*, Vol. 100, No. 2, p.618-628 doi: 10.1785/0120090085

Druken, K.A., M.D. Long, and C. Kincaid **(2011)** "Patterns in seismic anisotropy driven by rollback subduction beneath the High Lava Plains," *Geophysical Research Letters*, Vol. 38, No L13310, p. 6 doi: 10.1029/2011GL047541

Eagar, K.C., and M.J. Fouch **(2012)** "FuncLab: A MATLAB Interactive Toolbox for Handling Receiver Function Datasets," *Seismological Research Letters*, Vol. 83, No. 3, p.596-603 doi: 10.1785/gssrl.83.3.596

Eagar, K.C., M.J. Fouch, and D.E. James **(2009)** "Receiver function imaging of upper mantle complexity beneath the Pacific Northwest, United States," *Earth and Planetary Science Letters*, Vol. 297, No. 1-2, p.141-153 doi: 10.1016/j.epsl.2010.06.015

Ekström, G., G.A. Abers, and S.C. Webb **(2009)** "Determination of surface-wave phase velocities across USArray from noise and Aki's spectral formulation," *Geophysical Research Letters*, Vol. 36, p 1-1 - 1-5 doi: 10.1029/2009GL039131

Ellsworth, W.L. **(2013)** "Injection-Induced Earthquakes," *Science*, Vol. 341, No. 6142 doi: 10.1126/science.1225942

Farrell, J., R.B. Smith, T. Taira, W.L. Chang, and C.M. Puskas **(2009)** "Dynamics and rapid migration of the energetic 2008–2009 Yellowstone Lake earthquake swarm," *Geophysical Research Letters*, Vol. 37, No L19305, p.5-1 - 5-5 doi: 10.1029/2010GL044605

Fisk, M.D., and W.S. Phillips **(2013)** "Constraining Regional Phase Amplitude Models for Eurasia, Part 1: Accurate Source Parameters and Geometric Spreading," *Bulletin of the Seismological Society of America*, Vol. 103, No. 6, p.3248-3264 doi: 10.1785/0120130018

Ford, H.A., K.M. Fischer, D.L. Abt, C.A. Rychert, and L.T. Elkins-Tanton **(2009)** "The lithosphere-asthenosphere boundary and cratonic lithospheric layering beneath Australia from Sp wave imaging," *Earth and Planetary Science Letters*, Vol. 300, No. 3-4, p.299-310 doi: 10.1016/j.epsl.2010.10.007

Ford, S.R., R.A. Uhrhammer, and M. Hellweg **(2011)** "Local Magnitude Tomography in California," *Bulletin of the Seismological Society of America*, Vol. 101, No. 1, p.427-432 doi: 10.1785/0120100136

Fouch, M.J. **(2012)** "The Yellowstone Hotspot: Plume or Not?" *Geology*, Vol. 40, No. 5, p.479-480 doi: 10.1130/focus052012.1

Frederiksen, A.W., T. Bollmann, F. Darbyshire, and S. van der Lee **(2013)** "Modification of continental lithosphere by tectonic processes: A tomographic image of central North America," *Journal of Geophysical Research: Solid Earth*, Vol. 118, No. 3, p.1051-1066 doi: 10.1002/jgrb.50060

Frohlich, C., and M. Brunt **(2013)** "Two-year survey of earthquakes and injection/production wells in the Eagle Ford Shale, Texas, prior to the Mw4.8 20 October 2011 earthquake," *Earth and Planetary Science Letters*, Vol. 379, No. 0, p.56-63 doi: 10.1016/j.epsl.2013.07.025

Fukao, Y., K. Nishida, and N. Kobayashi **(2009)** "Seafloor topography, ocean infragravity waves, and background Love and Rayleigh waves," *Journal of Geophysical Research*, Vol. 115, No B04302, p. 2-1 - 2-10 doi: 10.1029/2009JB006678

Gaite, B., A. Iglesias, A. Villaseñor, M. Herraiz, and J.F. Pacheco **(2012)** "Crustal structure of Mexico and surrounding regions from seismic ambient noise tomography," *Geophysical Journal International*, Vol. 188, No. 3, p.1413-1424 doi: 10.1111/j.1365-246X.2011.05339.x

Galetti, E., and A. Curtis **(2011)** "Generalised receiver functions and seismic interferometry," *Tectonophysics*, Vol. In Press, No. 0 doi: 10.1016/j.tecto.2011.12.004

Galetti, E., and A. Curtis **(2012)** "Generalised receiver functions and seismic interferometry," *Tectonophysics*, Vol. 532-535, No. 0, p.1-126 doi: 10.1016/j.tecto.2011.12.004

Gao, H., E.D. Humphreys, H. Yao, and R.D. van der Hilst **(2011)** "Crust and lithosphere structure of the northwestern U.S. with ambient noise tomography: Terrane accretion and Cascade arc development," *Earth and Planetary Science Letters*, Vol. 304, No. 1-2, p.202-211 doi: 10.1016/j.epsl.2011.01.033

Gao, H., and Y. Shen **(2012)** "Validation of Shear-Wave Velocity Models of the Pacific Northwest," *Bulletin of the Seismological Society of America*, Vol. 102, No. 6, p.2611-2621 doi: 10.1785/0120110336

Gonzalez-Huizar, H., A.A. Velasco, Z. Peng, and R.R. Castro **(2012)** "Remote triggered seismicity caused by the 2011, M9.0 Tohoku-Oki, Japan earthquake," *Geophysical Research Letters*, Vol. 39, No. 10, pn/a doi: 10.1029/2012GL051015

Gouédard, P., H. Yao, F. Ernst, and R.D. van der Hilst **(2012)** "Surface wave eikonal tomography in heterogeneous media using exploration data," *Geophysical Journal International*, Vol. 191, No. 2, p.781 doi: 10.1111/j.1365-246X.2012.05652

Hamilton, W.B. **(2013)** "Evolution of the Archean Mohorovičić discontinuity from a synaccretionary 4.5 Ga protocrust," *Tectonophysics*, Vol. 609, No. 0, p.706-733 doi: 10.1016/j.tecto.2013.08.009

Hanna, J., and M.D. Long **(2012)** "SKS splitting beneath Alaska: Regional variability and implications for subduction processes at a slab edge," *Tectonophysics*, Vol. 530-531, No. 0, p.272-285 doi: 10.1016/j.tecto.2012.01.003

Hansen, R.T.J., M.G. Bostock, and N.I. Christensen **(2012)** "Nature of the low velocity zone in Cascadia from receiver function waveform inversion," *Earth and Planetary Science Letters*, Vol. 337-338, No. 0, p.25-38 doi: 10.1016/j.epsl.2012.05.031

Hanson-Hedgecock, S., L.S. Wagner, M.J. Fouch, and D.E. James **(2012)** "Constraints on the causes of mid-Miocene volcanism in the Pacific Northwest US from ambient noise tomography," *Geophysical Research Letters*, Vol. 39, No. 5, p. n/a doi: 10.1029/2012GL051108

Harmon, N., C.A. Rychert, and P. Gerstoft **(2009)** "Distribution of noise sources for seismic interferometry," *Geophysical Journal International*, Vol. 183, No. 3, p.1470 doi: 10.1111/j.1365-246X.2010.04802.x

Hedlin, M.A.H., C. de Groote Hedlin, and D. Drob **(2012)** "A Study of Infrasound Propagation Using Dense Seismic Network Recordings of Surface Explosions," *Bulletin of the Seismological Society of America*, Vol. 102, No. 5, p.1927-1937 doi: 10.1785/0120110300

Hedlin, M.A.H., D. Drob, K. Walker, and C. de Groot-Hedlin **(2010)** "A study of acoustic propagation from a large bolide in the atmosphere with a dense seismic network," *Journal of Geophysical Research*, Vol. 115, No B11312, p.17 doi: 10.1029/2010JB007669

Herrmann, R.B., H. Benz, and C.J. Ammon **(2011)** "Monitoring the Earthquake Source Process in North America," *Bulletin of the Seismological Society of America*, Vol. 101, No. 6, p.2609-2625 doi: 10.1785/0120110095

Hill, G.J., T.G. Caldwell, W. Heise, D.G. Chertkoff, H.M. Bibby, M.K. Burgess, J.P. Cull, and Ray A.F. Cas **(2009)** "Distribution of melt beneath Mount St Helens and Mount Adams inferred from magnetotelluric data," *Nature Geoscience*, Vol. 2, No. 11, p.785

Holland, A.A. **(2013)** "Earthquakes Triggered by Hydraulic Fracturing in South-Central Oklahoma," *Bulletin of the Seismological Society of America*, Vol. 103, No. 3, p.1784-1792 doi: 10.1785/0120120109

Holland, A.A. **(2013)** "Optimal Fault Orientations within Oklahoma," *Seismological Research Letters*, Vol. 84, No. 5, p.876-890 doi: 10.1785/0220120153

Hu, Xiao-G., Xiao-G Hao, and Lin-T. Liu **(2013)** "Azimuthal anisotropy in the mantle transition zone beneath the Tibetan Plateau: Evidence from normal mode coupling," *Journal of Geodynamics*, Vol. 64, No. 0, p.54-61 doi: 10.1016/j.jog.20132.09001

Hu, Xiao-Gang, Xiu-Xiu Xue, Lin-Tao Liu, and He-Ping Sun **(2012)** "Normal mode coupling due to azimuthal anisotropy in the transition zone: an example from Taiwan Island," *Geophysical Journal International*, Vol. 190, No. 1, p.323-334 doi: 10.1111/j.1365-246X.2012.05463

Huang, Guo-jiao, Chao-ying Bai, Duo-lin Zhu, and Stewart Greenhalgh **(2012)** "2D/3D Seismic Simultaneous Inversion for the Velocity and Interface Geometry Using Multiple Classes of Arrivals," *Bulletin of the Seismological Society of America*, Vol. 102, No. 2, p.790-801 doi: 10.1785/0120110155

Huang, Z., and D. Zhao **(2013)** "Mapping P-wave azimuthal anisotropy in the crust and upper mantle beneath the United States," *Physics of the Earth and Planetary Interiors*, Vol. 225, No. 0, p.28-40 doi: 10.1016/j.pepi.2013.10.003

Hutton, K., J. Woessner, and E. Hauksson **(2009)** "Earthquake Monitoring in Southern California for Seventy-Seven Years (1932-2008)," *Bulletin of the Seismological Society of America*, Vol. 100, No. 2, p.423-446 doi: 10.1785/0120090130

Hyndman, R.D., and C.A. Currie **(2011)** "Why is the North America Cordillera high? Hot backarcs, thermal isostasy, and mountain belts," *Geology*, Vol. 39, No. 8, p.783-786 doi: 10.1130/G31998.1

Ide, S. **(2012)** "Variety and spatial heterogeneity of tectonic tremor worldwide," *Journal of Geophysical Research: Solid Earth*, Vol. 117, No B3, p. n/a doi: 10.1029/2011JB008840

James, D.E., M.J. Fouch, R.W. Carlson, and J.B. Roth **(2011)** "Slab fragmentation, edge flow and the origin of the Yellowstone hotspot track," *Earth and Planetary Science Letters*, Vol. 311, No. 1-2, p.124-135 doi: 10.1016/j.epsl.2011.09.007

Justinic, A.H., B. Stump, C. Hayward, and C. Frohlich **(2013)** "Analysis of the Cleburne, Texas, Earthquake Sequence from June 2009 to June 2010," *Bulletin of the Seismological Society of America*, Vol. 103, No. 6, p.3083-3093. doi: 10.1785/0120120336.

Kao, H., Y. Behr, C.A. Currie, R. Hyndman, J. Townend, F.-C. Lin, M.H. Ritzwoller, S.-Ju Shan, and J. He **(2013)** "Ambient seismic noise tomography of Canada and adjacent regions: Part I. Crustal structures," *Journal of Geophysical Research: Solid Earth*, Vol. 118, No. 11, p.2013JB010535 doi: 10.1002/2013JB010535

Kelbert, A., G.D. Egbert, and C. deGroot-Hedlin **(2012)** "Crust and upper mantle electrical conductivity beneath the Yellowstone Hotspot Track," *Geology*, Vol. 40, No. 5, p.447-450 doi: 10.1130/G32655.1

Keller, G.R. **(2013)** "The Moho of North America: A brief review focused on recent studies," *Tectonophysics*, Vol. 609, No. 0, p.45-55 doi: 10.1016/j.tecto.2013.07.031

Kennett, B.L.N., A. Gorbatov, and E. Kiser **(2011)** "Structural controls on the Mw 9.0 2011 Offshore-Tohoku earthquake," *Earth and Planetary Science Letters*, Vol. 310, No. 3-4, p.462 doi: 10.1016/j.epsl.2011.08.039

Keranen, K.M., H.M. Savage, G.A. Abers, and E.S. Cochran **(2013)** "Potentially induced earthquakes in Oklahoma, USA: Links between wastewater injection and the 2011 Mw 5.7 earthquake sequence," *Geology*, Vol. 41, No. 6, p.699-702 doi: 10.1130/g34045.1

Kerr, R.A. **(2009)** "Scoping out unseen forces shaping North America," *Science*, Vol. 325, No. 5948, p.1620 - 1621

Kerr, R.A. **(2011)** "Tectonic Blow Ended Mountain Building, Fired Up Volcanoes," *Science*, Vol. 331, No. 6014, p.142 doi: 10.1126/science.331.6014.142-a

Kerr, R.A. **(2013)** "Geophysical Exploration Linking Deep Earth and Backyard Geology," *Science*, Vol. 340, No. 6138, p.1283-1285 doi: 10.1126/science.340.6138.1283

Kerr, R.A. **(2013)** "Some Earthquakes Warn That They Are About to Strike," *Science*, Vol. 341, No. 6142, p.117-118 doi: 10.1126/science.341.6142.117

Kim, W.-Y. **(2013)** "Induced seismicity associated with fluid injection into a deep well in Youngstown, Ohio," *Journal of Geophysical Research: Solid Earth*, Vol. 118, No. 7, p.3506-3518 doi: 10.1002/jgrb.50247

Kind, R., X. Yuan, and P. Kumar **(2012)** "Seismic receiver functions and the lithosphere-asthenosphere boundary," *Tectonophysics*, Vol. 536-537, No. 0, p.25-43 doi: 10.1016/j.tecto.2012.03.005

Kiser, E., and M. Ishii **(2012)** "The March 11, 2011 Tohoku-oki earthquake and cascading failure of the plate interface," *Geophysical Research Letters*, Vol. 39, No. 7, p.n/a. doi: 10.1029/2012GL051170

Kiser, E., and M. Ishii **(2012)** "Combining seismic arrays to image the high-frequency characteristics of large earthquakes," *Geophysical Journal International*, Vol. 188, No. 3, p.1117 doi: 10.1111/j.1365-246X.2011.05299

Kiser, E., and M. Ishii **(2013)** "The 2010 Maule, Chile, Coseismic Gap and Its Relationship to the 25 March 2012 Mw 7.1 Earthquake," *Bulletin of the Seismological Society of America*, Vol. 103, No. 2A, p.1148-1153 doi: 10.1785/0120120209

Kiser, E., and M. Ishii **(2013)** "Hidden aftershocks of the 2011 Mw 9.0 Tohoku, Japan earthquake imaged with the backprojection method," *Journal of Geophysical Research: Solid Earth*, Vol. 118, No. 10, p.5564-5576 doi: 10.1002/2013JB010158

Kumar, P., R. Kind, X. Yuan, and J. Mechie **(2012)** "USArray Receiver Function Images of the Lithosphere-Asthenosphere Boundary," *Seismological Research Letters*, Vol. 83, No. 3, p.486-491 doi: 10.1785/gssrl.83.3.486

Kurrle, D., and R. Widmer-Schnidrig **(2009)** "Excitation of long-period Rayleigh waves by large storms over the North Atlantic Ocean," *Geophysical Journal International*, Vol. 183, No. 1, p.330-338 doi: 10.1111/j.1365-246X.2010.04723.x

Lawrence, J.F., and G.A. Prieto **(2011)** "Attenuation tomography of the western United States from ambient seismic noise," *Journal of Geophysical Research*, Vol. 116, No B06302, p. 11 doi: 10.1029/2010JB007836

Lay, T., C.J. Ammon, H. Kanamori, L. Rivera, K.D. Koper, and A.R. Hutko **(2009)** "The 2009 Samoa-Tonga great earthquake triggered doublet," *Nature*, Vol. 466, No. 7309, p.964 doi: 10.1038/nature09214

Lay, T., H. Kanamori, C.J. Ammon, A.R. Hutko, K.P. Furlong, and L. Rivera **(2009)** "The 2006–2007 Kuril Islands great earthquake sequence," *Journal of Geophysical Research*, Vol. 114, p.8-1 - 8-31 doi: 0.1029/2008JB006280

Lay, T., H. Kanamori, C.J. Ammon, K.D. Koper, A.R. Hutko, L. Ye, H. Yue, and T.M. Rushing **(2012)** "Depth-varying rupture properties of subduction zone megathrust faults," *Journal of Geophysical Research: Solid Earth*, Vol. 117, No. B4, p n/a doi: 10.1029/2011JB009133

Levander, A., B. Schmandt, M.S. Miller, K. Liu, K.E. Karlstrom, R.S. Crow, C.T.A. Lee, and E.D. Humphreys **(2011)** "Continuing Colorado plateau uplift by delamination-style convective lithospheric downwelling," *Nature*, Vol. 472, No. 7344, p.461-465 doi: 10.1038/nature10001

Levandowski, W., C.H. Jones, H. Reeg, A. Frassetto, H. Gilbert, G. Zandt, and T.J. Owens **(2013)** "Seismological estimates of means of isostatic support of the Sierra Nevada," *Geosphere*, Vol. 9, No. 6, p.1552-1561 doi: 10.1130/ges00905.1

Levshin, A.L., M.P. Barmin, M.P. Moschetti, C. Mendoza, and M.H. Ritzwoller **(2012)** "Refinements to the method of epicentral location based on surface waves from ambient seismic noise: introducing Love waves," *Geophysical Journal International*, Vol. 191, No. 2, p.671-685 doi: 10.1111/j.1365-246X.2012.05631.x

Li, Q., R. Gao, F.T. Wu, Ye Guan, Z. Ye, Q. Liu, H. Kuo-Chen, R He, W. Li, and X. Shen **(2013)** "Seismic structure in the southeastern China using teleseismic receiver functions," *Tectonophysics*, Vol. 606, No. 0, p.24-35 doi: 10.1016/j.tecto.2013.06.033

Liang, C., and C.A. Langston **(2009)** "Wave gradiometry for USArray: Rayleigh waves," *Journal of Geophysical Research*, Vol. 114, p.8-1 - 8-19 doi: 10.1029/2008JB005918

Lin, F.-C., D. Li, R.W. Clayton, and D. Hollis **(2013)** "High-resolution 3D shallow crustal structure in Long Beach, California: Application of ambient noise tomography on a dense seismic array," *Geophysics*, Vol. 78, No. 4, p.Q45-Q56 doi: 10.1190/geo2012-0453.1

Lin, F.-C., and M.H. Ritzwoller **(2011)** "Helmholtz surface wave tomography for isotropic and azimuthally anisotropic structure," *Geophysical Journal International*, Vol. 186, No. 3, p.1104-1120 doi: 10.1111/j.1365-246X.2011.05070.x

Lin, Fan-Chi, M.H. Ritzwoller, and R. Snieder **(2009)** "Eikonal tomography: surface wave tomography by phase front tracking across a regional broad-band seismic array," *Geophysical Journal International*, Vol. 177, No. 3, p.1091-1110

Lin, F.-C., M.H. Ritzwoller, Y. Yang, M.P. Moschetti, and M.J. Fouch **(2009)** "Complex and variable crustal and uppermost mantle seismic anisotropy in the western United States," *Nature Geosci*, Vol. 4, No. 1, p.55-61 doi: 10.1038/ngeo1036

Lin, F.-Chi, B. Schmandt, and V.C. Tsai **(2012)** "Joint inversion of Rayleigh wave phase velocity and ellipticity using USArray: Constraining velocity and density structure in the upper crust," *Geophysical Research Letters*, Vol. 39, No. 12, p n/a doi: 10.1029/2012GL052196

Lin, F.-Chi, V.C. Tsai, and M.H. Ritzwoller **(2012)** "The local amplification of surface waves: A new observable to constrain elastic velocities, density, and anelastic attenuation," *Journal of Geophysical Research: Solid Earth*, Vol. 117, No. B6, p.n/a doi: 10.1029/2012JB009208

Lin, F.-C., V.C. Tsai, B. Schmandt, Z. Duputel, and Z. Zhan **(2013)** "Extracting seismic core phases with array interferometry," *Geophysical Research Letters*, Vol. 40, No. 6, p.1049-1053 doi: 10.1002/grl.50237

Lin, F.C., and M.H. Ritzwoller **(2009)** "Empirically determined finite frequency sensitivity kernels for surface waves," *Geophysical Journal International*, Vol. 182, No. 2, p.923 doi: 10.1111/j.1365-246X.2010.04643.x

Lin, G., C.H. Thurber, H. Zhang, E. Hauksson, P.M. Shearer, F. Waldhauser, T.M. Brocher, and J. Hardebeck **(2009)** "A California statewide three-dimensional seismic velocity model from both absolute and differential Times," *Bulletin of the Seismological Society of America*, Vol. 100, No. 1, p.225-240 doi: 10.1785/0120090028

Liu, K.H., and S.S. Gao **(2013)** "Making Reliable Shear-Wave Splitting Measurements," *Bulletin of the Seismological Society of America*, Vol. 103, No. 5, p.2680-2693 doi: 10.1785/0120120355

Liu, L., M. Gurnis, M. Seton, J. Saleeby, R.D. Muller, and J.M. Jackson **(2009)** "The role of oceanic plateau subduction in the Laramide orogeny," *Nature Geosci*, Vol. 3, No. 5, p.353 doi: 10.1038/ngeo829

Liu, L., and D.R. Stegman **(2011)** "Segmentation of the Farallon slab," *Earth and Planetary Science Letters*, Vol. 311, No. 1-2, p.1-10 doi: 10.1016/j.epsl.2011.09.027

Liu, L., and D.R. Stegman **(2012)** "Origin of Columbia River flood basalt controlled by propagating rupture of the Farallon slab," *Nature*, Vol. 482, p. 386-389 doi: 10.1038/nature10749

Liu, L., Y. Tan, D. Sun, M. Chen, and D. Helmberger **(2011)** "Trans-Pacific whole mantle structure," *Journal of Geophysical Research*, Vol. 116, No. B04306, p.14 doi: 10.1029/2010JB007907.

Lockridge, J.S., M.J. Fouch, and J.R. Arrowsmith **(2012)** "Seismicity within Arizona during the Deployment of the EarthScope USArray Transportable Array," *Bulletin of the Seismological Society of America*, Vol. 102, No. 4, p.1850-1863 doi: 10.1785/0120110297

Lockridge, J.S., M.J. Fouch, J.R. Arrowsmith, and L. Linkimer **(2012)** "Analysis of Seismic Activity near Theodore Roosevelt Dam, Arizona, during the Occupation of the EarthScope/USArray Transportable Array," *Seismological Research Letters*, Vol. 83, No. 6, p.1014-1022. doi: 10.1785/0220120034

Lomnitz, Cinna, and Chao-jun Zhang **(2009)** "Parkfield revisited: I. Data retrieval," *Lithosphere*, Vol. 1, No. 4, p.227-234. doi: 10.1130/l14.1

Long, M.D., and T.W. Becker **(2009)** "Mantle dynamics and seismic anisotropy," *Earth and Planetary Science Letters*, Vol. 297, No. 3-4, p.341 doi: 10.1016/j.epsl.2010.06.036

Long, M.D., H. Gao, A. Klaus, L.S. Wagner, M.J. Fouch, D.E. James, and E. Humphreys **(2009)** "Shear wave splitting and the pattern of mantle flow beneath eastern Oregon," *Earth and Planetary Science Letters*, Vol. 288, No. 3-4, p.359

Long, M.D., and P.G. Silver **(2009)** "Mantle flow in subduction systems: The subslab flow field and implications for mantle dynamics," *Journal of Geophysical Research*, Vol. 114, p.12-11 - 12-25 doi: 10.1029/2008JB006200

Lou, X., S. van der Lee, and S. Lloyd **(2013)** "AIMBAT: A Python/Matplotlib Tool for Measuring Teleseismic Arrival Times," *Seismological Research Letters*, Vol. 84, No. 1, p.85-93 doi: 10.1785/0220120033

Lubick, N. **(2009)** "Seismology: The secret chatter of giant faults," *Nature*, Vol. 466, p.312-313 doi: 10.1038/466312a

Luo, Y., Y. Xu, and Y. Yang **(2011)** "Crustal structure beneath the Dabie orogenic belt from ambient noise tomography," *Earth and Planetary Science Letters*, Vol. 313-314, No. 0, p.12-22 doi: 10.1016/j.epsl.2011.11.004, MacCarthy, J.K., B. Borchers, and R.C. Aster **(2011)** "Efficient stochastic estimation of the model resolution matrix diagonal and generalized cross–validation for large geophysical inverse problems," *Journal of Geophysical Research*, Vol. 116, No B10304, p.8 doi: 10.1029/2011JB008234

Malagnini, L., K. Mayeda, S. Nielsen, S.-H. Yoo, I. Munafo', Ch. Rawles, and E. Boschi **(2013)** "Scaling Transition in Earthquake Sources: A Possible Link Between Seismic and Laboratory Measurements," *Pure and Applied Geophysics*, p.1-23 doi: 10.1007/s00024-013-0749-8

Malagnini, L., S. Nielsen, K. Mayeda, and E. Boschi **(2009)** "Energy radiation from intermediate- to large-magnitude earthquakes: Implications for dynamic fault weakening," *Journal of Geophysical Research*, Vol. 115, p.19-11 - 19-30 doi: 10.1029/2009JB006786

Marshall, J. **(2013)** "Geology: North America's broken heart," *Nature*, Vol. 504, p.24-26 doi: 10.1038/504024a

Mayeda, K., and L. Malagnini **(2009)** "Source radiation invariant property of local and near-regional shear-wave coda: Application to source scaling for the Mw 5.9 Wells, Nevada sequence," *Geophysical Research Letters*, Vol. 37, No. L07306, p.6-1 - 6-5 doi: 10.1029/2009GL042148

McNutt, Marcia **(2013)** "What Awaits the New NSF Director," *Science*, Vol. 342, No. 6163, p.1145 doi: 10.1126/science.1248875

Mendoza, C., and S. Hartzell **(2009)** "Source analysis using regional empirical Green's functions: The 2008 Wells, Nevada, earthquake," *Geophysical Research Letters*, Vol. 36, p.2-1 - 2-6 doi: 10.1029/2009GL038073

Meng, L., J.P. Ampuero, A. Sladen, and H. Rendon **(2012)** "High-resolution backprojection at regional distance: Application to the Haiti M7.0 earthquake and comparisons with finite source studies," *Journal of Geophysical Research: Solid Earth*, Vol. 117, No. B4, p.n/a doi: 10.1029/2011JB008702

Meng, L., A. Inbal, and J.P. Ampuero **(2011)** "A window into the complexity of the dynamic rupture of the 2011 Mw 9 Tohoku-Oki earthquake," *Geophysical Research Letters*, Vol. 38, No L00G07, p.6 doi: 10.1029/2011GL048118

Monteiller, V., and S. Chevrot **(2011)** "High-resolution imaging of the deep anisotropic structure of the San Andreas Fault system beneath southern California," *Geophysical Journal International*, Vol. 186, No. 2, p.418-446 doi: 10.1111/j.1365-246X.2011.05082.x

Mooney, W.D., J. Ritsema, and Y.K. Hwang **(2012)** "Crustal seismicity and the earthquake catalog maximum moment magnitude (Mcmax) in stable continental regions (SCRs): Correlation with the seismic velocity of the lithosphere," *Earth and Planetary Science Letters*, Vol. 357-358, No. 0, p.78-83 doi: 10.1016/j.epsl.2012.08.032

Moore‐Driskell, M., H.R. DeShon, W. Rabbel, M. Thorwart, Y. Dzierma, and I.G. Arroyo **(2013)** "Integration of Arrival‐Time Datasets for Consistent Quality Control: A Case Study of Amphibious Experiments along the Middle America Trench," *Bulletin of the Seismological Society of America*, Vol. 103, No. 5, p.2752-2766 doi: 10.1785/0120120274

Moschetti, M.P., M.H. Ritzwoller, F. Lin, and Y. Yang **(2009)** "Seismic evidence for widespread western-US deep-crustal deformation caused by extension," *Nature*, Vol. 464, No. 7290, p.885 doi: 10.1038/nature08951

Naliboff, J.B., C. Lithgow-Bertelloni, L.J. Ruff, and N. de Koker **(2011)** "The effects of lithospheric thickness and density structure on Earth's stress field," *Geophysical Journal International*, Vol. 188, No. 1, p.1-17 doi: 10.1111/j.1365-246X.2011.05248.x

Naliboff, J.B., C. Lithgow-Bertelloni, L.J. Ruff, and N. de Koker **(2012)** "The effects of lithospheric thickness and density structure on Earth's stress field," *Geophysical Journal International*, Vol. 188, No. 1, p.1-17 doi: 10.1111/j.1365-246X.2011.05248

Nereson, A., J. Stroud, K. Karlstrom, M. Heizler, and W. McIntosh **(2013)** "Dynamic topography of the western Great Plains: Geomorphic and 40Ar/39Ar evidence for mantle-driven uplift associated with the Jemez lineament of NE New Mexico and SE Colorado," *Geosphere*, Vol. 9, No. 3, p.521-545. doi: 10.1130/ges00837.1

Obayashi, M., J. Yoshimitsu, G. Nolet, Y. Fukao, H. Shiobara, H. Sugioka, H. Miyamachi, and Y. Gao **(2013)** "Finite frequency whole mantle P wave tomography: Improvement of subducted slab images," *Geophysical Research Letters*, Vol. 40, No. 21, p.5652-5657 doi: 10.1002/2013GL057401

Obrebski, M., R.M. Allen, F. Pollitz, and S.-H. Hung **(2011)** "Lithosphere–asthenosphere interaction beneath the western United States from the joint inversion of body-wave traveltimes and surface-wave phase velocities," *Geophysical Journal International*, Vol. 185, No. 2, p.1003-1021 doi: 10.1111/j.1365-246X.2011.04990.x

Obrebski, M., R.M. Allen, M. Xue, and S.H. Hung **(2009)** "Slab-plume interaction beneath the Pacific Northwest," *Geophysical Research Letters*, Vol. 37, No L14305, p. 5-1 - 5-6 doi: 10.1029/2010GL043489

Obrebski, M., F. Ardhuin, E. Stutzmann, and M. Schimmel **(2013)** "Detection of microseismic compressional (P) body waves aided by numerical modeling of oceanic noise sources," *Journal of Geophysical Research: Solid Earth*, Vol. 118, No. 8, p.4312-4324 doi: 10.1002/jgrb.50233

Pararas-Carayannis, G. **(2013)** "The Great Tohoku-Oki Earthquake and Tsunami of March 11, 2011 in Japan: A Critical Review and Evaluation of the Tsunami Source Mechanism," *Pure and Applied Geophysics*, p.1-22 doi: 10.1007/s00024-013-0677-7

Pasyanos, M.E. **(2011)** "A Case for the Use of 3D Attenuation Models in Ground-Motion and Seismic-Hazard Assessment," *Bulletin of the Seismological Society of America*, Vol. 101, No. 4, p.1965-1970 doi: 10.1785/0120110004

Pasyanos, M.E. **(2013)** "A Lithospheric Attenuation Model of North America," *Bulletin of the Seismological Society of America*, Vol. 103, No. 6, p.3321-3333 doi: 10.1785/0120130122

Pavlis, G.L., K. Sigloch, S. Burdick, M.J. Fouch, and F.L. Vernon **(2012)** "Unraveling the geometry of the Farallon plate: Synthesis of three-dimensional imaging results from USArray," *Tectonophysics*, Vol. 532-535, No. 0, p.82-102 doi: 10.1016/j.tecto.2012.02.008,

Perkins, Sid **(2013)** "Seismic data reveal 'hotspot' passed under United States," *Nature* doi: 10.1038/nature.2013.13746

Pinsky, V., T. Meirova, A. Levshin, A. Hofstetter, N. Kraeva, and M. Barmin **(2013)** "Imaging heterogeneity of the crust adjacent to the Dead Sea fault using ambient seismic noise tomography," *Journal of Seismology*, Vol. 17, No. 2, p.385-397 doi: 10.1007/s10950-012-9326-3

Pollitz, F.F., P. McCrory, D. Wilson, J. Svarc, C.M. Puskas, and R.B. Smith **(2009)** "Viscoelastic-cycle model of interseismic deformation in the northwestern United States," *Geophysical Journal International*, Vol. 181, No. 2, p.665 doi: 10.1111/j.1365-246X.2010.04546.x

Pollitz, F.F., and J.A. Snoke **(2009)** "Rayleigh-wave phase-velocity maps and three-dimensional shear velocity structure of the western US from local non-plane surface wave tomography," *Geophysical Journal International*, Vol. 180, No. 3, p.1153 doi: 10.1111/j.1365-246X.2009.04441.x

Poppeliers, C. **(2011)** "Multiwavelet Seismic-Wave Gradiometry," *Bulletin of the Seismological Society of America*, Vol. 101, No. 5, p.2108-2121 doi: 10.1785/0120100226

Porritt, R.W., R.M. Allen, D.C. Boyarko, and M.R. Brudzinski **(2011)** "Investigation of Cascadia segmentation with ambient noise tomography," *Earth and Planetary Science Letters*, Vol. 309, No. 1-2, p.67-76 doi: 10.1016/j.epsl.2011.06.026

Prieto, G.A., J.F. Lawrence, and G.C. Beroza **(2009)** "Anelastic Earth structure from the coherency of the ambient seismic field," *Journal of Geophysical Research*, Vol. 114, p. 3-1 - 3-15 doi: 10.1029/2008JB006067

R.A., Hutko, T. Lay, and J. Revenaugh **(2009)** "Localized double-array stacking analysis of PcP: D″ and ULVZ structure beneath the Cocos plate, Mexico, central Pacific, and north Pacific," *Physics of the Earth and Planetary Interiors*, Vol. 173, No. 1-2, p.60-74

Rau, C.J., and D.W. Forsyth **(2011)** "Melt in the mantle beneath the amagmatic zone, southern Nevada," *Geology*, Vol. 39, No. 10, p.975-978 doi: 10.1130/G32179.1

Rawlinson, N., and S. Fishwick **(2011)** "Seismic structure of the southeast Australian lithosphere from surface and body wave tomography," *Tectonophysics* Vol. In Press, No. 0 doi: 10.1016/j.tecto.2011.11.016

Rawlinson, N., and S. Fishwick **(2012)** "Seismic structure of the southeast Australian lithosphere from surface and body wave tomography," *Tectonophysics*, Vol. 572-573, No. 0, p.111-122 doi: 10.1016/j.tecto.2011.11.016

Reid, M.R., R.A. Bouchet, J. Blichert-Toft, A. Levander, K. Liu, M.S. Miller, and F.C. Ramos **(2012)** "Melting under the Colorado Plateau, USA," *Geology*, Vol. 40, No. 5, p.387-390 doi: 10.1130/G32619.1

Rieger, D.M., and J. Park **(2009)** "USArray observations of quasi-Love surface wave scattering: Orienting anisotropy in the Cascadia plate boundary," *Journal of Geophysical Research*, Vol. 115, No. B05306, p.15 doi: 10.1029/2009JB006754

Ringler, A.T., L S. Gee, B. Marshall, C.R. Hutt, and T. Storm **(2012)** "Data Quality of Seismic Records from the Tohoku, Japan, Earthquake as Recorded across the Albuquerque Seismological Laboratory Networks," *Seismological Research Letters*, Vol. 83, No. 3, p.575-584 doi: 10.1785/gssrl.83.3.575

Ringler, A.T., C.R. Hutt, J.R. Evans, and L.D. Sandoval **(2011)** "A Comparison of Seismic Instrument Noise Coherence Analysis Techniques," *Bulletin of the Seismological Society of America*, Vol. 101, No. 2, p.558-567 doi: 10.1785/0120100182

Ringler, A.T., C.R. Hutt, K. Persefield, and L.S. Gee **(2013)** "Seismic Station Installation Orientation Errors at ANSS and IRIS/USGS Stations," *Seismological Research Letters*, Vol. 84, No. 6, p.926-931 doi: 10.1785/0220130072

Ritzwoller, M.H., F.-C. Lin, and W. Shen **(2011)** "Ambient noise tomography with a large seismic array," *Comptes Rendus Geoscience*, Vol. 343, No. 8, p.558-570 doi: 10.1016/j.crte.2011.03.007

Rodgers, A.J., N.A. Petersson, and B. Sjogreen **(2009)** "Simulation of topographic effects on seismic waves from shallow explosions near the North Korean nuclear test site with emphasis on shear wave generation," *Journal of Geophysical Research*, Vol. 115, p.9-1 - 9-27 doi: 10.1029/2010JB007707

Romanowicz, B. **(2009)** "The Thickness of Tectonic Plates," *Science*, Vol. 324, No. 5926, p.474 - 476

Rost, S. **(2013)** "Deep Earth: Core-mantle boundary landscapes," *Nature Geoscience*, Vol. 6, No. 2, p.89-90 doi: 10.1038/ngeo1715

Rost, S., E.J. Garnero, M.S. Thorne, and A.R. Hutko **(2009)** "On the absence of an ultralow-velocity zone in the North Pacific," *Journal of Geophysical Research*, Vol. 115, No B04312, p. 12 doi: 10.1029/2009JB006420

Ruhl, C., S. L. Bilek, and J. Stankova-Pursley **(2009)** "Relocation and characterization of the August 2009 microearthquake swarm above the Socorro magma body in the central Rio Grande Rift," *Geophysical Research Letters*, Vol. 37, No. L23304, p.4-1 - 4-4 doi: 10.1029/2010GL045162

Ruigrok, E., T.D. Mikesell, and K. van Wijk **(2012)** "Scanning for velocity anomalies in the crust and mantle with diffractions from the core-mantle boundary," *Geophysical Research Letters*, Vol. 39, No. 11, p. n/a doi: 10.1029/2012GL051443

Rung-Arunwan, T., and W. Siripunvaraporn **(2009)** "An efficient modified hierarchical domain decomposition for two-dimensional magnetotelluric forward modelling," *Geophysical Journal International*, Vol. 183, No. 2, p.634. doi: 10.1111/j.1365-246X.2010.04768.x

S., Karin, and Mitchell G.M. **(2013)** "Intra-oceanic subduction shaped the assembly of Cordilleran North America," *Nature*, Vol. 496, p. 50-56 doi: 10.1038/nature12019

S.W., Nicholas **(2012)** "Yellowstone's Deep Roots " *Science*, Vol. 336, No. 6084, p.961 doi: 10.1126/science.336.6084.961-b

Satsukawa, T., K. Michibayashi, E.Y. Anthony, R.J. Stern, S.S. Gao, and K.H. Liu **(2011)** "Seismic anisotropy of the uppermost mantle beneath the Rio Grande rift: Evidence from Kilbourne Hole peridotite xenoliths, New Mexico," *Earth and Planetary Science Letters*, Vol. 311, No. 1-2, p.172 doi: 10.1016/j.epsl.2011.09.013

Schellart, W.P. **(2009)** "Reply to comment on the potential influence of subduction zone polarity on overriding plate deformation, trench," *Tectonophysics*, Vol. 463, No. 1, p.214

Schellart, W.P., and N. Rawlinson **(2009)** "Convergent plate margin dynamics: New perspectives from structural geology, geophysics and geodynamic modelling," *Tectonophysics*, Vol. 483, No. 1-2, p.4 doi: 10.1016/j.tecto.2009.08.030

Schmandt, B. **(2012)** "Mantle transition zone shear velocity gradients beneath USArray," *Earth and Planetary Science Letters*, Vol. 355-356, No. 0, p.119-130 doi: 10.1016/j.epsl.2012.08.031

Schmandt, B., K. Dueker, E.D. Humphreys, and S.E. Hansen **(2012)** "Hot mantle upwelling across the 660 beneath Yellowstone," *Earth and Planetary Science Letters*, Vol. 331-332, No. 0, p.224-236 doi: 10.1016/j.epsl.2012.03.025

Schmandt, B., and E.D. Humphreys **(2009)** "Complex subduction and small-scale convection revealed by body-wave tomography of the western United States upper mantle," *Earth and Planetary Science Letters*, Vol. 297, No. 3-4, p.435 doi: 10.1016/j.epsl.2010.06.047

Schmandt, B., and E.D. Humphreys **(2011)** "Seismically imaged relict slab from the 55 Ma Siletzia accretion to the northwest United States," *Geology*, Vol. 39, No. 2, p.175-178 doi: 10.1130/G31558.1

Schmerr, N., E.J. Garnero, and A. McNamara **(2009)** "Deep mantle plumes and convective upwelling beneath the Pacific Ocean," *Earth and Planetary Science Letters*, Vol. 294, No. 1-2, p.143 doi: 10.1016/j.epsl.2010.03.014

Schultz, C. **(2013)** "Agulhas Current leakage could stabilize Atlantic overturning circulation," *Eos, Transactions American Geophysical Union*, Vol. 94, No. 20, p.188-188 doi: 10.1002/2013EO200009

Schultz, C. **(2013)** "Long-distance induced tremor observed off western Canada," *Eos, Transactions American Geophysical Union*, Vol. 94, No. 20, p.188-188 doi: 10.1002/2013EO200008

Schultz, Colin **(2013)** "New technique could boost researchers' view of Earth's core," *Eos, Transactions American Geophysical Union*, Vol. 94, No. 20, p.188-188 doi: 10.1002/2013EO200010

Shen, W., M.H. Ritzwoller, and V. Schulte-Pelkum **(2013)** "Crustal and uppermost mantle structure in the central U.S. encompassing the Midcontinent Rift," *Journal of Geophysical Research: Solid Earth*, Vol. 118, No. 8, p.4325-4344 doi: 10.1002/jgrb.50321

Shen, W., M.H. Ritzwoller, and V. Schulte-Pelkum **(2013)** "A 3-D model of the crust and uppermost mantle beneath the Central and Western US by joint inversion of receiver functions and surface wave dispersion," *Journal of Geophysical Research: Solid Earth*, Vol. 118, No. 1, p.262-276 doi: 10.1029/2012JB009602

Shen, Y., Y. Ren, H. Gao, and B. Savage **(2012)** "An Improved Method to Extract Very-Broadband Empirical Green's Functions from Ambient Seismic Noise," *Bulletin of the Seismological Society of America*, Vol. 102, No. 4, p.1872-1877. doi: 10.1785/0120120023

Simmons, N.A., S.C. Myers, G. Johannesson, and E. Matzel **(2012)** "LLNL-G3Dv3: Global P wave tomography model for improved regional and teleseismic travel time prediction," *Journal of Geophysical Research: Solid Earth*, Vol. 117, No. B10, p. n/a doi: 10.1029/2012JB009525

Simons, M., S.E. Minson, A. Sladen, F. Ortega, J. Jiang, S.E. Owen, L. Meng, J.-P. Ampuero, S. Wei, R. Chu, D.V. Helmberger, H. Kanamori, E. Hetland, A.W. Moore, and F.H. Webb **(2011)** "The 2011 Magnitude 9.0 Tohoku-Oki Earthquake: Mosaicking the Megathrust from Seconds to Centuries," *Science*, Vol. 332, No. 6036, p.1421-1425 doi: 10.1126/science.1206731

Siripunvaraporn, W., and G. Egbert **(2009)** "WSINV3DMT: Vertical magnetic field transfer function inversion and parallel implementation," *Physics of the Earth and Planetary Interiors*, Vol. 173, No. 3, p.317

Siripunvaraporn, W., and W. Sarakorn **(2011)** "An efficient data space conjugate gradient Occam's method for three-dimensional magnetotelluric inversion," *Geophysical Journal International*, Vol. 186, No. 2, p.567-579 doi: 10.1111/j.1365-246X.2011.05079.x

Sit, S., M. Brudzinski, and H. Kao **(2012)** "Detecting tectonic tremor through frequency scanning at a single station: Application to the Cascadia margin," *Earth and Planetary Science Letters*, Vol. 353-354, No. 0, p.134-144 doi: 10.1016/j.epsl.2012.08.002

Smith, N.R.A, A.M. Reading, M.W. Asten, and C.W. Funk **(2013)** "Constraining depth to basement for mineral exploration using microtremor: A demonstration study from remote inland Australia," *Geophysics*, Vol. 78, No. 5, p. B227-B242 doi: 10.1190/geo2012-0449.1

Stachnik, J.C., A.F. Sheehan, D.W. Zietlow, Z. Yang, J. Collins, and A. Ferris **(2012)** "2012 SSA Annual Meeting Report

Determination of New Zealand Ocean Bottom Seismometer Orientation via Rayleigh-Wave Polarization," *Seismological Research Letters*, Vol. 83, No. 5, p.877-918 doi: 10.1785/0220120104 doi: 10.1785/0220110128

Steck, L.K., M.L. Begnaud, S. Phillips, and R. Stead **(2011)** "Tomography of crustal P and S travel times across the western United States," *Journal of Geophysical Research*, Vol. 116, No B11304, p.14 doi: 10.1029/2011JB008260

Stein, S., M. Liu, E. Calais, and Q. Li **(2009)** "Mid-Continent Earthquakes as a Complex System," *Seismological Research Letters*, Vol. 80, No. 4, p.551-553 doi: 10.1785/gssrl.80.4.551

Steltenpohl, M.G., I. Zietz, J.W.Jr. Horton, and D.L. Daniels **(2009)** "New York-Alabama lineament: A buried right-slip fault bordering the Appalachians and mid-continent North America," *Geology*, Vol. 38, No. 6, p.571-574 doi: 10.1130/g30978.1

Sufri, O., K.D. Koper, and T. Lay **(2012)** "Along-dip seismic radiation segmentation during the 2007 Mw 8.0 Pisco, Peru earthquake," *Geophysical Research Letters*, Vol. 39, No. 8, p.n/a doi: 10.1029/2012GL051316

Sun, D., and D.V. Helmberger **(2011)** "Upper-mantle structures beneath USArray derived from waveform complexity," *Geophysical Journal International*, Vol. 184, No. 1, p.416-438 doi: 10.1111/j.1365-246X.2010.04847.x

Taira, T., R.B. Smith, and W.L. Chang **(2009)** "Seismic evidence for dilatational source deformations accompanying the 2004–2008 Yellowstone accelerated uplift episode," *Journal of Geophysical Research*, Vol. 115, No B02301, p.1-1 - 1-16 doi: 10.1029/2008JB006281

Takeuchi, N., and K. Obara **(2009)** "Fine-scale topography of the D'' discontinuity and its correlation to volumetric velocity fluctuations," *Physics of the Earth and Planetary Interiors*, Vol. 183, No. 1-2, p.126 doi: 10.1016/j.pepi.2010.06.002

Tape, C., Q. Liu, A. Maggi, and J. Tromp **(2009)** "Seismic tomography of the Southern California crust based on spectral-element and adjoint methods," *Geophysical Journal International*, Vol. 180, No. 1, p.433 doi: 10.1111/j.1365-246X.2009.04429.x

Tape, C., A. Plesch, J.H. Shaw, and H. Gilbert **(2012)** "Estimating a Continuous Moho Surface for the California Unified Velocity Model," *Seismological Research Letters*, Vol. 83, No. 4, p.728-735 doi: 10.1785/0220110118

Tauzin, B., R.D. van der Hilst, G. Wittlinger, and Y. Ricard **(2013)** "Multiple transition zone seismic discontinuities and low velocity layers below western United States," *Journal of Geophysical Research: Solid Earth*, Vol. 118, No. 5, p.2307-2322 doi: 10.1002/jgrb.50182

Thorne, M.S., E.J. Garnero, G. Jahnke, He Igel, and A.K. McNamara **(2013)** "Mega ultra low velocity zone and mantle flow," *Earth and Planetary Science Letters*, Vol. 364, No. 0, p.59-67 doi: 10.1016/j.epsl.2012.12.034

Thorne, M.S., Y. Zhang, and J. Ritsema **(2013)** "Evaluation of 1-D and 3-D seismic models of the Pacific lower mantle with S, SKS, and SKKS traveltimes and amplitudes," *Journal of Geophysical Research: Solid Earth*, Vol. 118, No. 3, p.985-995 doi: 10.1002/jgrb.50054

Tian, T., K. Sigloch, and N. Nolet **(2009)** "Multiple-frequency SH-wave tomography of the western US upper mantle," *Geophysical Journal International*, Vol. 178, No. 3, p.1384-1402

Tian, Y., W. Shen, and M.H. Ritzwoller **(2013)** "Crustal and uppermost mantle shear velocity structure adjacent to the Juan de Fuca Ridge from ambient seismic noise," *Geochemistry, Geophysics, Geosystems*, Vol. 14, No. 8, p.3221-3233 doi: 10.1002/ggge.20206

Tian, Y., and D. Zhao **(2012)** "P-wave tomography of the western United States: Insight into the Yellowstone hotspot and the Juan de Fuca slab," *Physics of the Earth and Planetary Interiors*, Vol. 200-201, No. 0, p.72-84 doi: 10.1016/j.pepi.2012.04.004

Tian, Y., Y. Zhou, K. Sigloch, G. Nolet, and G. Laske **(2011)** "Structure of North American mantle constrained by simultaneous inversion of multiple-frequency SH, SS, and Love waves," *Journal of Geophysical Research*, Vol. 116, No. B02307, p.18 doi: 10.1029/2010JB007704

Tibuleac, I.M., and D. von Seggern **(2012)** "Crust–mantle boundary reflectors in Nevada from ambient seismic noise autocorrelations," *Geophysical Journal International*, Vol. 189, No. 1, p.493-500 doi: 10.1111/j.1365-246X.2011.05336

Tibuleac, I.M., D.H. von Seggern, J.G. Anderson, and J.N. Louie **(2011)** "Computing Green's Functions from Ambient Noise Recorded by Accelerometers and Analog, Broadband, and Narrow-Band Seismometers," *Seismological Research Letters*, Vol. 82, No. 5, p.661-675 doi: 10.1785/gssrl.82.5.661

Tollefson, J. **(2013)** "Oil recovery may have triggered Texas tremors," *Nature* doi: 10.1038/nature.2013.1408

Trabant, C., A.R. Hutko, M. Bahavar, R. Karstens, T. Ahern, and R. Aster **(2012)** "Data Products at the IRIS DMC: Stepping Stones for Research and Other Applications," *Seismological Research Letters*, Vol. 83, No. 5, p.846-854 doi: 10.1785/0220120032

Traer, J., P. Gerstoft, P.D. Bromirski, and P.M. Shearer **(2012)** "Microseisms and hum from ocean surface gravity waves," *Journal of Geophysical Research: Solid Earth*, Vol. 117, No B11, p. n/a doi: 10.1029/2012JB009550

Tsai, V.C., and M.P. Moschetti **(2009)** "An explicit relationship between time-domain noise correlation and spatial autocorrelation (SPAC) results," *Geophysical Journal International*, Vol. 182, No. 1, p.454 doi: 10.1111/j.1365-246X.2010.04633.x

Uchide, T., H. Yao, and P.M. Shearer **(2013)** "Spatio-temporal distribution of fault slip and high-frequency radiation of the 2010 El Mayor-Cucapah, Mexico earthquake," *Journal of Geophysical Research: Solid Earth*, Vol. 118, No. 4, p.1546-1555 doi: 10.1002/jgrb.50144

Uhrhammer, R.A., M. Hellweg, K. Hutton, P. Lombard, A.W. Walters, E. Hauksson, and D. Oppenheimer **(2011)** "California Integrated Seismic Network (CISN) Local Magnitude Determination in California and Vicinity," *Bulletin of the Seismological Society of America*, Vol. 101, No. 6, p.2685-2693 doi: 10.1785/0120100106

Van Leeuwen, T., and W.A. Mulder **(2009)** "A correlation-based misfit criterion for wave-equation traveltime tomography," *Geophysical Journal International*, Vol. 182, No. 3, p.1383 doi: 10.1111/j.1365-246X.2010.04681.x

van Wijk, K. , T.D. Mikesell, V. Schulte-Pelkum, and J. Stachnik **(2011)** "Estimating the Rayleigh-wave impulse response between seismic stations with the cross terms of the Green tensor," *Geophysical Research Letters*, Vol. 38, No. L16301, p.4 doi: 10.1029/2011GL047442

Wagner, L., D.W. Forsyth, M.J. Fouch, and D.E. James **(2009)** "Detailed three-dimensional shear wave velocity structure of the northwestern United States from Rayleigh wave tomography," *Earth and Planetary Science Letters*, Vol. 299, No. 3-4, p.273 doi: 10.1016/j.epsl.2010.09.005

Wagner, L.S., and M.D. Long **(2013)** "Distinctive upper mantle anisotropy beneath the High Lava Plains and Eastern Snake River Plain, Pacific Northwest, USA," *Geochemistry, Geophysics, Geosystems*, Vol. 14, No. 10, p.4647-4666. doi: 10.1002/ggge.20275

Wagner, Lara S., Maureen D. Long, Mignon D. Johnston, and Margaret H. Benoit **(2012)** "Lithospheric and asthenospheric contributions to shear-wave splitting observations in the southeastern United States," *Earth and Planetary Science Letters*, Vol. 341-44, No. 0, p.128-138 doi: 10.1016/j.epsl.2012.06.020

Walker, K., R. Shelby, M. Hedlin, A.H., C. de Groot-Hedlin, and F.L. Vernon **(2011)** "Western U.S. Infrasonic Catalog: Illuminating infrasonic hot spots with the USArray," *Journal of Geophysical Research*, Vol. 116, No. B12305, p.15 doi: 10.1029/2011JB008579

Walker, K.T., M.A.H. Hedlin, C. de Groot-Hedlin, J. Vergoz, A. Le Pichon, and D.P. Drob **(2009)** "Source location of the 19 February 2008 Oregon bolide using seismic networks and infrasound arrays," *Journal of Geophysical Research*, Vol. 115, No. B12329, p.17 doi: 10.1029/2010JB007863

Walker, K.T., R. Shelby, Mi.A.H. Hedlin, C. de Groot-Hedlin, and F.L. Vernon **(2011)** "Western U.S. Infrasonic Catalog: Illuminating infrasonic hot spots with the USArray," *Journal of Geophysical Research*, Vol. 116, No. B12305, p.15 doi: 10.1029/2011JB008579

Wang, D., and J. Mori **(2011)** "Frequency-dependent energy radiation and fault coupling for the 2010 Mw8.8 Maule, Chile, and 2011 Mw9.0 Tohoku, Japan, earthquakes," *Geophysical Research Letters*, Vol. 38, No. L22308, p.6 doi: 10.1029/2011GL049652

Wang, R., B. Schurr, C. Milkereit, Z. Shao, and M. Jin **(2011)** "An Improved Automatic Scheme for Empirical Baseline Correction of Digital Strong-Motion Records," *Bulletin of the Seismological Society of America*, Vol. 101, No. 5, p.2029-2044 doi: 10.1785/0120110039

Wannamaker, P.E., T.G. Caldwell, G.R. Jiracek, V. Maris, G.J. Hill, Y. Ogawa, H.M. Bibby, S.L. Bennie, and W. Heise **(2009)** "Fluid and deformation regime of an advancing subduction system at Marlborough, New Zealand," *Nature*, Vol. 460, p.733-736

Wapenaar, K., E. Ruigrok, J. van der Neut, and D. Draganov **(2011)** "Improved surface-wave retrieval from ambient seismic noise by multi-dimensional deconvolution," *Geophysical Research Letters*, Vol. 38, No. L01313, p.5 pp. doi: 10.1029/2010GL045523

Weemstra, C., L. Boschi, A. Goertz, and B. Artman **(2013)** "Seismic attenuation from recordings of ambient noise," *Geophysics*, Vol. 78, No. 1, p. Q1-Q14 doi: 10.1190/geo2012-0132.1

Wei, S., R. Graves, D.V. Helmberger, J.-P. Avouac, and J. Jiang **(2012)** "Sources of shaking and flooding during the Tohoku-Oki earthquake: A mixture of rupture styles," *Earth and Planetary Science Letters*, Vol. 333-334, No. 0, p.91 doi: 10.1016/j.epsl.2012.04.006

Weidle, C., V. Maupin, J. Ritter, T. Kvaerna, J. Schweitzer, N. Balling, H. Thybo, J.I. Faleide, and F. Wenzel **(2009)** "MAGNUS--A Seismological Broadband Experiment to Resolve Crustal and Upper Mantle Structure beneath the Southern Scandes Mountains in Norway," *Seismological Research Letters*, Vol. 81, No. 1, p.76-84 doi: 10.1785/gssrl.81.1.76

West, J.D., and M.J. Fouch **(2012)** "EMERALD: A Web Application for Seismic Event Data Processing," *Seismological Research Letters*, Vol. 83, No. 6, p.1061-1067 doi: 10.1785/0220110138

West, J.D., M.J. Fouch, J.B. Roth, and L.T. Elkins-Tanton **(2009)** "Vertical mantle flow associated with a lithospheric drip beneath the Great Basin," *Nature Geoscience*, Vol. 2, No. 6, p.439

Williams, M.C., A.M. Trehu, and J. Braunmiller **(2011)** "Seismicity at the Cascadia Plate Boundary beneath the Oregon Continental Shelf," *Bulletin of the Seismological Society of America*, Vol. 101, No. 3, p.940-950 doi: 10.1785/0120100198

Witze, A. **(2013)** "US seismic array eyes its final frontier," *Nature*, Vol. 503, No. 7474, p.16-17 doi: 10.1038/503016a

Wolin, E., S. Stein, F. Pazzaglia, A. Meltzer, A. Kafka, and C. Berti **(2012)** "Mineral, Virginia, earthquake illustrates seismicity of a passive-aggressive margin," *Geophysical Research Letters*, Vol. 39, No. 2, p. n/a doi: 10.1029/2011GL050310

Xu, Z., P. Chen, and Y.-G. Chen **(2013)** "Sensitivity Kernel for the Weighted Norm of the Frequency-Dependent Phase Correlation," *Pure and Applied Geophysics*, Vol. 170, No. 3, p.353-371 doi: 10.1007/s00024-012-0507-3

Xue, M., and R.M. Allen **(2009)** "Mantle structure beneath the western United States and its implications for convection processes," *Journal of Geophysical Research*, Vol. 115, No. B07303, p.26 doi: 10.1029/2008JB006079

Yagi, Y., A. Nakao, and A. Kasahara **(2012)** "Smooth and rapid slip near the Japan Trench during the 2011 Tohoku-oki earthquake revealed by a hybrid back-projection method," *Earth and Planetary Science Letters*, Vol. 355-356, No. 0, p.94-101 doi: 10.1016/j.epsl.2012.08.018,

Yao, H., P. Gerstoft, P.M. Shearer, and C. Mecklenbräuker **(2011)** "Compressive sensing of the Tohoku-Oki Mw 9.0 earthquake: Frequency-dependent rupture modes," *Geophysical Research Letters*, Vol. 38, No. L20310, p.5 doi: 10.1029/2011GL049223

Yao, H., P.M. Shearer, and P. Gerstoft **(2012)** "Subevent location and rupture imaging using iterative backprojection for the 2011 Tohoku Mw 9.0 earthquake," *Geophysical Journal International*, Vol. 190, No. 2, p.1152-1168 doi: 10.1111/j.1365-246X.2012.05541

Yao, H., and R.D. van der Hilst **(2009)** "Analysis of ambient noise energy distribution and phase velocity bias in ambient noise tomography, with application to SE Tibet," *Geophysical Journal International*, Vol. 179, No. 2, p.1113-1132

Ye, L., T. Lay, and H. Kanamori **(2013)** "Ground Shaking and Seismic Source Spectra for Large Earthquakes around the Megathrust Fault Offshore of Northeastern Honshu, Japan," *Bulletin of the Seismological Society of America*, Vol. 103, No. 2B, p.1221-1241 doi: 10.1785/0120120115

Yong, A., S.E. Hough, J. Iwahashi, and A. Braverman **(2012)** "A Terrain-Based Site-Conditions Map of California with Implications for the Contiguous United States," *Bulletin of the Seismological Society of America*, Vol. 102, No. 1, p.114-128 doi: 10.1785/0120100262

Yoo, S.-H., and K. Mayeda **(2013)** "Validation of Non-Self-Similar Source Scaling Using Ground Motions from the 2008 Wells, Nevada, Earthquake Sequence," *Bulletin of the Seismological Society of America*, Vol. 103, No. 4, p.2508-2519 doi: 10.1785/0120120327

Yoshizawa, K., and G. Ekström **(2009)** "Automated multimode phase speed measurements for high-resolution regional-scale tomography: application to North America," *Geophysical Journal International*, Vol. 183, No. 3, p.1538-1558 doi: 10.1111/j.1365-246X.2010.04814.x

Yuan, H., and B. Romanowicz **(2009)** "Depth dependent azimuthal anisotropy in the western US upper mantle," *Earth and Planetary Science Letters*, Vol. 300, No. 3-4, p.385 doi: 10.1016/j.epsl.2010.10.020

Yuan, H., and B. Romanowicz **(2009)** "Lithospheric layering in the North American craton," *Nature*, Vol. 466, No. 7310, p.1063 doi: 10.1038/nature09332

Zahradnik, J., and S. Custidio **(2012)** "Moment Tensor Resolvability: Application to Southwest Iberia," *Bulletin of the Seismological Society of America*, Vol. 102, No. 3, p.1235-1254 doi: 10.1785/0120110216

Zaroli, C., E. Debayle, and M. Sambridge **(2009)** "Frequency-dependent effects on global S-wave traveltimes: wavefront-healing, scattering and attenuation," *Geophysical Journal International*, Vol. 182, No. 2, p.1025 doi: 10.1016/j.epsl.2010.06.002

Zha, Y., S.C. Webb, and W. Menke **(2013)** "Determining the orientations of ocean bottom seismometers using ambient noise correlation," *Geophysical Research Letters*, Vol. 40, No. 14, p.3585-3590 doi: 10.1002/grl.50698

Zhan, Z., S. Wei, S. Ni, and D.V. Helmberger **(2011)** "Earthquake Centroid Locations Using Calibration from Ambient Seismic Noise," *Bulletin of the Seismological Society of America*, Vol. 101, No. 3, p.1438-1445 doi: 10.1785/0120100118

Zhang, H., P. Wang, R.D. van der Hilst, M.N. Toksoz, C. Thurber, and L. Zhu **(2009)** "Three-dimensional passive seismic waveform imaging around the SAFOD site, California, using the generalized Radon transform," *Geophysical Research Letters*, Vol. 36, No. 23, p.8-1 - 8-6 doi: 10.1029/2009GL040372

Zhang, J., and A.W. Frederiksen **(2013)** "3-D crust and mantle structure in southern Ontario, Canada via receiver function imaging," *Tectonophysics*, Vol. 608, No. 0, p.700-712. doi: 10.1016/j.tecto.2013.08.011

Zhang, Ji, and X. Yang **(2013)** "Extracting surface wave attenuation from seismic noise using correlation of the coda of correlation," *Journal of Geophysical Research: Solid Earth*, Vol. 118, No. 5, p.2191-2205 doi: 10.1002/jgrb.50186

Zhang, X., H. Paulssen, S. Lebedev, and T. Meier **(2009)** "3D shear velocity structure beneath the Gulf of California from Rayleigh wave dispersion," *Earth and Planetary Science Letters*, Vol. 279, No. 3, p.255

Zhdanov, M.S., R.B. Smith, A. Gribenko, M. Cuma, and M. Green **(2011)** "Three-dimensional inversion of large-scale EarthScope magnetotelluric data based on the integral equation method: Geoelectrical imaging of the Yellowstone conductive mantle plume," *Geophysical Research Letters*, Vol. 38, No. L08307, p.7 doi: 10.1029/2011GL046953

Zheng, Y., J. Li, Z. Xie, and M.H. Ritzwoller **(2012)** "5Hz GPS seismology of the El Mayor–Cucapah earthquake: estimating the earthquake focal mechanism," *Geophysical Journal International*, Vol. 190, No. 3, p.1723-1732 doi: 10.1111/j.1365-246X.2012.05576.x

Zheng, Z., and B. Romanowicz **(2012)** "Do double 'SS precursors' mean double discontinuities?" *Geophysical Journal International*, Vol. 191, No. 3, p.1361-1373 doi: 10.1111/j.1365-246X.2012.05683

Zhou, L., J. Xie, W. Shen, Y. Zheng, Y. Yang, H. Shi, and H. Ritzwoller **(2012)** "The structure of the crust and uppermost mantle beneath South China from ambient noise and earthquake tomography," *Geophysical Journal International*, Vol. 189, No. 3, p.1565-1583 doi: 10.1111/j.1365-246X.2012.05423

Zhou, L., C. Zhao, Z. Chen, and S. Zheng **(2011)** "Amplitude Tomography of Lg Waves in Xinjiang and Its Adjacent Regions," *Bulletin of the Seismological Society of America*, Vol. 101, No. 3, p.1302-1314 doi: 10.1785/0120100267

Zucca, J.J., W.R. Walter, A.J. Rodgers, P. Richards, M.E. Pasyanos, S.C. Myers, T. Lay, D. Harris, and T. Antoun **(2009)** "The Prospect of Using Three-Dimensional Earth Models to Improve Nuclear Explosion Monitoring and Ground-motion Hazard Assessment," *Seismological Research Letters*, Vol. 80, No. 1, p.31-39 doi: 10.1785/gssrl.80.1.31

Appendix C. List of USArray Data Users

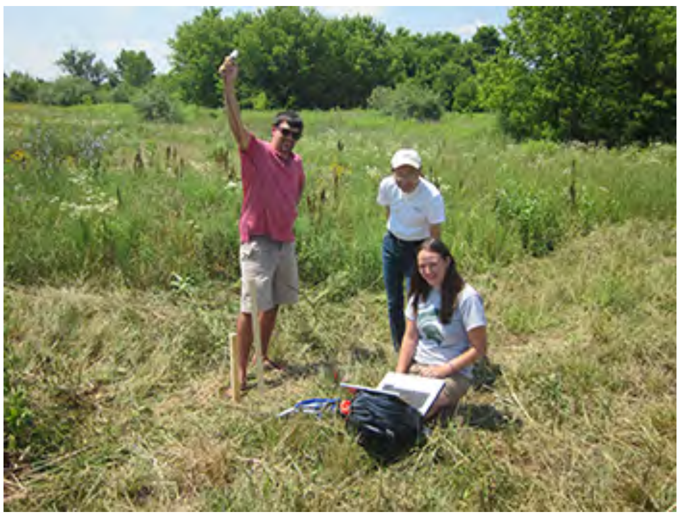
(Please see the separately uploaded document.)

USArray Stories from the Field

By Maia ten Brink

Ben Johnson: Student Siter

Ben Johnson was kneeling in a stranger's backyard, setting a stake in the ground to mark the spot for a seismometer. He and his partner Jamie Ryan, both geology undergraduates at Michigan State University, had spent a day and a half on the outskirts of Lansing, going door-to-door, looking for property far from all human activity. They were siting locations for 25 seismometer stations in a grid across eastern Michigan. Their region was just one patch in a quilt of seismometers called USArray that would cover the United States with over a thousand seismic stations spaced every 70 kilometers.


Ben, Jamie, and Professor Fujita inspect a potential site.

It was Johnson's first site; he was a little nervous about getting it right. As he bent down to hammer the stake, he backed his rear end against the electric fence around the landowner's donkey pen. ZAP! He stood up like a shot, not quite sure what had happened. He wasn't hurt, but felt a little shaken. For the rest of the day, he said, "I was just not the same."

That summer of 2011, teams of geology students like Johnson and Ryan racked up over 8000 kilometers driving around the Midwest, knocking on doors at ranches, farms, and rural properties. Each group of two or three students had to find 25 landowners willing to let scientists dig a refrigerator-sized hole on their property and leave a seismometer buried in the ground for two years. The students had two and a half months, some maps, a laptop, a car, and a cell modem. Go.

Finding a suitable site had been harder than Johnson expected. He and Ryan had scoped out possible locations using Google Earth's satellite images, but some landowners turned them away or weren't home, and some sites turned out to be too "noisy" to host a seismometer. The seismometers used in the USArray are sensitive enough to register small earthquakes on the other side of the world, trains passing eight to thirteen kilometers away, and even trees shaking the earth as they bend in the wind.

After an unsuccessful morning, Johnson stopped at a house with a porch cluttered with children's toys. Johnson had to work up the courage to approach; he hadn't gone door-to-door since selling popcorn in the Boy Scouts. He picked his way around the plastic cars on the porch and rang the doorbell at what appeared to be the front door. No one answered. As he got back in the car, a man came out from behind the house and stared at him. Johnson hissed to his partner, "What do I do? Should I go talk to him? Should we just get out of here? He doesn't look very happy to see us." Ryan pushed Johnson to go introduce himself.

"Hey, my name is Ben and this is Jamie. We're geologists from Michigan State," said Johnson, holding out his hand to the man. He mentioned Michigan State because he wanted landowners to feel connected to a local institution. "We're working on a large earthquake survey and we're installing sensors to monitor earthquakes. We're looking for somewhere out in the middle of nowhere, where we're not bothering anybody, where we can place an instrument for two years. You seem to have some property out there. We're potentially looking at your property for a site. Is this something you would be interested in?"

The landowner, Rick, was a mechanic working nights. He had been at the back of the house and missed the doorbell. He took care of his child during the day, played violin in his spare time, and had a niece at Michigan State. He smiled and immediately offered to show them his land, which he used to grow hay for his donkey and horse. Johnson and Ryan pulled out their instruments to assess the site — checking the soil, measuring the distance to the house and trees, looking for signs of animals, finding an electricity source, assessing shade to make sure that the station's solar panels would function, and using their cell modem and laptop to measure the strength of the cellular signal to ensure that real-time data could be sent from the seismometer to be aggregated and analyzed in San Diego. That was when Johnson bumped his rump into the electric fence.

That site was a shock to Johnson in more ways than one. "It was so eye-opening to me. I had this pre-conceived notion that people in the country wanted to be left alone and didn't want to be bothered, especially by some government-funded project, but people were really understanding," he said.

With practice, Johnson streamlined his pitch and the team's success rate improved. He focused on making personal connections and told them they would be part of a massive national science experiment. Johnson and Ryan also developed a finely tuned intuition about which houses to approach — almost a superstition. They looked for fields growing hay or lying fallow, properties larger than 40 acres, short driveways, and friendly animals. “I had to have a certain feeling about a house. There were a lot of houses we drove by and it was strictly based on a feeling,” Johnson said. The closer to the metro-Detroit area, the more hesitant and protective the landowners were. In the north, Johnson found landowners were more laid-back and had more available land. If people were home, Johnson estimated, 75% of the time they said yes.

“When I went through the workshop, I thought, ‘There’s no way this is as successful as they say it is.’” But Johnson and Ryan met schoolteachers, engineers, truck drivers, farmers, and war veterans who were willing and excited to host a seismic station. The team spent half a day talking to a hippie from the University of Michigan. They met up with a guy toting a large rock (“I figured, you’re geologists; you’d find me because I had this big rock with me”) in a tavern called Fisherman’s Happy Hour. They put a site near a cherry orchard at the northwest tip of the Michigan mitten, overlooking both Lake Michigan and the Grand Traverse Bay. They walked up to a house where a man was slaughtering chickens, his pants covered in guts. His dog ran up to them, chewing on a chicken foot. Ryan, who was a vegetarian and an animal-lover, looked a little queasy.

“We had a lady in one of the towns, she served us ice cream. I thought she was going to invite us to the family reunion that she had to go to,” Johnson said. “Some people were like, ‘Yeah, whatever. I’m going to the store. Help yourself to the fridge. Do whatever you want to do.’ And then there were some people who were really interested, and they wanted to talk to you.”

Near Saginaw, they spoke to a mother with two daughters. When Johnson explained that the girls could jump up and down beside the seismometer and then look online to see the vibration appear as a wiggle on the live seismogram, the older daughter immediately ran to look up the IRIS website. “I was telling her all about seismic waves. To me, that was a really special moment,” Johnson said. “People had been interested, but to see somebody young like that getting excited about earthquakes was really great.”

For two months, Johnson and Ryan meandered around the state, spending hours at the wheel of their rented Dodge Caliber, listening to Rush Limbaugh or the same 40 pop songs repeated on every radio station. Most nights, they stopped to sleep in EconoLodges. Johnson is a native of Grand Rapids, Michigan, but he visited parts of the state he’d never heard of. Ryan always got excited about roadside attractions. “I think her positive attitude toward being on the road really helped my positive attitude," Johnson said. They visited a covered bridge in Frankenbuth, a year-round Christmas town known as "Michigan's Little Bavaria" with a Cheese Haus and gift shops selling leiderhosen. They went swimming in both Lake Huron and Lake Michigan. They climbed a drumlin hill on the Leelanau Peninsula, formed when glaciers retreated back over the Canadian border around 10,000 years ago.

"When I look back on it, I miss the job. It was sort of gratifying because you had this big map in your office, and you had so many sites that you had to get. It was clear. When you completed the goal, you accomplished something," Johnson said. "It's completely different from science. There's nothing tangible about completing something in science. It was such a nice relief for me." (He laughed a little ruefully as he said this; he's now a graduate student studying structural geology at West Virginia University.)

Johnson and Ryan would submit reconnaissance reports for their finished sites online and check the progress of other teams they had met back in May at IRIS' student siting workshop. "It was a big race to be the first ones finished. I think that's also what bonded Jamie and I. We wanted to do a good job because we had this competitive feeling that, if we're not out getting a site, Indiana is going to get ahead of us by two sites."

Working so closely with Ryan prepared Johnson for other team efforts. He said, "We spent all that time trying to figure out where our strengths and weaknesses were in that dynamic. Jamie was always really quiet, but she was super organized. She did a lot of the pre-assessment of sites, looking on Google Earth, finding potential sites. Me, I was the outgoing one. I would initiate the conversations, but Jamie was always there to correct me when I had something wrong, keeping us on task. She filled in all the holes." She was also good with animals. "When dogs came up and were barking aggressively—I called her the Dog Whisperer—she could always calm the animal down, get the animal to warm up to us," Johnson remembers.

Even though he started the summer dreading interactions with strangers, Johnson learned how to talk to just about anybody. "It was as much a random sample of the public in the state of Michigan as you could possibly get. There was just a wide range of people with different backgrounds. Being able to convey the basic idea behind a really large, complicated national project was definitely a skill I will always carry with me."

James Taylor: Seismic Locator for EarthScope, Summer 2010

James Taylor, a geology student at Auburn University in Alabama, used to be terrified of public speaking. He swore it off after he coughed through a speech in eighth grade, and he got almost all the way through his undergraduate career at Auburn without having to speak in front of strangers. One day during his senior year, however, geology professor Dr. Lorraine Wolf emailed about a summer job that required students to approach landowners all over Alabama and ask them to participate in a national seismology experiment called EarthScope. At first, Taylor dismissed the email, but then he began to wonder if it might help him come out of his shell. He was considering graduate school and knew he would have to teach a roomful of students. “I thought it was going to give me some opportunities to learn how to talk to people one-on-one and it would keep me out of my comfort zone,” Taylor said.

Now he includes “Seismic site locator for EarthScope, Summer 2010” on every resume. “When people ask me about it, I can’t shut up about it. It was a big thing in my life,” he said.

James Taylor (left) and Stan Ingram (right).

Taylor was paired with Stan Ingram, a geology graduate student at the University of Alabama, to find 23 seismometer sites throughout the state. They quickly hit on a strategy to connect to landowners: play to the football teams. Alabama is split by a fierce football rivalry between Auburn University and the University of Alabama.

Taylor, in his Auburn hat, and Ingram, in his Crimson Tide hat, would drive up to a house in their white Chevy Impala with a University of Alabama magnet on the door. (Taylor enjoyed the shocked looks elicited when someone saw him wearing his Auburn hat while driving the Alabama car.) If Taylor and Ingram saw any crimson flags, signs, or elephants indicating a diehard Alabama fan, Ingram would make the first overture. If Auburn’s orange and navy blue colors hailed them in the front yard, Taylor would do the knocking and talking. “They were usually pretty nice, but there were some people that would just talk to him and some people that would just talk to me. That’s how bitter the rivalry was,” he said.

Many landowners would usher Taylor and Ingram into sitting rooms dedicated to their chosen team. In central Alabama, one man showed them an impressive “Alabama room” painted crimson and bedecked with team photos, watercolor prints of famous plays, lots of houndstooth, and elephant memorabilia.

When they first pulled up to his home, they saw a shirtless giant in the yard with his granddaughter. “He must’ve been about seven foot tall. He’s probably in his sixties, but he’s the most ripped person I’ve ever seen,” said Taylor.

“Can I help you?” asked the man in a deep, threatening voice. He pushed his granddaughter behind him.

“I almost turned around; he looked really intimidating,” recalled Taylor. “But a couple of hours later, we were best buddies with this guy.” The man revealed that he had been an Olympic javelin thrower once ranked third in the country. He described his favorite full-body workout: beating on one of the old tractor tires lying around his yard with a wood splitter until he tired out. “I wouldn’t have wanted to be his enemy,” Taylor said.

Most people invited Taylor and Ingram into their homes even if they could not host a seismometer station. Taylor, a Cincinnati native, appreciated the Southern hospitality. “If I were in Ohio, I would have been getting doors slammed in my face,” he said.

The optimal place to put a seismometer was in the middle of cleared fields, but farms could rarely spare the space for a seismometer in a seven-foot-deep vault. Taylor and Ingram got their first site with the help of the Alabama Cattleman’s Association, which boasted a chapter in every county. A retired couple in northern Alabama couldn’t host a site themselves, but drove Taylor and Ingram down to the local Cattleman’s Association cattle show and introduced them to the president of the local chapter. The chapter president took them out in his pasture to discuss possible locations for the seismometer. The cattle came running to investigate.

“Cows can look cute, but it gets to be intimidating when they come in groups. You get a big wall of animal,” said Taylor. “They are not going to move if they don’t want to.” The chapter president carried a large whip and cracked it in the air to disperse the cattle. “I was sitting there thinking, ‘Oh my goodness. No sudden movements,’” said Taylor.

“We did end up saving a cow,” he remembered. Somebody answered the door in central Alabama with a British accent. Taylor’s first thought was, “Where am I?” It turned out that the family who owned the property did horseback fox-hunting, a traditional aristocratic sport that is no longer legal in Britain. They gave Taylor and Ingram free reign to roam the grounds to find a good seismometer site. The team located a low spot, blocked from the road by trees. There they found a cow up to its back in mud. “It was a little bit emaciated; it had been there for a while,” Taylor said. “They would never have seen it if we weren’t out strolling around.” The family called the fire department and pulled the cow out of the muck.

Taylor encountered a menagerie of animals, including horses, sheep, goats, and catfish. He saw his first wild bald eagle while siting in timberlands in west central Alabama. Outside Birmingham, a medical doctor took them to a small piece of property tucked away behind his house. The doctor gave them a look and then asked, “Have you ever seen a zonkey?” He introduced them to his pet zebra-donkey hybrid. Taylor and Ingram staked out a seismometer site next to the zonkey.

Sometimes they would run across stray dogs. He explained, “You always have to be careful because you’re not sure which dogs are friendly and which dogs aren’t. People will train dogs for dogfighting. A lot of times, if a dog loses a fight, they will just get rid of it. It’s terrible.” Taylor’s father operates a hunting lodge in Midway, Alabama, and hosted an EarthScope seismometer on his property. Taylor said that a hunter at his father’s lodge found nine pit bulls over the course of a week.

Even pets could be vicious. “There was somebody’s house,” remembered Taylor, “where I pulled into the driveway and there were two Rottweilers. They were coming up the car door and about to bite the tire off. I just backed out and left. I wasn’t even going to get out of the car.”

Taylor and Ingram worked four days a week, sixteen hours a day. Several times, they found three sites in a day. “That was a little bit of luck, preparation, and a lot of driving.”

From Taylor’s home in Cincinnati, Ohio, to Auburn, Alabama, is a 9-hour, 900 km drive on interstates. Some days, Taylor would drive that distance within the state of Alabama on winding country roads, passing tomato, cotton, and tree farms, cattle pastures, and oil derricks. “I actually liked the driving off the interstate much more than on the interstate. That’s just because I was seeing things I didn’t normally see,” said Taylor. Rural Alabama didn’t always conform to “hick-town” stereotypes. Taylor sometimes stumbled across plantations and mansions and had to finagle his way past electronic gates in order to knock the doors and speak with a landowner.

Taylor also got to see Alabama’s geological variation. Cincinnati sits on slow-formed, smooth sedimentary rocks like sandstone, limestone, and shale—none of the crystals or metamorphic rocks formed under intense heat and pressure that can be found in Alabama. The hills of northern Alabama are ancient mountains at the edge of the Appalachian range. "There were times when we would be driving down the hill and I was worried I was going to burn the brakes up because we were going downhill for 35 minutes," Taylor said.

"To me, what I was doing was touristy, driving around and seeing the state, rather than stopping at some psychic reader in this little one-light town," he said. "Every day was different; that was the best part. I remember telling Stan, 'I wish I could do this forever.'"

Working for EarthScope changed the course of Taylor's studies. Sitting in countless kitchens and living rooms explaining the science behind the EarthScope projects made him want to be able to answer people's questions more thoroughly. He stayed at Auburn University for a Master's Degree, studying potential fields, gravity, and magnetics under Dr. Lorraine Wolf, the faculty member who had sent him that first email about EarthScope.

Taylor thinks more people should participate in "cultural exchanges" in their own state. "It helped give me a broader picture of how things are," he said. "It opened my eyes to the fact that everybody has a different story. It was cool to be personally involved in people's lives, even just for a couple of hours. Some of them had great stories. Some of them had sad stories. It helped me take a step back; it was a little bit of a humbling experience."

And all that talking did exactly what Taylor originally wanted: made him more comfortable in his skin. "It made me be able to go up and talk to people and see that they're not going to be scared away. They're wanting to talk too." He taught his first lab in graduate school six months after the EarthScope job. "I was sweating, but I started thinking about that summer and I thought, 'You know, I've got this.' I went in there and taught my lab, and it was good."

Dispatches from Howard

Meet Howard Peavey, the traveling serviceman who helps keep the Transportable Array of earthquake sensors running smoothly. When state-of-health readings show flooding, low batteries, or mysterious thumps in the night, Howard drives out to doctor to the seismometers. His hard work, intricate knowledge of bilge pumps, and courage in the war on fire ants allow the Transportable Array to continue to collect high-quality data that geophysicists and seismologists can analyze from the comfort of their office chairs.

Fellow seismometer serviceman Dan Knip says that Howard taught MacGyver everything he knows. Howard is a wiry, gray-bearded, suntanned New Mexican with a green plastic toolbox and a work ethic that's both frightening and inspiring. The team members who work on the Transportable Array—scientists, analysts, programmers, managers, construction crews, and service guys—often receive late night and holiday emails from Howard containing eloquent reflections on seismometer performance. His service reports from the road describe patched leaks, snow-covered solar panels, and repaired wiring with a certain literary flair. Howard always has a conjecture about the cause of a seismometer's misbehavior—even if sometimes it's just the "freight train of fate" or "the phase of the moon, the dance of the bumblebees." Luckily, adversity produces great comedy. His sarcastic wit and attention to detail give the more sedentary Transportable Array team members a vision of what it's really like to open up a flooded vault to rescue the seismometer instruments within or to have a horse eat your straw hat while you work.

Howard Peavey servicing a TA vault in southern Arizona.

We've mined hundreds of emails and seismometer station service reports for Howard's best turns of phrase and pithiest quotes.

Please Re-Schedule Your Earthquakes

Subject: TA_M55A clepsydra

Hattiesburg, Mississippi

The vault at M55A filled with rain between construction and installation… Since then the bilge pump has cycled eight times. M55 will be reworked in better weather. Until then, all earthquakes must be scheduled to arrive between pump cycles.

Animal Encounters

Service Report: 553A

Crawfordville, Florida

The pond next to the station is patrolled by an alligator 5 feet long.

Service Report: Z54A

Sparta, Georgia

UPON ARRIVAL:

Ants nibbled all around the outer edge of the rubber gasket but haven't tunneled into the vault. Not yet.

COMMENTS:

Terrain favoring a dry vault also attracts ants, tiny feisty welting fire ants.

Service Report: A27A

Antler, North Dakota

Resident border collie supervised the entire visit but did not lift a paw to help.

Service Report: J28A

Norris, South Dakota

Forty head of angus cattle supervised the visit and disapproved of my every move.

Exasperated By Leaks

Subject: TA_E40A about to flood, again

Minden, Louisiana

Fresh water is less conductive than sea water, but inundating the vault will not improve its operation. Sited in the low spot between two fields, this station should be equipped with an ocean bottom seismometer.

Service Report: 236A
Corbet, Texas
Despite a continuing drought, six feet below grade, the floor is wet.
There is no justice.

Unsolved Mysteries
Service Report: 444A
Pine Grove, Louisiana
SERVICE DESCRIPTION:
Sudden noise in the seismic data that wasn't fixed by locking and unlocking the sensor.
Communication steadily decayed this week…
ACTIONS TAKEN:
Replaced the sensor. Joy.
Experimented with different cellular antennae, height, orientation. No joy…
COMMENTS:
Sometimes the dragon wins.

Service Report: 631A
Del Rio, Texas
ACTIONS TAKEN:
Held the pump closer to the floor and forced the switch on.
Sponged the floor.
Piled more dirt on the lid.
Crossed my fingers.
COMMENTS:
Circumstances I cannot reconcile:
1. The lid seals tight enough to create considerable vacuum while prying along the rim with a long lever.

2. More than a dozen gallons of water trickled through the dirt and around the seal.

The Life of a Service Guy

Subject: Wednesday morning's leaky stations

Socorro, New Mexico

Survived a tornado on Sunday. Patched heavy leaks around the penetrations. Freshened the battery bank. Raised bilge hose out of the muck.

Service Report: M33A

Clarkson, Nebraska

COMMENTS:

Subzero windchill, little biting snowflakes, and waning light encouraged economy of motion.

Service Report: G31A

Conde, South Dakota

ACTIONS TAKEN:

Removed weeds over nine feet tall…

COMMENTS:

None. Too busy watching for lions or elephants to attack.

ON NEXT VISIT:

Bring a chain saw.

Service Report: T38A

Diamond, Missouri

COMMENTS:

After the visit, a pickup truck slathered with opinionated stickers was parked in the driveway. Front door of the house was ajar. Door bell, knocking, and an aggressive puppy did not roust any human occupant.

The Original MacGyver

Service Report: KSCO

Stratton, Colorado

COMMENTS:

Wind turned my beach umbrella into a pretzel. Recycled the center pole to hold the communication antenna skyward.

Landscape Paintings

Subject: TA_646A debris field

BF, Mississippi

Most hurricane fencing along highway 23 is leaning into the property. The gate into the site is standing open. The caretaker house pushed north a few feet, exposing or tilting its pylons. Contractors cleared the driveway to each building or empty foundation. But the last quarter mile of abandoned rail grade going to the station is covered with two feet of coarse marsh reeds and litter. Glass and plastic bottles, buoys, a porch railing, half of a wooden power pole, sticks of bamboo, marine floats, pressure treated lumber, a wooden interior door with very old knob and latch, incandescent light bulbs ripped from their metal bases, an orange life ring no longer attached to a boat. Who knows what dense, sharp, pointy evil lurks deeper in the reeds. Two months after the hurricane, only the top surface of the reed mat has dried. Clearing 1/4 mile of rail grade with a bucket loader to reach the station will take extra time during removal… The vault is somewhere under a thicker pile of reeds.

No Comment

Bowling Green, Kentucky

COMMENTS: None. Too many wood ticks.

Enochs, Texas

COMMENTS: None. Too busy driving.

Centerville, Texas

COMMENTS: None. Too thirsty.

Caspar, Wyoming

COMMENTS: None. Roads are too skinny for multitasking.

Crystal City, Texas

COMMENTS: None. Too many mosquitoes, female type, intent on replicating and venting my plasma.

Incompetent Nitwits

Subject: TA_HDA coffee stirrer combo

Oklahoma City, Oklahoma

As long as Alaska's commo [communication] infrastructure and commercial electrical grid are robust, seismic data will be continuous. And they were robust for months — until Monday.

But unlike most stations that stop communicating, HDA's telemetry rate plot dropped from 2500 bits per second to single digits, not to zero. If true, this minuscule telemetry rate suggests HDA is intact and energized, but somewhere upstream, AT&T is now routing HDA telemetry through a coffee stirrer. Again.

AT&T is American Telephone and Telegraph. It delivered both communication services for decades. But five bits per second is too slow for speech or Morse code. If AT&T is now unable to deliver phone or telegraph services, it should be required to update its corporate acronym to ASS&S: Anemic Smoke Signal and Semaphore.

Service Report: ABTX

Abilene, Texas

UPON ARRIVAL:

Another (!!) mildly curious pedestrian dug down to the lid in two spots, found the west lock, removed the tape, and twiddled the combination wheels.

Howard's Haiku

Rising Star, Texas

Old parts break. New ones, too.

Padre Island, Texas

The ocean is audible without donning a seashell.

Dallas, South Dakota

Owners just returned from Hawaii. Sigh.

Claude, Texas

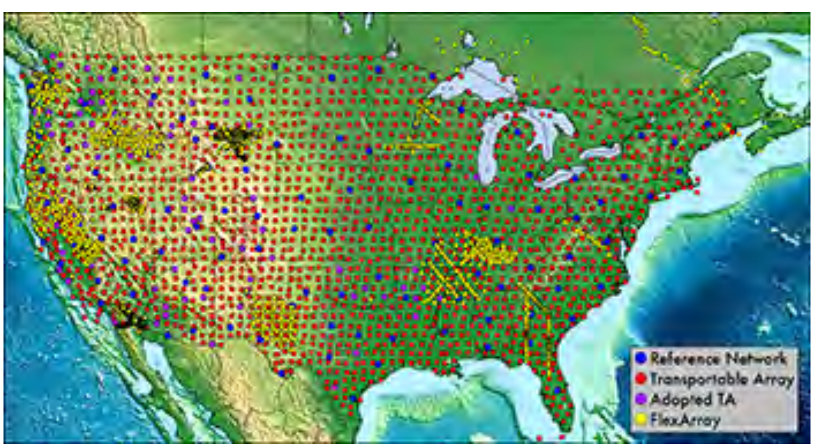
Hiking across pasture in sticky mud and rain: tolerable. Lightning: not so much.

Wimauma, Florida

Ants were hungry. Bilge was dry.

Challenges of Recon

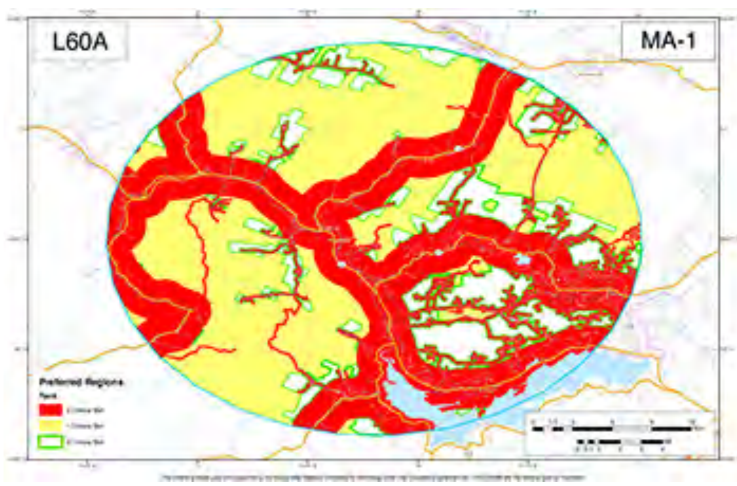
Popular Science magazine calls EarthScope the most epic science experiment in the universe, with 2000 earthquake sensors covering eight million square kilometers of the continental United States. How did the EarthScope team deploy the massive "USArray" in just 10 years? It was a multi-stage process, but the very first step was finding suitable sites. Somebody had to track down civilians willing to lend their private land to the experiment and make certain that those locations would provide high-caliber seismic data. That somebody was Graylan Vincent. At twenty-five, the Incorporated Research Institutions for Seismology (IRIS) hired Vincent to zigzag around the country in a dusty pickup truck with an EarthScope t-shirt, an eager handshake, and a business card that read: "Graylan Vincent, Reconnaissance Specialist."



Location map of the ~2,000 Transportable Array (red dots) deployed over 10 years.

The title befits a secret agent, but Vincent describes himself as a land permitting specialist whose goal was finding sites that would provide quality recordings of earthquakes deep beneath Earth's surface. Seismometers are a little too sensitive for their own good. They not only pick up earthquakes, but also minuscule vibrations—ground shifts when the temperature changes, trees leaning in the wind, cars passing—and distant noise sources such as hydroelectric dams, trains, tractors, oil pipelines, ocean waves pounding on the shore, and the drone of ships' engines. These other sounds obscure the vibrations from earthquakes. The geoscientists running the EarthScope experiment therefore wanted to ensure that the sound waves that each seismometer registered were truly earthquakes, not artifacts caused by other noise sources.

First Vincent needed to know where *not* to place seismometers. He consulted specially-created geographic information system (GIS) maps that ruled out areas that were too close to noise sources like highways, railroads, waterways, and large towns. These suitability maps were covered in an even grid of circles spaced 70 kilometers apart, indicating 250-square-kilometer regions where the seismometers had to be stationed. Opaque red swaths on the maps meant that the land was unsuitable, while white areas meant "good to go." Sometimes the entire circular region was awash in a tide of red. Vincent said that the Southwest proved the most challenging area to site. It was easier and faster to get permission to use private land than public land, but finding private landowners in states like Utah, where 70% of land belongs to the federal or state government, involved considerable detective work using Google Earth and the state land registry.



Suitability map showing one circular region of interest in Massachusetts. The map is shaded according to how many criteria for a site are met. Red is none, yellow is one criterion, and green outline is two criteria.

Seismometers had to be several dozen meters from trees, at least 1.5 kilometers away from major roads, but close enough so that construction crew could drive in a backhoe to dig a hole in which the seismometer would be buried. Siting in densely populated, forested New England was a headache of an optimization problem. Likewise, Vincent had to balance remote location with cellular coverage. The seismometers sent real-time seismic data over cellular networks to a data collection and analysis center at the University of California, San Diego. Reconnaissance was truly an art of compromise.

It also involved rhetorical skill. Imagine being a traveling salesman nowadays, in the era of do-not-call lists. Now imagine you're not selling anything, but asking people to do you a favor in the name of science. Vincent still seems slightly astonished that it actually worked.

One of the reasons for its success was the student siters. As the array progressed across the country from west to east, EarthScope began hiring local university students to do reconnaissance during their summer breaks. Vincent followed behind, double-checking the quality of the students' sites and getting landowners' written permission. Sometimes, in the months since the students had visited, landowners had rotated their crops and covered the chosen site in corn, sold their property, changed their minds, forgotten that they had agreed to participate, or even died. Vincent cleaned up any misunderstandings, moving from north to south, from summer until snow obscured the ground he was siting on.

There was no perfect strategy to find willing participants, but many of the student siters benefitted from making local contacts. In Vermont, Boston College senior Alissa Kotowski found that she could tap connections between dairy farmers and ask them to recommend other sites. Catherine Cox, then a graduate student at the University of Oklahoma, partnered with the Department of Agriculture's conservation districts, which are county subdivisions in Oklahoma that help citizens with resource use and management. James Taylor, from Auburn University, located several sites through the Alabama Cattleman's Association. Michigan State student Ben Johnson appealed to college connections, but mainly relied on the old door-to-door technique.

In rural America, an unfamiliar figure driving around your fields tends to signal "up to no good." Student siters would mention that they came from the local university; Vincent, unfortunately, raised suspicion as soon as he pulled up in a truck with government plates. People would query, "Do you work for Mr. Obama?" or "Are you tapping my phone?" He estimated that, throughout the US, about 25% of his initial contacts worked out. That number varied immensely depending on region and circumstance. People on the West Coast were far more enthusiastic about earthquake research

Graylan Vincent posing for photo on his truck.

because they felt directly affected; in New England, however, Kotowski and another student siter had to visit at least ten potential sites for each circular region of interest.[1] "We might get one or two yeses, and if we were lucky one of those might be good for a sensor," she said.

Vincent recited his pitch at least 800 times during his eight years of reconnaissance. He said, "It's kind of weird that such a unique project and such a unique experience for the landowners became such a routine thing for me that, by the end, I didn't even have to think about answering their questions."

In the highest and lowest latitudes of the USArray, however, language barriers sometimes thwarted reconnaissance efforts. Vincent said that a student from Paris siting in southern Quebec couldn't understand many of the landowners' heavy Québecois accents — "which made me feel good, because I can't understand a word they said, even though I took French for eight years." Vincent wished he'd studied Spanish instead. He once chased down a school bus in south Texas in hopes that the driver knew English. In Logan, Utah, Vincent came across a lone individual who was tending to cattle. "He was the only person around for miles. He only spoke Spanish and I only spoke English. I just couldn't make it work."

Although landowners generally expressed curiosity about the EarthScope experiment, a few were outright hostile. In southeastern Oklahoma, Catherine Cox and her siting partner pulled up to a house with a long driveway, and as they started walking down it, "We didn't really follow our gut instincts," said Cox. "We just kind of kept walking, and the landowner threatened us to get off her property. She was screaming at us and went to grab a rifle to chase us off." The two young women turned tail and ran. From that point on, she used the conservation districts and third party connections to procure sites instead of knocking on random doors.

Catherine Cox next to the shot-up sign in Oklahoma.

[1] When Kotowski mentioned earthquakes, New Englanders usually laughed at her. In fact, New England has experienced eleven earthquakes in the last 150 strong enough to crack chimneys, damage homes, and warp roads. Most earthquakes in New England are just too small for humans to feel.

Another time, Cox was searching for a site in the Ouachita Mountains. Five employees from the county conservation district had to escort Cox and her partner in order to find a site. “I definitely saw more of Oklahoma than I think I ever needed to see,” she said.

In an affluent suburb of Washington, DC, Vincent stepped out of his truck to deliver his usual pitch. A man came outside with what seemed to be a handgun held behind his back.

“Hi, my name is Graylan and I do earthquake research,” said Vincent. He was wearing his EarthScope shirt. “I’m out here looking for someplace to put an earthquake sensor for a research project.”

“You got any ID?” the man asked. Vincent showed him his business card and driver’s license. Then the man laid him over the hood of his truck, holding his wrists in a handcuff.

“Are you kidding me?” asked Vincent. The man said no.

“I’m sorry that I bothered you. I think I should leave,” Vincent said, attempting to disengage.

“No, I think you should stay. I don’t think you should go anywhere.”

Vincent continued to protest, and at last the man seemed to realize that EarthScope was no ruse. Finally he released Vincent, explaining that there had been a spate of recent break-ins involving someone with a pickup.

“You shouldn’t be going around with your truck knocking on doors,” the man advised.

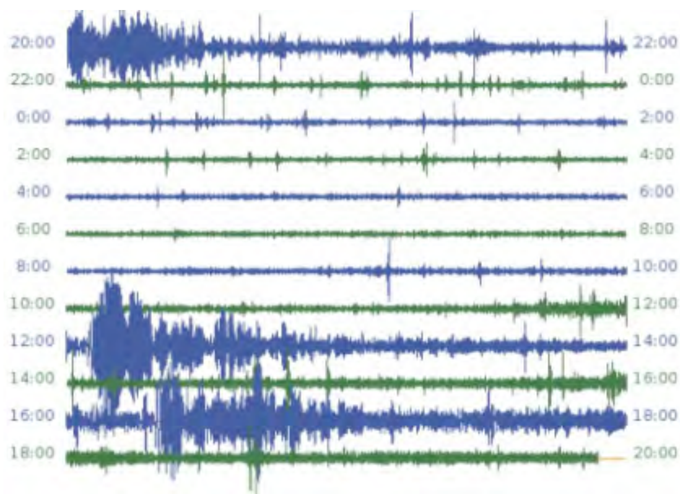
“Well, that’s what I do. I don’t really have a choice,” Vincent said wryly.

The man’s wife called Vincent that evening to apologize, and the couple ended up hosting a site.

“I had some rough ones, but there’s no site that went un-done,” said Vincent. “FBI or US marshals, they always get their man. I kind of feel the same way.”

Mike Hamlin: USArray Station Host

Every morning, Mike Hamlin gets his coffee, reads his email, checks the weather, and then clicks on the USArray's station monitor website to see what's shaking. He downloads a readout of the previous day's seismic activity measured by an earthquake sensor that sits in his own backyard, USArray Station M49A.



USArray seismogram showing the February 2013 earthquake in the Solomon Islands.

On Feb. 7, 2013, Hamlin saw a huge spike in amplitude in the seismogram, representing vibrations caused by ground motion. The sensitive seismometer on his farm in northwestern Ohio had registered shockwaves from an 8.0 magnitude quake near Papua New Guinea, on the other side of the world! After a quick search on the United States Geological Survey's real-time earthquake update page, Hamlin calculated that it had taken just tens of minutes for the waves to travel over 12,500 km from the South Pacific to his farm. He posted a photo of the seismogram on a science blog he curates with his son. "It still amazes me how small our planet really is," he wrote.

Hamlin was a high school science teacher for 30 years and now teaches biology and anatomy at a local community college. His obsession with Earth science, however, only started in 2011 when a reconnaissance siter with the USArray project called to ask if he would host a seismic station on his property for two or three years. According to Hamlin, the siter initially approached a neighbor, who said, "You will want to talk to Mike. He's crazy. He will love this stuff."

The nearest town to Hamlin is Liberty Center, population 1180. It's a farming community 40 minutes outside Toledo, Ohio. When you drive down the roads, you have to give the tractors, combines, and farm equipment a wide berth. "We laugh at people who just don't get it…people who are what we call 'from the city.'" There used to be one red light, but now it's just a four-way stop. Hamlin's quiet corn, soybean, and wheat fields provide the perfect location for a seismometer—no highways, rivers, railways, or football stadiums generating vibrations that obscure true seismic activity.

At first, Hamlin says, people worried that he had unwittingly invited an oil company onto his land. To allay their fears, he took a USArray brochure around to his neighbors, explaining that they would see a solar panel out in his field to power the seismometer and a communication antenna to send the data in real time back to California to be processed. Hamlin recalls neighbors asking, “Is it going to cause earthquakes?”

“Good gosh, no!” he replied. “It’s going to *measure* earthquakes!”

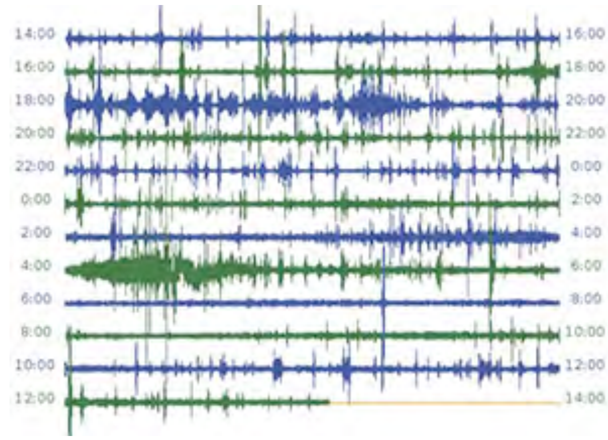
The USArray field crew installed the station in the ground in July 2012, with Hamlin excitedly hovering at the edge of the hole and asking them to explain each piece of equipment. He showed off the new station as proudly as if he had put it there himself. “I told enough people about it that they would start calling me up: ‘Hey, Mike, we heard about the, uh, earthquake there. Do you have it?’” Hamlin would direct them to his blog, where he would post, “This just happened in Russia. This just happened in Iran. This is what happens when a neighbor had a big tree down.” Eventually, with a little education, Hamlin says, people were won over.

Hamlin’s granddaughter Hannah trying to make waves.

“We were gathered for an engagement party for my son…That was the best day ever.” Hamlin did a hayride and drove a wagon full of kids and adults about 450 meters behind the house to see the seismic station. He instructed everyone to stomp on the ground. Hamlin’s grandchildren, three and eight at the time, had to jump pretty hard for the seismometer to register their stomps. Then everybody went back to look online at the near-real-time station readout. It takes just minutes for the seismometer’s measurements to be sent to data relay centers, filtered, and posted on the web.

“Do you see the difference here?” Hamlin pointed. “Do you see the scribbles? That’s each time you jump! Or when a farmer will go by, like when he’s mowing the hay on his tractor, you could actually see when he circled around. The vibrations would get greater and then diminish, greater and then diminish.” In the nearby town of Edgerton, the next seismometer in the USArray, Station M48A, lies close enough to railroad tracks that Hamlin says he can discern the train schedule just by looking at the waveforms on the seismogram. Even thunderstorms show up on the seismogram. "We had a house explosion about 19 km away and it actually registered. It was amazing!"

Between his blog and word of mouth, Hamlin estimates that he introduced over 100 people to Station M49A, maybe 200. The USArray project has involved thousands of landowners like Hamlin. Even if only a few demonstrate his enthusiasm, it is a powerful, grassroots way to spread awareness about earthquake research.



USArray seismogram captures local thunderstorms.

"You know what? I think there's been more earthquakes since they put that thing in," Hamlin's friends quipped. "No, it's just that I'm talking about it more," he explained. "Now that you have a device to measure it, you are aware more often that things are happening all over the world."

Hamlin experienced a large earthquake as a kindergartener when his family was living in Turkey. "I swear the ground moved like a water wave; it rose up and fell back down." In northwestern Ohio, however, he has never felt anything stronger than a tremor. "Nobody really thinks about earthquakes in this area because they are very rare." He says that his family, friends, and neighbors have learned not to mention earthquakes around him unless they want their ears talked off. "My wife laughs. She says, 'You've got to know when to shut up.'"

Hamlin has followed a few of the discoveries that came out of the USArray data so far. Scientists mainly use the seismic readings to make detailed images of Earth's crust and mantle beneath North America, but some data can tell them about what is happening beneath Earth's surface in other parts of the world. Seismologists have also made back-projections, triangulating earthquake sources from the USArray data and showing how earthquake vibrations move across North America like ripples on a pond. Hamlin was astonished to learn that the waves don't just travel along Earth's surface (these are called surface waves), but also radiate through the Earth (these are known as body waves). "I still can't tell a P-wave from an S-wave on the recording," Hamlin laments, but "I just like looking at what they found." He says he'll leave the questions to the pros.

As a science teacher, Hamlin feels privileged to participate in experiments like USArray that push the frontiers of research. “You need to have the courage and the finances to go where things have never been done before and see what you’re going to find out,” he says. Hamlin tries to tell friends and neighbors about how earthquake-proof building codes and a little preparation could save thousands of lives, but he says that people don’t always like to hear uncomfortable truths. If he could share just two facts, it would be that 1) the earth is not as stable as it seems, and 2) nothing is certain. “Things can go wrong,” he says. “The ground can suddenly shift.”

Hamlin at the USArray solar panel on his farm in northwestern Ohio.

Hamlin hopes that the USArray data will help convince lawmakers around the world that time spent studying earthquake hazards and preparing for earthquakes is a worthwhile investment. “It seems like every time a catastrophe occurs (obviously we can’t predict when), the world is terrible at getting aid to certain areas,” he says. “There needs to be a better way!”

Just a few weeks ago, Hamlin received a telephone call from USArray about removing Station M49A. “Aww man,” says Hamlin, “I’ll miss it.” Until the station disappears, he will keep the grass around the station’s solar panel meticulously trimmed and a vigilant eye on M49A’s seismograms every day at breakfast.

For more information about earthquakes, visit IRIS’s education and outreach links at http://www.iris.edu/hq/programs/education_and_outreach

Maintaining a Healthy USArray

Vacation never stopped Howard Peavey from working. At 9 PM on a Wednesday during his week off, Peavey sat down at the computer and pulled up the online real-time USArray data monitor, a color-coded table showing temperature, humidity, bilge pump activity, battery power, and other state-of-health measures for the earthquake sensors in the USArray Transportable Array. He noticed that Station C40A, located in the middle of Lake Superior on Isle Royale National Park, had stopped sending data. C40A had been troubling Peavey since it was buried in the ground in October 2011.

Howard Peavey carrying a digitizer after servicing a station in Marblemount, WA. *Photo by Maia ten Brink*

Peavey is a service technician for the Transportable Array (TA). He works about three weeks on and one week off, driving all over the country to doctor broken seismic stations. A graying New Mexican with a fierce focus and a skeptical eye, he spends most of his time alone in his car, which functions as a traveling home and office. It's crammed with laundry, two laptops, cold weather gear, spare sensor cables, GPS antennae, cans of expanding urethane foam, and a solar panel or two.

Peavey got this job with the TA by accident when a friend invited him out for Mexican food. At his last job, he was trying to figure out how to turn off car engines using microwaves. By his own admission, he doesn't know what he wants to be when he grows up and survives by his wits.

As Peavey looked at the state-of-health channel readings, he considered possible diagnoses: "The energy supply could have been pinched by failure of the modem, its AC-DC power supply, the AC outlet strip, the DC-AC inverter, the low-voltage-disconnect controller, an animal savoring cables between the satellite radio and modem, or a large ill-tempered animal taking great exception to the array of solar panels suddenly appearing in the neighborhood." In summer, you can only access Isle Royale by ferry. "Commercial boat service from Minnesota resumes in seven months," Peavey concluded grimly.

Earthquakes are always happening somewhere, and the TA aims to provide 24/7 monitoring of ground vibrations all over North America. In the ten years that the array has rolled from west to east across the continent, it has collected 19 terabytes of data about Earth's geophysical processes. Each of the 400 stations in the TA gathers six channels of seismic data and 25 channels of data about the station's "state of health."

The staff who run the TA focus on "metadata": the science *behind* the science. Peavey and other field technicians, along with analysts at the Array Network Facility (ANF) in San Diego and the Data Management Center in Seattle, keep track of the seismometers' performance to make sure that scientists, students, and civilians can freely download reliable data.

"C40A needed maintenance in the worst way. There was no way in God's green earth to get to it," says Peavey's fellow TA service technician Daniel Knip. "I know it bugged Howard for months. And the first time the ice came off Lake Superior, he bought a sailboat."

Dan Knip (pronounced "K-*NIP*") is an affable Minnesotan of lumberjack build with a checkered background: military training, a Master's in psychology, a stint in law school, and ballroom dance lessons with his wife. He wears flannel and a pair of black reading glasses with flowers curling around the temples.

On the shore of Isle Royale. *Photo by Dan Knip*

When Peavey told Knip that he intended to sail from Grand Portage across Lake Superior in March in a 4.8-meter sailboat, he knew that he'd have a better chance of dissuading Peavey if he pretended to go along with the harebrained plan.

"Howard tries too hard sometimes," Knip chuckles. "Lake Superior is like 0.1°C in March." Peavey didn't even know how to sail.

"You will absolutely not go on that boat," said Knip's boss.

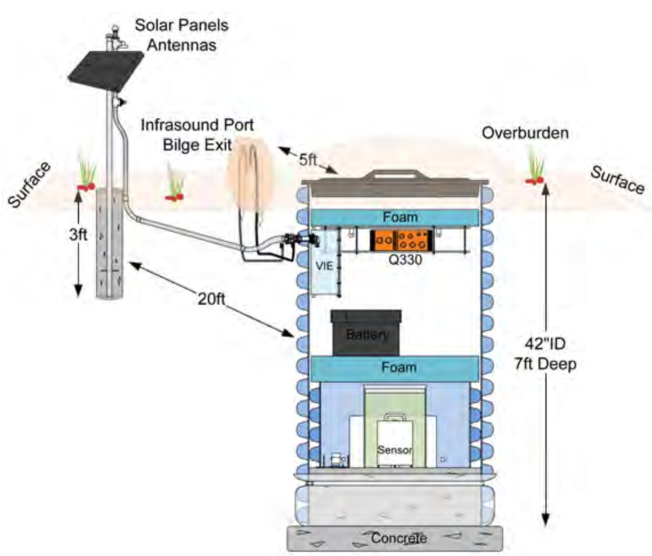
"You'll die, but if you make it, it will be an excellent adventure," commented another field technician.

Knip acquired two life jackets and met Peavey at the shore of Lake Superior. After testing the water (freezing), Peavey was convinced to scrap the sailboat scheme. Airplanes on skis couldn't land on the weak ice. Finally, they found a commercial boat to shuttle them over to the island, and then they took a rubber raft to shore, pounded by waves.

Peavey and Knip carted their equipment uphill to the station, which looks like a small bump of dirt about twenty meters from a pole with some solar panels and a communication antenna attached to the top. They dug away soil covering the vault, which helps stabilize the temperature inside and protect it from ice and rain.

Peavey climbed down into the vault, a plastic tank just big enough to stand in, buried about three meters underground. He stood on a flat shelf of grey Styrofoam that splits into two half moons. He picked up the other half, which revealed a lower lever with what looks like a PVC pipe screwed into the concrete floor. The PVC pipe was filled with sand, and inside the sand was the seismometer.

"The seismometers we use come in two shapes," explains Bob Busby, TA's manager. "One looks like a basketball on three little legs, and the other looks like a cylinder. They don't have any lights or parts on the outside, but on the inside they are sort of like $20,000 Swiss watches. They are extremely precise mechanical pendulum arrangements with electronics, balancing springs, motors, and so on."



USArray vault design (click here for more information).

Seismometers register vertical motion, north-south motion, and east-west motion as a voltage. Computers in the upper part of the vault measure the voltage output from the seismometer and send those measurements to the ANF data collection center in California via phone lines, satellite radios, and cell phone networks.

Each station is powered by solar panels and runs on seven Watts, about as much as an LED light. Batteries stored in the vault collect excess power to operate the station in bad weather. The entire TA produces about 11 gigabytes of data per day.

Peavey found water in the digitizer that transforms the seismometer's voltage readings. He replaced the broken pieces, handed them up to Knip, and then they re-buried the vault. It took them about two hours to get the station back on the air. The crew of the commercial boat told Peavey and Knip it was the earliest they had ever crossed Lake Superior.

It is a truth universally acknowledged by anyone who has ever used a printer that machines break in mysterious ways. The #1 cause of TA station failures is "unknown cause." From Peavey's perspective, leaks present the most urgent problem because water does most damage to the electrical equipment. Every week, he makes a list of high-priority fixes and tries to split the work between himself and Knip based on their current locations.

"Lots of times I don't know when I finish a station where the next station will be," Knip says. "I get on the web and see what's broken nearby and sort of draw a path in the direction of travel."

Since 2006, Peavey's Toyota RAV4 has racked up more than 800,000 kilometers. "I've driven through Texas for miles in the dark and driven until I can't drive another mile, and stopped at the first hotel on the highway," says Knip. When he walked in, the woman at the front desk said, "Well, gosh! I haven't seen you for a while!"

"Who knows?" laughs Knip. "Who knows where I've been?"

The time spent driving relative to the time spent actually fixing a station can be pretty absurd. Knip once drove 800 kilometers through a snowstorm to Montana in order to plug in an electrical cord that the wind had shaken loose. About once a year, he has to hike or ski out with a deer sled full of solar panels to a station that cannot be accessed from winter roads. "You can get stuck in places in the wintertime that you would never be stuck in the summer," he says. "In the rain, I've had to cross streams on foot to see if the truck could get across, and then come back."

Peavey and Knip brave blizzards, bail out flooded vaults, and drive 16 kilometers per hour for 12 hours on "roads people haven't been on since the Civil War, and maybe they took a goat." Meanwhile, analysts and programmers at the ANF in San Diego, California, do quality control on the data to keep the TA running reliably and go surfing on their lunch breaks. Rob Newman created the web tools that keep Peavey and Knip appraised of stations' state-of-health statistics. He had four surfboards behind his office door and brought his dog Nia to work, where she would lounge on his couch.

“My working conditions were so much better than those guys,’ so the way that I would compensate for that would be to work hard and make the best tool for them,” says Newman. “For a guy who is in the field who has only got a tiny laptop or smartphone to figure out and fix a problem with the station, you want to make it as easy as possible.”

The Transportable Array has set a new standard for seismic arrays, thanks to Peavey, Knip, the analysts at the ANF, and the rest of the TA team.

“Everybody I know in the seismic network world wants to replicate what the TA did,” says Newman.

According to Göran Ekström, a professor at Columbia University whose research uses data gathered by USArray, the TA outperforms other seismic networks around the world. The metadata TA has collected allows seismologists to better calibrate between seismometers at different locations to figure out how waves generated by earthquakes lose amplitude as they pass through rock. Those measurements help scientists make inferences about structures beneath Earth’s surface. “Quality is the greater challenge, not the quantity,” says Ekström. “TA has shown us that you can achieve it.”

~

And what became of the sailboat? After the whole icy ordeal, Knip bought it off of Peavey to prevent his landlubber colleague from attempting another ill-fated voyage.

How Do We Know What's Inside Earth?

How do we know what's inside Earth? We can't just cut into it like a cake. It's extremely difficult to drill past Earth's crust because the pressure and temperature increase the deeper down we drill. In fact, the deepest man-made hole ever only made it 12.3 kilometers, barely 1% of the 1300-kilometer distance to Earth's center.

Instead, seismologists measure vibrations at Earth's surface in order to observe what is inside, just as doctors use x-rays to image the interior of the body without making any incisions. What provides the source for vibrations big enough to take a sonic "picture"? Earthquakes. When tectonic plates slide past each other, they release huge amounts of energy that ripple outward from the earthquake epicenter. Seismologists can determine what lies beneath Earth's surface based on the time it takes for those seismic waves to reach seismometers in other parts of the world and changes to the wave amplitude that occur as the waves travel. By mapping these wave propagations, seismologists can then figure out what structures, rocks, and temperatures must exist beneath Earth's surface to explain their observations.

The more seismometers scientists deploy on the surface, the clearer the images they can make of Earth's interior. The Transportable Array (TA) is a network of seismometers spread every 70 kilometers across the United States that gives scientists a high-resolution look at the North American continent.

Dean Lashway is one of the field crew members who built over 2000 seismic stations all over the United States as part of the USArray Transportable Array experiment. He sees seismology research from the technical, rather than theoretical, perspective. He helped roll the array from west to east across the continent, installing seismometers and then removing them after two years in order to re-bury them at new locations. Lashway is burly and bald-headed with glasses and a boyish smile. Before this job, he worked a contractor in Baghdad.

At the annual TA meeting, Lashway listened to seismologists talk about the discoveries they have made using TA data. He leaned over to another field crew member, shaking his head. "This data is Greek to me. Something happened seven billion years ago? How do they know that? Because of a hole we dug."

Transportable Array field crew.

Scientists like Göran Ekström, a seismologist at Columbia University, leave the fieldwork to Lashway and the rest of the TA field crew. Deploying seismometers and collecting data could take an individual scientist years working alone, so the Incorporated Research Institutions for Seismology (IRIS), which runs the TA experiment, shares data sets and data products with anybody who wants it. This principle of "open access" means that Ekström can download data from the TA to model Earth's underlying structure while he sits in his office.

For Ekström's research, the TA helps answer the question: What are the properties of the rock beneath the North American continent? "How thick is the Earth's crust? What are the rocks that make up the Earth's crust? What is the composition of the mantle rocks that lie beneath the crust, and what is the temperature of those rocks? Once you know that, you can start inferring the history of the continent," said Ekström.

In 1998, Ekström helped propose the first plans for what would become the Transportable Array. Such a dense array of seismometers had never been attempted. "There was a lot of skepticism that any of this would actually work," he said. One of the biggest concerns was how to transmit data collected by seismometers in remote locations back to data collection centers in California and Washington. "In the late 1990's, the idea that you would have cell phone coverage in the less populated areas of the United States was not even *thought* as an option for collecting data." Moreover, the whole project hinged on the kindness of strangers; each seismic site was hosted by landowners who agreed to participate for free in a government-funded science project.

It did indeed prove challenging to pull off. TA manager Bob Busby tried to approach the project with a manufacturer's mindset. Instead of employing graduate students and professors, he hired a specialized field crew. Lashway, on the construction team, dug holes at each station site. The install guys put together each station, with a 2.7-meter watertight vault containing a seismometer and several computers. The service technicians fixed up ailing sites, and the removal crew dismantled each seismic station at the end of its two-year lifetime and handed the parts off to the install crew.

Remote locations, weather, and technical failures made for a constant battle. The field crew members spent weeks or months at a time on the road, hauling supplies around the country. Most of them worked alone, and the annual TA meetings were one of the few times they got to interact face-to-face.

When they converged on Woods Hole, Massachusetts in October 2013 for TA's 10-year anniversary, the field crew guys had been feverishly installing the final 60 stations on the East Coast. They looked haggard but satisfied at completing their goal.

Over a lobster dinner, it was time to trade tales, some taller than others. Best state? Everybody liked the scenery in Montana and Wyoming. Worst state?

"Texas. I wrecked the truck. I almost died on that one," said Lashway grimly. "I had a pickup truck. I'm towing a 6-meter trailer," full of expensive seismic sensors and computers. "I hit black ice and the truck started moving like this." Lashway snaked his hand in a side-to-side whip motion.


Transportable Array field crew member.

"I'm pumping the brakes and I'm working the trailer brakes to slow me down. So I straighten out and I'm heading over to the grass at the side of the median. As soon as the truck hit the grass, the trailer tilted and flipped. The lucky thing was that it broke the hitch, so the truck didn't flip with it."

He got out of the truck and called his supervisor. "It was thirty or forty-five seconds later, the semi hit and everything exploded. I was thinkin' to myself, I would still be climbin' out of that truck if that hitch didn't break, and I'd have been dead."

All the guys around the table muttered darkly about winter driving. Everybody agreed that spending so much time on the road is the most dangerous part of the job. “Colorado, the Million Dollar Highway,” said Dan Knip, who fixes the broken seismic stations, “gave me all my gray hairs. I got vertigo.”

Bob Pierce, an install guy who has been with TA since its beginning in 2004, said Nevada was his worst state because it was so remote. “There was no cell phones, no state highways. State highways are dirt roads with 110-kilometer-an-hour signs on ‘em.” The station sites chosen by the reconnaissance siter at the time were in difficult-to-reach places, far from the road. “It made it doubly difficult because our only supply points [to pick up equipment for new seismic stations] were Reno or Las Vegas. So we’d have to load up our truck with eight or twelve sites and go out for three weeks at a time and you couldn’t get resupplied. And if you wanted to go back to a hotel, you’d have a six-hour drive.”

So what did Pierce do, camp? “Well, no, we usually drove the long hours to the hotel,” he said. “One site, Soldier Meadow, we started off in Reno. It took us an entire day just to get to the site. Sunup to sundown. Then we had to stay in the [landowner’s] ranch house for the night and finish the site. It took two days. A whole lot of sites in Nevada were like that.”

“Funny story is—” Pierce leaned back with a smirk on his usually impassive face—“the best sand is in Reno. So I keep going to the hardware store in Reno and buying a pallet of sand [used to pack around the seismometer]. Each time, 54 bags of 23 kg of sand. I’d do it once a month.”

Finally an employee at the hardware store asked Pierce, “What are you doing with all that sand?”

Pierce replied, “Well, I’m taking it out in the desert and I’m burying it.”

Lashway laughs, “Yeah, I’m sick of giving the official IRIS explanation. I should say instead that we install time capsule graves.”

Some of the landowners who host the seismic sites are curious about the seismometers that the field crews install, but most just leave them be. Occasionally the field guys run into suspicious neighbors who think they’re cattle thieves or conspiracy theorists who become belligerent at the mention of a government-funded experiment.

The majority of the landowners who host sites are incredibly generous and hospitable. The field crew guys have been treated to picnics, barbecues, and handmade tortillas. Impromptu parties have sprung up around them as they work. They’ve been taken fishing and shooting—“it’s how you say ‘hi’ out West,” said Knip.

Pride in being part of something meaningful keeps Lashway motivated. Howard Peavey, one of the other field crew members, agreed: “We have a chance of actually learning something about the planet we are on.”

It takes a certain grit and sense of purpose, as well as a problem-solving mind. “We’re not crazy,” said Lashway. “We just love what we do.”

Infrasound

On February 15, 2013, an asteroid 18 meters wide plummeted into Earth’s atmosphere and exploded over Chelyabinsk, Russia, with the force of 500 kilotons of TNT. Nearby eyewitnesses saw an intense light flare across the gray morning sky, leaving a trail of smoke. The meteor’s explosion generated low-frequency shock waves, known as infrasound, so powerful that, on the ground 30 kilometers below the explosion, thousands of windows blew out, more than 7,000 buildings sustained damage, and nearly 1,500 people were injured. These infrasound waves traveled twice around the world and were recorded by the USArray Transportable Array, a seismic network spanning the United States, as they bounced off Earth’s surface and shook the ground.

For Michael Hedlin, a geophysicist at the Scripps Institute of Oceanography in San Diego, the Chelyabinsk meteor was a once-in-a-lifetime sonic experiment. Hedlin has been investigating atmospheric acoustics since the late 1990s. He uses data from the Transportable Array (TA), originally intended to record seismic waves in the solid Earth, to learn how infrasound waves lower than 20 Hertz propagate through the atmosphere.

“There are all these sound waves traveling through the atmosphere, traveling past us at any moment wherever we are,” says Hedlin. “And people have no idea that they’re there because they are such a low frequency sound that they can’t hear them or even feel them.” At close range and large amplitudes, however, infrasound waves can make a physical impact. Hedlin had the opportunity to stand aboard a Kitty Hawk aircraft carrier as it was launching fighter planes off using a catapult. He says he felt pulses of sound vibrating within his chest cavity.

Although infrasound is below humans’ hearing range, elephants, whales, and other animals actually use it to communicate across immense distances. To their ears, the Chelyabinsk meteor must have created a terrible racket.

"The planet is really noisy. It is always making these natural sounds that we can listen to and learn more about how the planet functions," says Hedlin.

Hedlin has an extremely deep voice, fitting for someone who studies low-frequency acoustics. He's a lanky Californian who wears skinny jeans and flip-flops to work, exercises avidly, and keeps a kayak in his wood-paneled office on the cliffs of La Jolla overlooking the Pacific Ocean. His wife and collaborator, Catherine de Groot-Hedlin, has a matching kayak in her office, which is just around the corner. They keep framed photos of each other propped on their respective desks from their graduate student days at the University of California, San Diego.

Hedlin and de Groot-Hedlin first started looking for infrasound waves in the TA seismic data in 2007 after NASA's Atlantis space shuttle made an emergency landing at Edwards Air Force Base north of Los Angeles. The TA's seismic sensors, placed along the West Coast at the time, picked up infrasound waves from the shuttle's re-entry. De Groot-Hedlin remembers hearing the windows shake as the shuttle flew overhead. Since then, Hedlin says, seismic readings from the TA have provided "an acoustic fingerprint of the United States."

The sound sources Hedlin and de Groot-Hedlin usually pick up are on a smaller scale: bombs, mining explosions, sonic booms, landslides, volcanic eruptions, and large storms. "Basically anything natural or man-made that moves a lot of air," Hedlin explains.

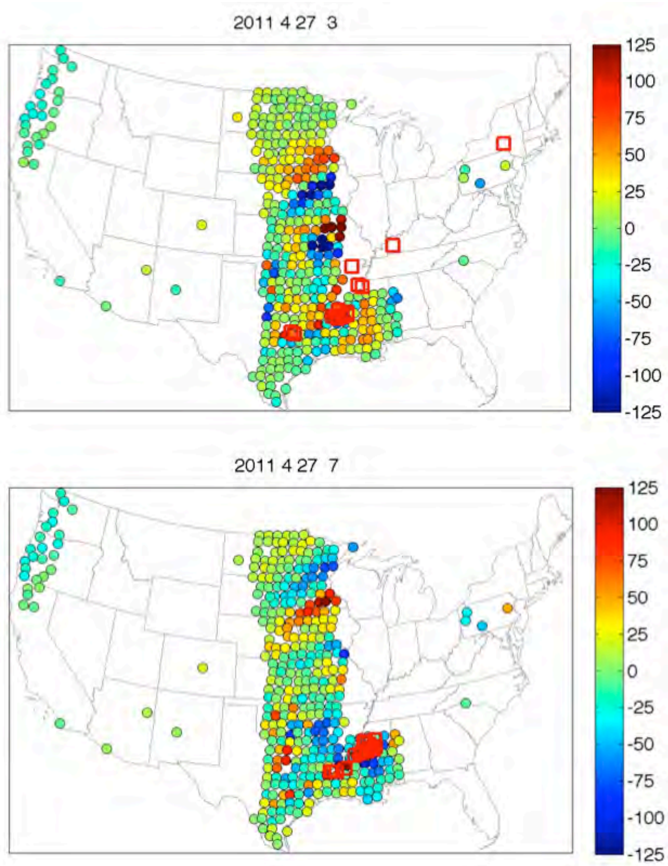
Some of the largest man-made infrasound signals come from nuclear bombs. Part of Hedlin's work involves monitoring the skies to ensure that nations uphold the Comprehensive Nuclear-Test-Ban Treaty, an international agreement to abstain from nuclear testing. Events like the Chelyabinsk meteor provide a good approximation for small nuclear explosions[2]. Right now, Hedlin says, the only nuclear detonations they detect occur underground in North Korea.

Infrasound may also be able to provide early warnings about avalanches and volcanic eruptions. "A volcano is a very turbulent, hot location," says Hedlin. "It will move the ground, generate seismic waves, and can also send pulses [of infrasound] into the atmosphere." Volcanic ash poses a threat for airplanes flying nearby, and infrasound waves can be powerful enough to cause damage several kilometers downwind.

[2] The Tsar Bomba, the largest nuclear test ever conducted, occurred in October 1961 over Novaya Zemlya, Russia. One hundred times as powerful as the Chelyabinsk meteor explosion, it had an explosive yield of 50–58 megatons of TNT.

But before infrasound can be used for real-time hazard detection, it needs to be better understood. “You can determine that you have an infrasound source, but then you have the mystery of what caused it,” Hedlin says. Acoustic scientists don’t want to sound a false alarm about a nuclear explosion; it could have dire political consequences. “That’s why we’re doing this research to try to understand why the atmosphere is stretching signals,” he says. “We want to learn how to model the [infrasound] propagation well enough to understand what happened at the source.”

In 2011, Hedlin and his colleague Frank Vernon got a proposal funded to add infrasound sensors to all 400 TA seismic stations. Each TA station is now equipped with an infrasound microphone and two pressure sensors that measure air pressure at 40 samples per second, as well as a broadband seismic sensor to detect ground motion. “The beautiful thing about this project was that the Transportable Array infrastructure was already in place,” Hedlin says. Now the TA is the world’s most extensive infrasound array, providing Hedlin and other researchers with an unprecedented range of atmospheric and meteorological data.



Screen shot from April 2011 when a two- to six-hour gravity wave propagated slowly (about 40 meters per second) from south to north across the Transportable Array. Red is high atmospheric pressure, blue is low. The scale is in Pascals. The red squares are tornados.

With seismic stations every 70 kilometers, it’s easy to track signals from one station to the next across the TA network. Compared to the International Monitoring System, a sparse global infrasonic array with stations 2,000 kilometers apart, it is easier to study infrasound in greater detail. “The Transportable Array is really the backbone of our research right now,” says Hedlin. “It’s been incredibly helpful to us.”

Hedlin has used TA findings to model how infrasound waves propagate through the atmosphere. Just like seismologists use seismic waves from earthquakes to image the layers inside Earth, Hedlin looks at how infrasound waves stretch and warp as they travel in order to get an accurate picture of the atmosphere. But while Earth's structure changes extremely slowly, the atmosphere is constantly changing.

Infrasound waves travel extremely slowly, at 300–310 meters per second. That's less than 10% of the speed of seismic waves. What starts as a relatively simple sound signal from an explosion gets modified as it ripples out for hundreds or thousands of kilometers. Turbulence, seasonal winds, and gravity waves—sound waves so slow that gravity acts on them—alter infrasound. "Everything in the atmosphere from the temperature to the direction and speed of the wind is important to determine how infrasound propagates," says Hedlin.

Meanwhile, de Groot-Hedlin has been scouring the TA data for even lower-frequency waves known as gravity waves. "A gravity wave is a bundle of air like a tsunami," she explains. "With a tsunami, water gets displaced from its usual position. It gets uplifted [by fault movements producing an earthquake] and it wants to spread out and down." In the atmosphere, convective events caused by rising columns of warm air, severe storms, or wind flow over mountains might set off long-period gravity waves.

Sometimes, analyzing the entire array can overlook activity happening on a more local scale, so de Groot-Hedlin had the idea to break down the TA's 400 stations into triangular sub-arrays consisting of three adjacent stations. She searched "Tornado Alley" in the central United States for gravity waves caused by swarms of tornadoes and passing over each sub-array, which she called triads.

De Groot-Hedlin came to the field of atmospheric acoustics from hydro-acoustics, the science of sound moving through water. Now that she has created a code that automatically detects gravity waves, she has to learn more about atmospheric science to figure out how gravity waves interact with climate and weather dynamics.

For Hedlin, studying the atmosphere was a logical extension of his graduate school seismology research on Earth's interior. "Earth is a system. You've got the solid interior, the atmosphere, the cryosphere (the ice caps), the hydrosphere (the ocean), and all these parts are interacting and communicating," he says. For example, when an earthquake occurs under a mountain range, Hedlin says, "it will cause the mountains to sway back and forth really slowly. As they rock, they push on the air in the atmosphere and generate low-frequency sound waves."

Even extra-terrestrial objects like the Chelyabinsk meteor can affect Earth's systems.

Barring further surprise meteors or nuclear explosions, Hedlin and de Groot-Hedlin are looking forward to the TA's upcoming deployment in Alaska. "There are phenomena in Alaska that we don't have here in the continental US. There are a lot of volcanic eruptions along the Aleutians for example," says Hedlin. Aurora, frequent landslides, and calving glaciers also generate infrasound waves.

"Much of what we are going to learn is still in the future," Hedlin says. "We have been collecting the data for a relatively short time. We are just scratching the surface of what is in this huge data set."

Vladik Marynov: Eavesdropping on North America

Vladik Martynov is eavesdropping on North America. From his computer in San Diego, he gets real-time updates of what's going on at the ground—and underground—from a dense grid of seismometers stationed across the United States called the USArray Transportable Array (TA). Sound waves registered on TA seismometers can tell him if earthquakes happen, where mining blasts occur, when storms thunder overhead, or whether a train passed near a seismic station.

Vladik Martynov at his desk at the Array Network Facility.

Martynov is a senior analyst at the Array Network Facility (ANF) at the University of California at San Diego. He speaks in a Russian accent rich with consonants and thoughtful pauses. By the edge of the Pacific Ocean, Martynov sits at his computer in a dim office making "phase picks," also known as "picking." His eyes flick over yellow seismic waveforms on a vivid blue background, assessing incoming seismograms. He scans all 400+ stations for correlated activity, then picks what he determines are the beginnings of P-waves and S-waves. He decides which types of waves they are based on their velocities, their shapes, and their arrival on the seismogram's vertical and horizontal channels.

He enters that information about the timing of incoming seismic waves into a program that accounts for the dynamics of Earth's crust in order to calculate the coordinates, locations, and depths of earthquakes. Martynov's pickings are essentially surface observations that allow him to infer backward about what happened underground.

Martynov has a reputation at the ANF as a processing wizard. "Vladik is a machine," says Jon Tytell, a fellow analyst. "He loves processing earthquakes in realtime. I think it is kind of a puzzle-solving daily thing for him."

Most days, he arrives at the office at 7:30 AM and spends the first two or three hours of his day processing seismic recordings from the previous 12 hours. Then he begins to process events as they pop up, in "quasi-real time," with a delay of about half an hour. He checks the results of the automatic detector's pickings, tweaks them, adds new phase picks, cleans up data, and calculates earthquakes' locations.

The job requires a keen sense of geological context. For example, earthquakes in Japan have produced different waveforms as the TA stations that record them have rolled from west to east across the United States. The shapes of waveforms also depend on local geography. For instance, waveforms from a station a valley or a basin will resonate, so Martynov will check satellite images to confirm that the station does indeed sit in a sedimentary basin, and the ringing is not an erroneous signal. It is not so much frustrating as a great challenge that the network is so dynamic.

"I like to process good teleseismic [i.e. extremely far-off] events with good, sharp phases you can see clearly," says Martynov. Those seismograms look like textbook examples. He dislikes earthquakes from Mexico's Baja Peninsula; "they have very weak P-wave arrivals. It is just so difficult to get good results of picking."

He averages around 30,000 picks per week. "He does the work of probably five people," says an old colleague, Rob Newman. "He's just incredible; he has his eyes on all the data and an ability to pick out large and small events that other people wouldn't notice."

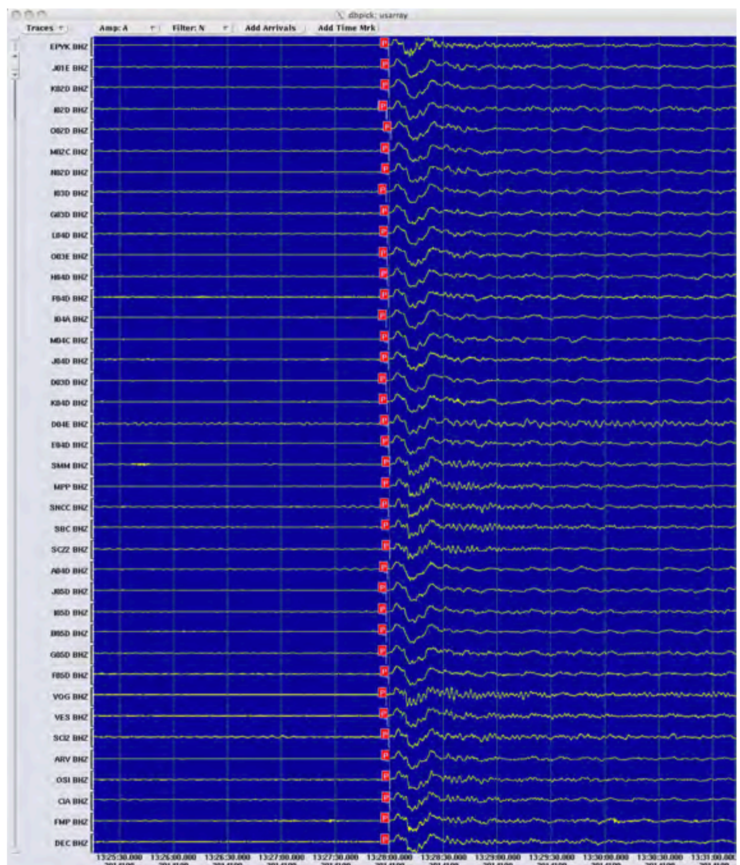
Although Martynov runs the data through a computer program called a detector that makes automated phase picks, it is no substitute for vigilant eyes and experience. To ensure accuracy, he checks the detector's picks, then checks his own picks a week later with fresh eyes.

He has developed a finely tuned sense of what looks right, like a radiologist examining an x-ray. He diagnoses the frenzy and lull of North America's rhythms.

In the 1980's, Martynov was a researcher at the Institute of Physics of the Earth in Moscow. He was working on an expedition in the Pamir Mountains of Central Asia with a group of American geophysicists that included ANF director Frank Vernon. When the Soviet Union collapsed, Martynov continued to collaborate with Vernon's research group in San Diego. "Step by step I decided that I could do nothing in Russia and it is interesting for me to work here and I could work with very good, high-quality digital data," says Martynov.

Now his main responsibility is analyzing and quality-controlling the TA data set. It is no small feat. In the last decade, the ANF has logged and processed over 18 terabytes of data from nearly 2000 TA stations. Martynov and the other ANF analysts have picked over 6.7 million wave arrivals for more than 78,000 events. Eleven thousand four hundred of those events were earthquakes with a magnitude of 5.0 or greater.

Aside from earthquakes, the second most common sounds recorded in the United States are mining explosions. Since the TA seismometers are currently stationed on the East Coast, Martynov has been observing lots of quarry blasts in the late afternoon. He points to a squiggle on the seismic trace. "It's near the end of the working day, and during this part of the working day is when explosions will usually happen. The distance is about 40 kilometers from the closest stations, and about 200 kilometers from the farthest stations [that registered the blast]." With large events, Martynov sees



Screenshot from Vladik's computer of a magnitude 7.5 earthquake that occurred on April 19, 2014, in the Solomon Islands. The figure shows the waveforms across most or all of the Transportable Array stations, which are along the vertical axis; time is the y-axis.

the vibration ripple beneath dozens of adjacent stations.

There are certain telltale signatures Martynov can read on the seismograms. “Sometimes it is easy to recognize, is it a [mining] blast or an earthquake?” he says. “Some blasts have very intensive surface waves, poor P-waves, and weak S-waves. When you see these recordings, you are absolutely sure it is a blast. What does it mean? That it was a bad-quality blast because seismograms from a good explosion are difficult to discriminate from earthquakes.”

TA’s seismic stations are so sensitive that they can pick up noise from ocean surf, cars, running water, and storms. Vibrations from highways and heavy farm equipment show up as high-frequency sound waves of 8–10 Hertz. Martynov can also see human-generated seismic noise shift exactly one hour during Daylight Savings.

Errors in the seismograms look like flatlined waves, rectangular boxes, or spikes. Martynov notifies other members of the ANF’s team, who figure out the root of the problem. They can solve some malfunctions by remotely recalibrating seismometers or resetting computers, but other times they have to send a service person out in the field to fix a sickly station.

Martynov enters every pick into the ANF’s official bulletin of seismic events, whether it was a natural or human-generated sound. Why? For one thing, there’s not enough time to agonize over every pick. “We have just two guys, me and Malcolm,” says Martynov. “We have to be fast fast fast fast fast. Sometimes you don’t have time to think. It’s rote.” He also wants to avoid biasing the analysis by throwing out so-called unimportant sounds. Scientists around the world reference the ANF seismic bulletin to corroborate with other seismic networks, access TA data, or run analyses of their own. The goal is to make the full spectrum of raw and processed data freely available so that others can use it in ways that haven’t even been imagined yet.

The TA has set a new standard for data collection and quality control, despite having to manage such massive amounts of data. Their data return rates soar at 98%. With Martynov’s eyes combing the seismograms, the TA *team* can fix errors quickly and ensure highly accurate picks.

“I am feeling proud not for myself, but about our team,” says Martynov. “We have a small team and you see how much we are doing.”

The fruits of their labors are just beginning to ripen. Scientists are just now combing through TA data and recordings. As they listen, they will be able to hear the sounds and secrets of deep Earth.

Additional information about seismic waves and how seismometers work:
http://www.iris.edu/hq/programs/education_and_outreach/animations/9
http://www.iris.edu/hq/programs/education_and_outreach/animations/8

Gems Hidden in the Details of the Transportable Array Data

Before microscopes, we had no idea that the human body was teeming with microbes. Before telescopes, we could only wonder how stars formed. Sometimes, it takes the right scientific instrument to see old questions from new angles and spark new advances in research.

The USArray Transportable Array (TA) is a grid of more than 400 seismometers spaced every 70 kilometers. For the last ten years, the TA has marched slowly across North America measuring seismic waves from Earth's vibrations. The TA acts as a kind of microscope and telescope—an "EarthScope"—to observe what goes on right beneath our feet.

Because the TA is the densest, most extensive seismic array of its kind, researchers have been able to zoom in and out to see patterns and features they might have missed with a smaller or sparser seismic network. Combing through a decade of TA data, analysts at the Array Network Facility (ANF) at the University of California, San Diego, have been able to provide more details on three phenomena: microseismicity, seismic waves generated by meteorological events, and seismic noise.


Luciana Astiz in her office at the Array Network Facility.

An Earthquake Up Close

Luciana Astiz, the associate director of the ANF, has seen earthquakes on a personal scale. She grew up in a tall apartment in Mexico City that magnified the shaking from distant quakes. Early one morning in 1979, when she was a teenager, a magnitude 7.6 earthquake jarred Astiz from her sleep. When her eyes snapped open, she saw her bedroom window yawning overhead, deformed by the tremors. Cracks were snaking up the walls. The city buildings, constructed of cement bricks and rebar, ruptured and whined as they warped. The power lines snapped and the high-tension wire buzzed and flailed as people ran screaming from the street. “It [was] kind of exciting and scary,” she says.

Nowadays, Astiz deals with earthquakes as waveforms on her computer screen in her book-lined office overlooking a popular surfing beach in La Jolla, California. Her watchful gaze is at the same time piercing and warm. She tells the story with theatrical sound effects and scrubs her hands together to demonstrate the violent frictions of tectonic plates catching at strike-slip faults and then jolting horizontally past each other.

Astiz has been captivated by seismology since that earthquake jolted her awake. “Everybody gets fascinated by astronomy, when you look at the stars,” she says. “I thought it would be like looking inside, like astronomy but inwards.”

Regional Differences

The TA put some of the more under-studied regions in the central and eastern United States under the microscope. As the TA deployment moved eastward from California, Astiz began to notice a strange trend. TA seismometers were registering 53% more events than other networks—not massive earthquakes, but tiny tremors less than magnitude 2.7 collectively known as microseismsicity.

“I thought, ‘Maybe these are just flukes, something not working right in the processing,’” says Astiz. When she and other ANF analysts probed further, however, they realized that the microseismic events spiked near the end of working hours and shared a characteristic waveform shape. Most of the microseismicity was located in the vicinity of underground coal mines in Kentucky, Virginia, and other areas of the Appalachians.

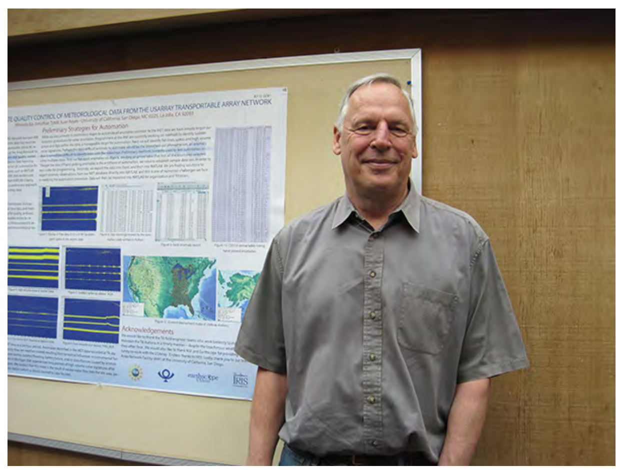
In fact, many of the microseismic events were actually mining blasts. Other regional networks in the United States tended to exclude the explosions from their bulletins because they knew where and when local companies mined. The ANF’s lack of bias proved to be a valuable asset because it allowed them to notice seismic patterns that regional networks often ignored.

“We also started seeing all this induced [i.e. human-generated] seismicity from gas exploration and all these events in Oklahoma,” says Astiz. Before 2006, Oklahoma had experienced about one magnitude 4.0 earthquake every century. After 2006, the TA registered magnitude 4.0 quakes nearly every two months. According to Astiz, “the ANF was the first one saying, “Hey, why are there so many earthquakes here?’”

They contacted the United States Geological Survey to share their findings. Using TA data, USGS researchers discovered the link between microseismicity and wastewater injected underground as a byproduct of gas extraction. “Right now it is pretty well accepted,” Astiz says, “that the injection of wastewater close to a fault is going to lubricate the fault and allow it to move.”[3]

The TA just happened to be deployed at the right time and in the right place to pick up on the surge in microseismicity. Astiz says, “It was totally fortuitous that gas exploration started to increase in 2005 and the USArray started around that same time.”

Earth Aboveground



Frank Vernon outside his office.

Observations from the TA have prompted researchers to raise their gazes from the ground and look to the atmosphere. In 2010, some peculiar noise characteristics showed up on a subset of TA stations. Astiz’s supervisor, ANF director Frank Vernon, recognized that the signals could not be an earthquake; the propagation speed of the waves made no sense. Upon closer inspection, the signals formed a systematic pattern that correlated with large storm fronts sweeping across the Midwest. It turned out that TA’s seismometers, which were intended to record seismic waves from earthquakes, could register sound waves generated in the atmosphere. “We started looking in more and more detail and started getting more and more interesting signals,” says Vernon. “You could see how the ground actually got deflected as these big storms came across.”

Vernon realized the potential for the TA to benefit other fields outside seismology. The following year, he was awarded a grant to add pressure sensors to every TA station. As a result, the TA can now record infrasound, or low-frequency sound waves, from large storms

[3] Wastewater injection from gas exploration is not the only culprit that can induce seismicity. When humans dam up water in canyons, the strain of such huge volumes of water can alter the stress field of a fault.

reverberating off the troposphere and Earth's surface.

Vernon also hired one of his old students, Jon Tytell, to process TA's meteorological data. "If there's a thunderstorm, we can see a slight tilt in the crust," explains Tytell. "There was a tornado that went over the ground about a kilometer away from one of our stations. The seismic reading shows that the ground actually tilted to the northwest toward the tornado for just over a minute and a half."

"When you make a really high-quality data set with really good measurements, there are lots of things you don't expect to see," says Vernon. "They start appearing and that generates new science."

TA's Telescopic View

One of the biggest challenges of running a seismic array is to suppress the natural noises that seismometers record in order to improve the quality of the earthquake signal. But what if seismologists re-framed their concept of "noise"?

Seismic noise is the continuous vibration caused by waves, water, human activity, and natural motion that make the heartbeat of the planet. On a seismogram, seismic noise looks like perpetual fuzz instead of a sharp amplitude jump. For a long time, seismic noise was considered unimportant and impossible to analyze. In the 1950s, however, scientists began to realize that what seemed like pesky artifacts mucking up seismic recordings could actually be data. But debate surrounds how to interpret them.

A geophysicist at the University of Colorado at Boulder named Michael Ritzwoller has figured out a way to use seismic noise recorded by the TA. He calls this method ambient noise tomography (ANT). Seismologists usually map the structure of Earth's interior by analyzing how seismic waves ripple out from earthquakes. ANT, however, involves extracting information from the different frequency bands that make up the "Earth hum." The key to ANT is zooming out to look at broad patterns. Instead of focusing on single events, ANT smoothes out the varied content of seismic noise by looking at extremely long time scales—more than a year's worth of data—and vast areas, made possible by TA's continental footprint.

Astiz thinks the TA is the ideal instrument to probe the nature of seismic noise: "The grid geometry and relatively small inter-station spacing of the array facilitate tracking seismic noise across the array and hopefully makes it easier to identify some of this 'noise' as being generated by a particular source."

Right now Astiz is collaborating with ANF analyst Vladik Martynov to figure out how the moon and sun might affect seismic noise. She and Martynov have observed that high-frequency seismic noise recorded from a small network of seismometers in the desert of Southern California correlates with tides pulled by the moon and sun during Earth's daily rotation. Their next step will be to search TA's data set for the same tide-related seismic noise. "Pretty neat," she says with a grin.

With a continent-sized instrument like the TA, Astiz and her colleagues at the ANF have their hands full keeping it tuned up and well calibrated so that scientists from other institutions can access standardized, high-quality information. "We support them by giving them data," she says.

It takes an entire scientific community to explore the potential of a tool like the TA. Researchers and analysts from around the world bring their own perspectives to a data set that provides both close-ups and wide angles. As for Astiz, she has "a bird's eye view."

For more information, visit:
http://www.usgs.gov/faq/?q=taxonomy/term/9833
http://geology.gsapubs.org/content/41/6/699.short
http://www.sciencemag.org/content/341/6142/1225942.short
http://ciei.colorado.edu/pubs/2008/Yang_WUSA_phase.pdf

On the Road with Graylan Vincent:
EarthScope Recon Across the United States

Spiral Jetty.

Spiral Jetty, Robert Smithson's earthwork of mud and basalt, uncurls like a giant chameleon's tongue taking a drink from the Great Salt Lake. It's an 80-km drive west of Brigham City, Utah, and once you get there, the sculpture might not even be visible, depending on the seasonal rains. Graylan Vincent visited *Spiral Jetty* one August evening in 2006 after finding a site for an earthquake sensor on a nearby ranch. The winding drive up to the earthwork did not seem so ludicrous compared to some of the journeys he had made while hunting for remote, undisturbed locations to place the hundreds of other seismometers that constitute the EarthScope Transportable Array. In fact, Vincent kind of liked how *Spiral Jetty* was in the middle of nowhere.

He arrived just after sunset and waded out in the warm air and saltwater. Barefoot in the twilight, Vincent filled with a sense of peace. *This* was why he had taken the reconnaissance job with the Incorporated Research Institutions for Seismology (IRIS). This was why he drove around the United States asking strangers to host a seismometer on their property and why he spent ten days out of every two weeks on the road, either in the seat of his pickup or in identically-decorated hotel rooms. "Holy smokes," he thought, "I get paid to travel the country."

You can count on Graylan Vincent to be unabashedly *interested* in things. He has just spent eight years talking to strangers for his job, finding points of connection with them, and it's clear that he relishes conversation. He has explained the EarthScope Transportable Array, IRIS' nationwide seismology experiment, to hundreds of landowners all over the country. He estimates that he has repeated his spiel—"Hi, I'm Graylan and I'm out here looking for someplace to put an earthquake sensor for a research project"—at least 800 times during the last eight years. Vincent is thirty-three but looks like a lanky college student with cargo shorts and a windbreaker tied around his waist, bouncing on the balls of his feet. He swears all the time, with excited abandon. After eight years of travel, he says, somehow, "I still have a bit of wanderlust."

America boasts more miles of road than any other country in the world—nearly 6.5 million kilometers, according to the Department of Transportation.[4] It's an infrastructure that rivals ancient Rome's. In the last eight years, Vincent drove over 300,000 kilometers on those roads. That's about one light-second, or 80% of the distance to the moon. If he drove continuously at highway speeds (about 96 kilometers per hour), that amounts to driving 24 hours a day for 463 days straight.

Vincent listened to music, podcasts, and NPR as he drove. He recalls "a lot of talking to myself." He passed the Oscar Meyer Weinermobile twice. His travels took him down the furthest capillaries of dirt roads and deadest ends of the nowhere-est towns in America.

"It's a unique lifestyle," admits Vincent. "You meet a lot of 'road warriors,' as the term is." He estimates that by now he's spent a total of five or six years of his life in hotels or restaurants. "I can throw a dart at a map of the country and I can tell you where to eat where it lands," he laughs. "I can identify a hotel by its hairdryer." After his first day on the job, he did laps in the hotel pool, intending to exercise away the long hours spent at the wheel. "Yeah… that lasted one day," he chuckles guiltily.

Road atlases from travels around the United States.

Vincent visited 47 states, three provinces, and one territory in total. Northern Minnesota, Utah, Nevada, the Guadalupe Mountains in west Texas, and central and Western Montana make up his top-five list. "There are beautiful places all around the country that I didn't know existed," he says. "Prior to this job, I had driven across the country once, but I felt like a sailboat in the ocean. Everything around me was foreign. Now the whole country, it's not this big unknown thing."

~

[4] Twenty percent of the world's passenger vehicles and 40% of the world's buses and trucks are driving on American roads at any given time. Each year, Americans rack up about 3.5 trillion vehicle-kilometers of travel.

The challenge of reconnaissance work was getting strangers to grant Vincent a favor in the name of science. As soon as he pulled up to a property and stepped out of his truck, he needed to put the landowners at ease. The first two sentences out of his mouth could secure a site or sabotage it. His technique: “Keep it short, sweet, blindingly honest—enough to catch them off guard. Be straightforward and quick before they have time to develop a defensive tactic.” He has practiced his speaking voice—polite, direct, and sincere, with an audible grin.

Don Lippert trained Vincent during his first month. At Vincent’s very first site, he and Lippert drove up a narrow dusty road outside Winslow, Arizona. “There’s a gentleman sittin’ in the chair just outside his garage, just sittin’ there, kickin’ back, but he had a gun on in his holster,” says Lippert. “The guy turned out to be very nice… He could see that Graylan was just out of school so he gave him a bad time. He said, ‘Oh, c’mon, you gotta fire a gun.’ He had a big .44 Magnum or something, a pistol. Graylan shot that a couple of times. It was sorta fun. An hour later, we had a site and we were gone.”

“It was a honkin’ huge dirty hairy gun,” Vincent recalls with awe.

Graylan Vincent staking out a seismic station.

Vincent primarily interacted with farmers and ranchers whose properties had plenty of space to host a seismometer. “A lot of my job was approaching people working on their tractor or in their shop,” says Vincent. “I’d wave at them to get their attention, and they’d wonder, ‘Who is this yahoo?’” He thinks that someone from agriculture school would have been better suited to his job because they could have bonded with landowners over tractors; he holds degrees from the University of Washington in the more esoteric fields of geology and aerospace engineering.

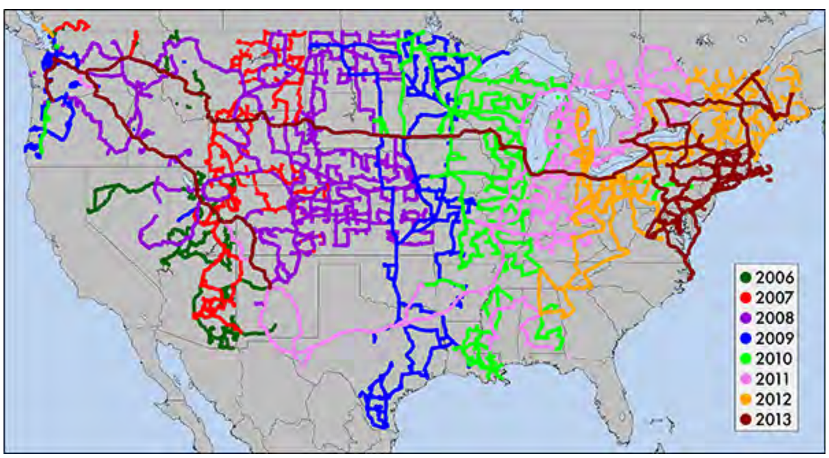
Traveling made him confront his own stereotypes about rural America. To save time, Vincent often tried to figure out whether a landowner would want to participate in the EarthScope experiment based on “their land, what kind of house, vehicles, tractors, whether [he] saw a dog, whether [he] saw college flags.”

He admits that the system never worked. “I met friendly people everywhere, regardless of how they lived and what they drove. You've got to meet them; you can't make assumptions."

Stop sign for horses.

In southwestern Arizona, Vincent came across one dusty retiree whose ranch looked, to his eyes, like a machinery graveyard overrun with dogs. "I thought of him as an old rancher," Vincent says, "but I learned he was an engineer and he had designed the batteries for the International Space Station." The ranch was his hobby farm. He enjoyed fixing broken machinery and his wife ran a dog rescue. "That just took my brain, flipped it upside-down, and punched it through the field goal," says Vincent.

After completing his tour of the nation, Vincent has concluded that "anywhere you go, people are pretty much the same. People are willing to help you out if you give them the chance and get to know them one-on-one… People have some really different accents, different politics, different crops or farming techniques, but that's all. Maybe that wouldn't have been the case fifty or seventy years ago, before Internet, before cable."



Graylan's GPS trajectories over time. Note that a few of the early tracks are missing. *Credit: Graylan Vincent and Andy Frassetto*

The Transportable Array stations moved across the country in a stripe from west to east, and Vincent tried to work from north to south in order to stay ahead of the snow. His goal was to find seismometer sites spaced every 70 km, but he could go about it nearly any way he chose.

There is, in fact, a famous quandary in computational mathematics that deals with that very question. The traveling salesman problem, or the TSP, involves calculating the shortest-distance round-trip route between *n* number of cities. Unfortunately, when you add more cities to the route, the number of possible routes increases exponentially. Just 15 cities yields tens of billions of permutations.[5]

Vincent's route between seismometer sites was definitely not the most efficient solution for his personal traveling salesman problem. He liked to stop and get to know places. His trajectories, tracked on his GPS (nicknamed Sheila because he programmed her to have an Australian accent—"more friendly to deal with"), look like a spider's embroidery.

"I took little detours here and there, whatever chance I got," says Vincent. "The Black Hills of South Dakota. The Wind Cave, the Jewel Cave… Anytime there was anything that would be interesting, I'd pull over and stop." Along Kansas State Highway 47 a crowd of welded wire dinosaurs munches the grass. Maine has a scaled model of the solar system.[i]

Rodon crater.

Vincent made it his particular mission to see as many art museums and pieces of land art as he could. *Spiral Jetty* is one of more than a dozen monumental land artworks around the United States that blur the line between sculpture and geology. "There's something about the scale, boldness, and desolate locations of these works that I love. Plus the adventure of getting to them," Vincent explains.

Vincent got lost in someone's cattle pasture outside Flagstaff, Arizona while trying to get to Roden Crater, an extinct cinder cone volcano that artist James Turrell landscaped into what

---

[5] Solving a TSP means finding the shortest route *and* making sure that none of the other possible routes are shorter—a tall order when you have to test a number of possibilities so huge that we don't even have a name to describe it.

No one has yet discovered a single algorithm that can efficiently solve any TSP with any number of cities. The most recent breakthrough occurred in 2011, when computer scientists solved an 85,900-city TSP with an approximate route that was 49.99999999999999999999999999999999999999999999999996% longer (as opposed to the previous record of 50%) than the most optimal route.

With each TSP challenge involving more and more cities, mathematicians and computer scientists continue to push the limits of computational theory. The TSP's applications include DNA sequencing, computer wiring, neural networks, microchip manufacturing, scheduling, and logistics. Robert Bosch even created a TSP *Mona Lisa* that forms a continuous-line drawing between 100,000 points.

Biologists have also taken a crack at the TSP. It turns out that slime molds and ant colonies, not just computers, can solve traveling salesmen problems. A single-celled slime mold, *Physalum polycepharum*, spreads over unfamiliar areas, and then prunes back its growth until it has established the shortest-distance pathways that connect it to food sources. Ants sniff out pheromones from other ants to find the shortest distance to delicious crumbs.

Vincent calls “a giant art piece/temple/observatory/…thing.” His truck got stuck on the way to Michael Heizer’s earthwork *Double Negative*. He noticed a Jeep abandoned on the road up ahead, but didn’t see the mud until his own wheels had sunk in it. The Jeep’s owner returned with help a few minutes later, and they used the winch on the back of Vincent’s truck to pull both vehicles out. When he finally arrived, it was too dark to see much—“basically a pit dug in the ground across a canyon. But,” he says, “it’s more of the journey of getting out to these places.”

In northern Minnesota, Vincent heard about the Soudan Mine, an old iron mine that now houses an underground particle physics laboratory. He rode an old mining elevator 0.8 km down to the Soudan Underground Laboratory, a research facility run by the University of Minnesota that studies neutrinos and dark matter. Picture two caverns, each about six times the volume of an Olympic swimming pool, carved out of 2.7-billion-year-old green metamorphic rock that formed when lava hardened underwater. Beams of neutrinos are shot from the Fermi National Accelerator near Chicago, located about 700 km away, at 8-meter-wide octagonal detector plates that weigh as much as navy destroyers. “I stuck around an extra day just to go on that tour,” says Vincent. “It was really cool.”

He loved visiting national parks. “In southwestern Utah, there’s a site in the middle of nowhere, site S018A.” It was hours away from any hotels, so Vincent stopped at the nearby Natural Bridges National Monument to camp overnight. He pitched his tent and curled up in his sleeping bag. As his eyes adjusted, he noticed that his tent was illuminated.

“I look up and realize there’s no moon, and then I look a little bit harder and realize, it’s the Milky Way that’s lighting up my tent! I just sit there with my mouth open. It’s so bright! Not light I’d be able to read by, but I could find my way around. Not only could you see the Milky Way, you see the galactic dust clouds that are blocking the Milky Way.”

Vincent retrieved his binoculars from his truck and fell asleep with his head sticking out of the tent, gazing up at the spangled sky. He later realized that Natural Bridges National Monument had been declared the first international dark sky park—a place where no artificial light obscures the nighttime vista. According to the National Park Service, some 15,000 stars are visible from Natural Bridges National Monument, while only 500 stars can be seen in populated areas. “As far as eye-opening experiences,” Vincent says, “that’s one I’ll remember.”

~

Eight years of mowing rows across the country took its toll on Vincent. He would fly out of

Seattle on a Monday and fly home the following Wednesday. He couldn't commit to any regular schedule, maintain a gym membership, or stay current with his Volunteer Search and Rescue certification. He found it difficult to adjust to the city after spending weeks in near-total isolation.

"Day to day, I had so little interaction," says Vincent. "It wore me down. I got burned out, tired of traveling. All the long airline flights. I'm kind of tall. I got tired of not having a life. I really missed getting to take classes and being in a learning environment."

Don Lippert, who trained and supervised Vincent, explains, "At the end, this wasn't him. He was on ten days, off four, so he was gettin' antsy."

In August of 2013, Vincent finally threw in the towel after he finished locating the very last Transportable Array site on the East Coast. The project's scientific rewards as the world's largest seismic data set motivated him to stick around until all the reconnaissance was "tucked into bed, squared away."

"Because of USArray and EarthScope, we expect a whole lot more students going into geophysics and seismology," says Vincent. "Before USArray, you'd have to apply for a grant, borrow equipment, deploy seismometers, recover the equipment, and try to work on results. That's going to take you years. Now you can download a USArray data set in about a second." On top of that, Vincent says, the data are accurate and high quality. "That's directly because of the reconnaissance. I'm really proud."

Now Vincent is in what he jokingly calls "early retirement" in Seattle. He takes woodworking classes at community college, bikes around, and revels in the knowledge that he doesn't have to set foot in Sea-Tac Airport.

"I don't have these multi-hour drives anymore. It's just these five-minute hops. Not even long enough to listen to a podcast," he grins.

He relishes spending time with people, especially now that he can hang around for longer than a few days. When new acquaintances tell him, "I'm from a teeny little town in someplace-or-other," Vincent will respond, "Oh, yeah, I ate barbecue there." He likes eliciting a shocked "What were you doing out there?"

Vincent has a photograph he took that the warm evening at *Spiral Jetty* as his computer desktop background. It's a visual reminder of a journey that took him around the United States—and around and around and around and around again.

For more wacky roadside attractions, see http://www.roadsideamerica.com/

Transportable Array Stations "Adopted" in the Pacific Northwest

The Pacific Northwest is due for a catastrophic earthquake. Offshore from Washington State, the Pacific Plate is grinding slowly eastward, forcing the Juan de Fuca Plate under the edge of the North American Plate. This region of clashing tectonic plates is known as the Cascadia subduction zone, a hotbed of seismic activity that has spawned mountain ranges, volcanic eruptions, and earthquakes. A large earthquake in Cascadia could trigger tsunamis and landslides that would devastate Seattle, Puget Sound, and the Pacific Rim. In a region as soggy as the Pacific Northwest, tremblors could also shake the soil loose and induce deadly landslides. The last megathrust quake, in 1700, generated a tsunami so large that it battered the shores of Japan.

The Pacific Northwest Seismic Network (PNSN) monitors Cascadia's seismic activity and provides early warnings of seismic hazards. In 2009, the PNSN "adopted" 18 seismic stations in Cascadia from the USArray Transportable Array (TA), a temporary seismic network of more than 500 stations that has measured ground vibrations across North America. The TA handled land permitting, construction, and installation in exchange for the cost of the station equipment. Now the PNSN is working on integrating the adopted TA stations into their operations.

On a gray March morning in 2014, one of the TA field engineers, Howard Peavey, accompanied two PNSN technicians to an adopted TA station in Marblemount, WA. MRBL seismic station—formerly TA station B06A—is buried in a meter-wide, 3-meter-deep plastic vault in a private landowner's back field. It lies at the foot of the North Cascades, a mountain range collaged out of volcanic islands, ancient continents, ocean bottom basalt, and mantle rock that were melded together under huge pressure deep inside Earth and then thrust upward.

Peavey needed to hand over a piece of a equipment called a digitizer so that Lynn Simmons and Karl Hagel from the PNSN could install a new seismic sensor in MRBL. Sharing equipment and knowledge is one of the TA's central tenets. A team of TA field engineers travelled to Chile following the February 2010 earthquake to help establish a permanent network of seismic sensors. Members of TA's operating team routinely collaborate with smaller networks like the PNSN. The TA's "adopt a station" program has even led to the creation of a new seismic network consisting of 159 stations along the Atlantic seaboard, a kind of East Coast mirror network to the PNSN that is called the Central and Eastern United States Seismic Network (CEUSN).

Howard Peavey (with shovel) plus Lynn Simmons and Karl Hagel from the Pacific Northwest Seismic Network working on an adopted TA station in Marblemount, WA.

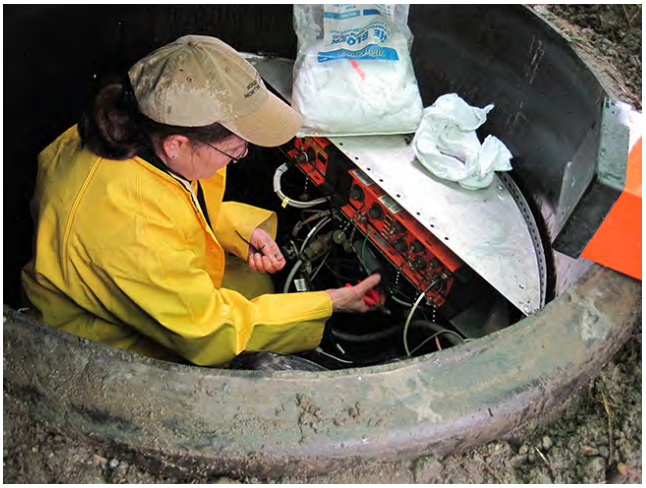
Peavey, Simmons, and Hagel took the North Cascades Highway towards Marblemount, winding alongside the Skagit River. Their windshield wipers beat a frenzied rhythm. With the downpour of the past few days, the river had swelled and swamped up the fields. Peavey predicted a very damp excursion to the station.

During the drive, Simmons explained that many of the PNSN's seismometers are deployed on school and government grounds around Washington and Oregon. If you want a school to host a seismic station, she confided, ask the janitor which teacher is the most enthusiastic science nerd. Fortunately, all the landowners who originally agreed to host TA stations for a two-year stint agreed to participate in the PNSN's long-term network.

The car braked suddenly, sliding on a sheen of mud that covered the one-lane highway. A fresh sludge-stain and splintered boughs marred the pavement; the mudslide must have just happened a few minutes earlier. Several downed trees poked into the opposite lane.

Unexpected obstacles and foul weather are the daily reality of running a seismic network. Peavey keeps boots and a sleeping bag rated to 0°C in his car in case he gets stuck along some country road.

Peavey and the PNSN technicians continued more carefully onward to the landowner's property in Marblemount. They parked about half a kilometer away from the buried station vault rather than sink their vehicles in the muck. Simmons pulled on bright yellow rain pants and a slicker, Hagel shrugged on his coat, and Peavey set a floppy fishing hat on his balding head. They set out across the fallow field laden with laptops, the digitizer, paper towels, rags, shovels, tarps, and umbrellas. Peavey loped along with a blue 11-liter bucket filled with six cans of urethane foam and a wide shovel. "Life is too short for a little shovel," he quipped.


Lynn Simmons working inside the TA vault.

The vault that housed the seismic equipment was buried about three meters from a solar panel mast, which powers the station. Hagel excavated the chained black lid of the vault, then propped it up with a shovel and draped a green tarp over it to shield the vault from the rain.

There was just enough space inside for Simmons to kneel inside without bumping against the metal shelf that housed a row of computers. Peavey handed her the six-channel digitizer, a boxy orange computer with black rubber encasing the corners and six input sockets that look like surprised faces. The digitizer transforms voltage information about the velocity and acceleration of the seismometer's moving parts into measurements of the strength of an earthquake.

Simmons needed the six-channel digitizer to hook up to a seismometer called a strong motion sensor. Strong motion sensors pick up vibrations large enough to cause structural damage, while broadband sensors record tiny vibrations from weak or distant sources. MRBL station has both. A strong earthquake can throw a person sideways off their feet with more than half the acceleration of gravity—that's like freefalling sideways. A cat napping on a windowsill will go flying across the room. During earthquakes that powerful, the shaking is far too strong for broadband sensors to measure. All the TA stations are outfitted with broadband sensors, but the PNSN wants strong motion sensors because they are especially interested in preparing for earthquake hazards.

While Simmons worked on installing the new digitizer, Peavey quizzed Hagel about how the adopted TA stations have been faring. After servicing more than 1000 stations, Peavey knows how to troubleshoot almost any problem with a TA station. For every snarl Hagel had encountered, Peavey had an answering anecdote. Shadows on the lower part of the solar panel? Bend the wire fencing down a bit. Signals that look like lightning strikes? Check whether one of the components is overheating. Is it effective to stick the solar panels up in a tree to get more sunshine? Sometimes more trouble than it's worth.

"I just try to remember what didn't work last time and stop doing that," Peavey said. "It's empirical. If I've seen crazy symptoms in the past, I try to remember and either not do that again or at least remember how it went last time. I don't have the theoretical education; I just have to live on my wits."

A green tarp shelters the vault from the rain while the station was being worked on.

Finally, Simmons heaved herself out of the vault to let Peavey take a gander. He noticed water dribbling in from a screw hole in the wall of the vault that could foul up the seismometers' measurements. The temperature and humidity need to remain stable for the seismometers to work properly.

The best method to caulk the ribbed wall of the vault, Peavey told Simmons and Hagel, uses expanding urethane foam. The foam would eject water in both directions, he said, then harden and keep moisture from filling the rib again. He fit the nozzle of a can of foam into the offending leak point. Foam spewed into the space between the ribs and water sputtered out of a screw hole on the other side of the vault.

"When I pull the can out, it is going to belch a big wad of foam," he warned. It burbled out, the color and consistency of whipped butter on pancakes at a diner, cascaded down around the batteries, and gummed up his shoelaces. "Worse than boogers," Peavey said. He looked down at his sticky pants. "These were my nicest jeans this morning. Now they are work jeans."

At last Peavey, Simmons, and Hagel reburied the vault and tramped back to their vehicles, soaked and muddy. MRBL station was now watertight and functional, sending seismogram recordings of ground vibrations—including the technicians' footfalls—back to PNSN headquarters at the University of Washington. Adopted TA stations like MRBL collect new data so that the Pacific Northwest can prepare for the next big quake.

For more information about how often large earthquakes happen, go to:
http://www.iris.edu/hq/files/publications/brochures_onepagers/doc/EN_OnePager3.pdf

IRIS DMC: Long-Term Archive of All USArray Earthquake Data

It's a nondescript entrance in Seattle's University District, the kind of shadowed door that your eye slides over as chattering students and harried bicyclists rush past. You would never know that it houses the Library of Alexandria of earthquake data.

The Data Management Center for the Incorporated Research Institutions for Seismology, otherwise known as the IRIS DMC, is an archive and clearinghouse of global earthquake recordings. It's the long-term home of every earthquake recorded by EarthScope's USArray, an experimental seismic network of almost 500 seismometers that were sequentially deployed for two-year stints all over the United States during the last decade. Eventually, when the last USArray stations are long gone, students and academics will still be able to study Earth's interior structure using high-quality USArray recordings downloaded from the DMC.

A team of seismologists, Web developers, and analysts at the DMC keep millions of seismograms electronically "stacked and shelved" so that anyone can easily access them online. The stewards of the USArray data set include Gillian Sharer, an analyst who sifts through seismic waveforms and ensures that the instruments are accurately capturing Earth's motion. Manoch Bahavar and Alex Hutko create visualizations and data products to aid other scientists in analyzing massive quantities of seismograms. Sarah Ashmore archives the data, ensuring that they are packed correctly, without gaps or broken files.

The old model of scholars visiting observatories and libraries to pore over charts is obsolete. Now scientists can download terabytes of data at the click of a mouse. Hutko compares it to the rise of online movie streaming and the demise of VCR rentals. "Decades ago, seismologists were happy to look at one or two or tens of seismograms," says Chad Trabant, who manages the USArray team at the DMC. "That age is diminishing. The number of problems that you can address with that few seismograms or recordings is quite small compared to what you can do with a lot more data."

Tim Ahern, the director of the DMC, has overseen data services for the IRIS for 26 years. His wedding ring has a seismogram etched onto its inner surface. Under his leadership, the DMC has pioneered open access to seismology so that anyone anywhere in the world can obtain and play around with data. Not only does IRIS make data freely available, it also lends out seismic


Tim Ahern, the director of the IRIS Data Management Center.

instruments for any researcher to do fieldwork through PASSCAL, the Program for Array Seismic Studies of the Continental Lithosphere. "IRIS totally changed the field of seismology," says Ahern. "The big science used to be done by big institutions. Now the big science can be done by any individual seismologist in any institution. Little universities now participate on a level playing field… We changed the way our science is done, and that has tremendous impact."

Bahavar, Hutko, and the other developers at the DMC generate tools, visualizations, and charts to help seismologists digest and analyze large volumes of data. One type of animation that Bahavar created, called ground motion visualizations, demonstrates how waveforms travel across Earth's surface. Just like when you toss a rock into a pond, earthquakes generate energy in the form of seismic waves that ripple out from the source in concentric circles. With seismic stations evenly spaced every 70 km around the United States, USArray is the ideal scale to reveal those rippling seismic waves.

One of Bahavar's ground motion visualizations combines seismograms from hundreds of seismic stations over the course of ten years. Colored dots representing each station flash red or blue to represent upward or downward ground motion. When you press play on the animation, alternating bands of red and blue sprout in Southern California and shudder across a map of the United States.

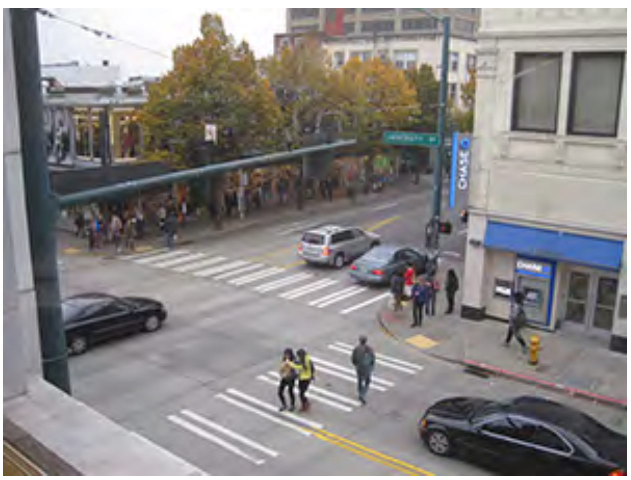
"That ground motion visualization page is so easy to use," says Graylan Vincent, whose job it was to convince private landowners to host USArray stations on their properties. He would show landowners the DMC animations, he said, to emphasize how their contribution to the USArray experiment translated into new scientific insights.

Other data products include back-projection movies showing the sources of earthquakes based on how seismic waves propagated through Earth, software to transform seismograms into audible sounds, and figures showing how infrasound, low-frequency sound waves detected by USArray stations, travel through the atmosphere.

After Hurricane Sandy, Hutko created a visualization that showed the storm blowing across the USArray. "We have this big super-array taking up a good chunk of the US and it can do things like see the effects of a hurricane, in addition to picking up earthquake data," says Hutko.

When major events happen, the DMC creates special webpages with graphics illustrating how faults rupture or how low-pressure airwaves from landslides and storms register on seismic networks. "We try to galvanize the community by collecting disparate pieces of informal or very quick research and put them into a webpage that is a one-stop shop for all preliminary results," says Hutko. Those web pages get cited and circulated by news media. "I got onto the front page of Yahoo," he says.

Another crucial role the DMC plays is in quality controlling the data that streams in 24 hours a day from the USArray seismic stations. Every morning, Sharer runs software custom made by the DMC that combs through seismic recordings to find errors or weird waveforms. "It automatically scans for gaps and overlaps, noise levels, things like that," she explains. She notifies the USArray field engineers when she suspects that a seismometer's masses are misaligned or leaking rainwater has thrown the instruments out of whack so that they can repair the station. She says the daily process of scouring all 500 stations for unusual noise artifacts in the waveforms usually takes her about four hours. Ashmore, a data control technician, then electronically "boxes" and "shelves" the seismic recordings properly so that Bahavar, Hutko, and other scientists can easily pull up the waveforms that interest them.


A view of the "Ave" from the DMC offices in Seattle.

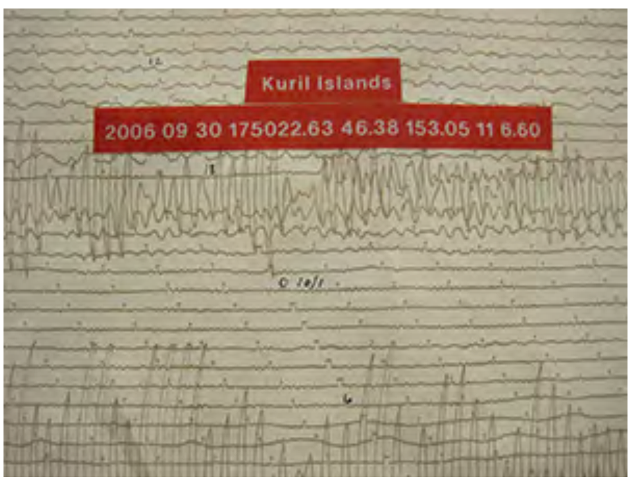
"I would argue that USArray is probably the 'cleanest' network in terms of data," says Hutko. "USArray data are consistently logistical-problem-free. Because of Gillian."

"A lot of other networks don't have resources applied to quality assurance the way that USArray does," says Ahern. Most seismic networks are designed to monitor earthquakes, so they can simply toss out data when stations malfunction. Every recording collected by the USArray, however, can be used to image the structure beneath Earth's surface. Because of USArray's systematic approach, with stations laid out in a grid across the continent, it has set new standards for research networks.

“The fact that we hit 98–99% [data returns] completely changed everyone’s perceptions of what a good seismic array can really do,” says Rob Newman, who builds Web tools at the DMC. “It has been a game changer and everybody I know in the seismic network world wants to replicate what [USArray] did.”

In 1991, the DMC moved into its current building next door to Northwest Net, the Internet provider for the entire Northwest at the time, so that it could rapidly receive data from remote seismic stations. Now that high-speed Internet is so ubiquitous, the DMC’s eight racks of servers fit easily into two small, dimly lit rooms that you enter through a maze of other offices. Three racks of disk storage are located in an adjacent building.

The DMC’s interior reflects the idiosyncrasies of previous tenants; the patchwork layout includes remnants of a ballroom, a basketball court, and medical exam rooms. Ornate columns embellish the attic space. From one office window, you can watch skateboarding students, restaurant deliveries, and careening ambulances along “the Ave,” a populous thoroughfare that runs parallel to the University of Washington’s campus. From another, you can glimpse Seattle’s underside in a back alley. “I’ve seen fights, drumming circles, protests,” says Hutko.



An analog seismogram.

Along one hallway, someone has pinned up an analog seismogram. Pre-digital seismograms used to be recorded by a stylus with ink attached to an arm that drew lines along a scroll of paper. When the seismometer would register a vibration, the arm would oscillate and the stylus would draw a squiggle. Now seismograms are recorded as bits in a computer.

In the largest office space, two prominent screens display seismic waveforms scrolling in from the Global Seismographic Network, which IRIS also manages. The roughly 150 GSN stations are distributed around the world. Ahern points to parallel wiggles: “This is in Antarctica. This is a Venuzuelan station. Greenland. This one is Siberia. This one’s in Arizona.”

Data from about 2600 stations globally, which include many IRIS-affiliated seismic networks, flow into the DMC in real-time, with only a few seconds' delay. "There's a small earthquake happening there," Ahern indicates on the screen. "You can tell by the frequency [of the seismic waves] that these events are probably local, something close to the station. If they were distant, you'd see longer period waves, different frequency content. Also, if it's a big earthquake, you'd see it on many stations."

The employees at the DMC frequently glance up the tiled screens as if monitoring a sports game or stock market. They're genuinely jazzed about earthquakes and they geek out about shifting landmasses.

"In 2004, the Sumatra earthquake ruptured a fault that was almost 1000 kilometers long. That's basically almost the length of California," says Hutko, bouncing in his chair. "For the 2011 Japan earthquake, one thing that even surprised seismologists was that there were 50 meters of slip on that earthquake. That's almost half a football field sliding past each other. And that extended for hundreds of kilometers! That's pretty awesome."

"The amount of energy released is incredible," interjects Sharer.

"These great earthquakes are so large and they move so much mass that there's actually measurable difference in the length of day," says Hutko. "You and I wouldn't notice on our watches, but physicists and geophysicists can calculate it."

They aren't flippant, however, about the destruction that follows in the wake of monster quakes. USArray has helped seismologists analyze how faults rupture and informed preparations for earthquake damage. Seismologists can't predict earthquakes, but "give us a couple of hundred years' timescale," says Hutko, "and we'll give you a percentage likelihood, which is actually useful for construction." "The hazard assessment is extremely useful for society," adds Sharer. "What we're doing now is going to be mined for information for decades," says Trabant. "Right now we're laying the foundation for people to actually access it."

Road Warriors

Show the Transportable Array field engineers a map of the United States and ask them to point out where they've been. "I've been here," they'll say, sweeping a hand from California to Maine.

They are carrying out one of the largest-scale science experiments in history. The USArray Transportable Array (TA) is a dense seismic network that measures earthquakes in order to study the structure of Earth's interior. The field engineers have installed more than 1700 seismic stations at 70-kilometer intervals across North America.

In the taxonomy of road warriors, TA field engineers lie somewhere between truckers and cellular service providers. They work everywhere and nowhere. They live out of trucks and take-out containers. They're drive-by tourists who have seen almost every American city at a 70 kilometers' resolution through a dusty windshield. Lone travelers, they haunt the tar, eating up the yellow lines, bumping along back roads, stomping around dude-ranches, digging holes and installing seismic instruments in backyards and pastures across the United States.

The TA operates by rolling its 400 seismic instruments from West to East. The field crew deploy stations in one region of the country for two years, then remove them in order to re-deploy them elsewhere. Reusing the seismic instruments in this way requires a finely tuned schedule of operations and a lot of driving time. The construction and install guys—Mike Couch, Dean Lashway, and Bob Pierce—set up a central base in a small town for a few weeks and build surrounding stations in a spoke pattern. The service crew—Dan Knip, Doan Nguyen, and Howard Peavey—snake around the country, fixing up whichever stations have sent out distress signals or need to be drained of rain. Anthony Kim, who removes stations at the end of their tenure and prepares parts for the installers to re-use, mows along about 500 kilometers west of the construction crews.

Bob Pierce and Dan Knipp's sleeping arrangement while installing solar-powered equipment in Quebec in August 2012.

The job requires an unusual level of commitment: three weeks of travel every month, hours of highway transit carrying supplies between seismic stations, and long days of construction in remote locations. Many of the field crew come from a military background and are used to relocating frequently, but this lifestyle is even more transient than what they're accustomed to. "Sometimes I don't get home for a couple of months," says Doan Nguyen, a soft-spoken older engineer from Washington State. Traditional family life proves challenging; none of the field crew have young children, and only a few are married. "The loneliness factor is high," admits Dan Knip, whose job fixing broken TA stations means he doesn't know where he'll be each week. "I think if I were to fall into a hole in the ground, people wouldn't know where I was for a month."

Bob Pierce has been installing TA stations since the very beginning, April 2004. "I have a house in Albuquerque I haven't lived in for about ten years," he says. "I used to visit every few months, but not anymore." He likes the reclusive nature of the job. He frequently disappears on camping trips between installs and won't answer his phone. His colleagues once called the National Park Service to report him missing; turns out he was just off in the woods.

~

The TA field engineers mostly work alone, coming together only for difficult installs, in particularly remote areas of Alaska and southern Québec, or for annual team meetings. The majority of their time is spent in solitude at the wheel.

Drives between stations can be brutal. Pierce's personal rule is that he finishes a station, gets to a hotel and has dinner, and the next day drives to wherever the next station is, no matter the distance. Knip rode around with Pierce for six weeks of training. "One day we drove 17 hours to get to the next station," Knip says. "That guy has a work ethic." Knip drives on average 240 kilometers per day, but his record was 1200 kilometers in one shot. "The miles are tough," he says. "I find myself driving less per day than I did earlier in the project… Howard [Peavey], on the other hand, just this past month went from Socorro, New Mexico to Oregon, fixed the station, and now is on his way to Maine. That's an insane amount of driving."

During the long drives, Pierce plays language tapes and mouths along to Spanish and Italian pronunciations. His GPS, Francesca, sends him "a destra" and "a sinistra" instead of right and left. Knip listens to Jared Diamond audiobooks or ham radios with strangers 1000 kilometers away. Couch, Nguyen, and Peavey listen to nothing but the hum of the wheels.

Knip says he has considered getting a pet to keep him company. "I stopped at a hardware store once and they had little baby ducks for farmers to buy. I thought I would take a duck along with me while I was working, but I realized that one day I would get to the hotel and forget him in the car or get out the site and forget about him and a wolf would eat him," he says. "I thought about maybe I could grow carrots or something on top of the truck, have a garden in the box, so that as I'm driving down the highway the sun will grow the whole garden. But I haven't done that either."

The field crew breaks the monotony of travel with little personal rituals. Pierce is on a quest to visit every Starbucks in the country. Knip tries to fish in every state. Anthony Kim keeps a stack of menus as souvenirs from his favorite meals. He's been audited three times because the higher-ups can't fathom how one person could spend $200 at mom-and-pop restaurants in rural towns. Pierce vouches for Kim's formidable appetite. "He'd get a grocery bag, sometimes two, full of food. He'd have the full family-size cans of ravioli and Spaghetti-o's," Pierce says. "He'd sit in the passenger seat while I'm driving for like three hours, opening cans and eating and eating and eating and throwing the can in the back and eating and eating. Constantly."

~

"This is kind of a 24-hour-a-day job," says Howard Peavey, a frenetic, graying New Mexican who has been known to fix stations with any material at hand, including a hockey stick and some duct tape. While he drives, he muses about which clues he missed while working on the last station or considers what to do at the next one. "When I wake up in the middle of the night, I'm usually back on the computer again," reading statistics about broken stations and trying to diagnose what's causing malfunctions.

What keeps the field crew from burning out? Everybody credits the team mentality cultivated by TA's manager, Bob Busby. "We are really fortunate to have him running the project," says Knip.

Juggling a team of field engineers, analysts, and researchers spread around the United States proves challenging, but Busby's strategy is to focus on the daily logistical issues that crop up in the field. "Whenever somebody has a problem in the field or calls in from a remote location, they actually take priority over the people who are in offices," he says.

He credits the field crew's resourcefulness and slight obsessiveness for a seismic array that delivers data of unprecedented quality. "A lot of my management style is to find skilled experts and grow their skill level outward to encompass more and more people, build variety of expertise, and let people try to do their job or improve the project from within," he says.

"I don't want to go home without the job accomplished," shrugs Nguyen, whose record of installing two to three seismic stations a day around New England has some of the other field crew members shaking their heads in disbelief.

“There are a lot of rewarding, disciplined, interesting people,” says Knip. “So you get hooked up in a team that is really driven, and it starts to consume your thinking. I’ve had many important jobs where, at five o’clock, I would wash my hands and go back to my own life. I don’t do that here. You see this [work ethic] in all the guys… That’s Busby’s gift to the whole world. We are a bunch of kittens and he keeps us all herded without using a whip.”

~

In October 2013, the TA turned 10 and the field crew finished installing the final phase of seismic stations along the Atlantic coast. The team comes together for a wrap-up meeting in Woods Hole, Massachusetts. The men look haggard. Many have driven straight from their last installs in Maine. They’re eager to hear what scientific discoveries their years of driving and digging had enabled—they joke that they had completed “Ph.D’s in dirt.”

During the science presentations, Knip stands at the back of the room; he’s been sitting in his truck for too long, he says. After three days of meetings and more social contact than he’s had in an entire year, he and the other field engineers return home for a mandatory month-long vacation. “My preference would be *not* to go somewhere,” says Knip. “Have a staycation.”

A TA Field Engineer's Guide to the United States

The United States road system is a feat of human engineering, an extensive web of arteries supplying resources and providing access to the furthest corners of the country. If you gathered all the roads in the US, from interstate highways down to dusty washboard lanes, and laid them side by side, they would take up an area the size of South Carolina. The Transportable Array field engineers have traveled roughly 2.5 million kilometers of those roads.

The USArray Transportable Array (TA) is a network of more than 1700 seismic stations deployed across the United States in order to record earthquakes and study Earth's interior structure. The TA field engineers construct and install those seismic stations, fix broken stations, then remove them after two-year stints. The field engineers are nomads of the interstate system. They live three weeks out of every month in hotels and play tourist in the towns and lives of the landowners who host TA seismic stations on their properties. Collectively, the field crew have slept in hundreds of hotel beds, dined alone in thousands of corner booths, and visited every single county in the United States.

Construction on a seismic station site. *Photo credit: Graylan Vincent*

They have seen a lot of mile markers and yellow line in transit between seismic stations. They've criss-crossed the continent dozens of times, sometimes sitting behind the wheel for an entire day in order to keep up the TA's schedule of operations. "Driving across the Dakotas, it seems like there's a time warp or something," says Howard Peavey, a service technician from New Mexico who fixes malfunctioning stations. "You're driving past the same three bushes every hour for hours and hours, thinking it'll never end."[6]

Dan Knip, a service technician who hails from Minnesota, was astonished at just how extensive the country's network of roads turned out to be. "I suspect you could drop somebody

[6] Read more about unbearable stretches of highway here.

off in the middle of the US and they would have to walk no more than 16 kilometers to bump into a road, anywhere in the country[7]," he says. "The whole US is consumed by roads and agriculture. There is nothing else."

Roads not only make remote areas accessible, they also bring infrastructure with them—gas stations, convenience stores, hotels, restaurants, and cell phone towers. It is this infrastructure that made the TA possible. The field engineers mailed spare station parts via UPS and FedEx, slept in Motel 6's and Holiday Inns, and sent seismic data back to California and Washington via cellular networks like Verizon and AT&T. Without easy access to communication services, fuel, and lodging, they would have had to carry supplies with them for hundreds of kilometers.

Only in a few locations, like Nevada, were stations set so far from civilization that veteran station installer Bob Pierce remembers loading up on sand and supplies in Reno and spending the next two weeks working on three seismic stations. "One site, Soldier Meadow, we started off in Reno. It took an entire day just to get to the site. Sunup to sundown, going through some ungodly places. Then we had to stay in the ranch house for the night and finish the site. It took two days to finish the site. A whole lot of sites in Nevada were like that."

"[Homogeneity] makes it easy to go from one place to another and be successful at buying hardware at an Ace Hardware or a Home Depot, get coffee at a Starbucks that will taste the same anywhere," says Knip. "It makes travel at a high rate possible. But there is some degree of monotony to it."

Precarious drives to get to remote stations. *Photo credit: Graylan Vincent*

Many people credit the interstate highways with speeding up America's homogenization. The interstate highway system was constructed during the Cold War as an efficient transportation network for defense modeled on

[7] Knip's estimation is spot on; according to a report by the US Geological Survey, any location in the Lower 48 is at most 20 kilometers from some kind of road.

Germany's Autobahn. Mass transit connected distant cities and made it easier for Americans to move between previously isolated communities, bringing familiar chain businesses and development with them.

"Most of the country is asphalt roads, truck stops, Outback Steakhouses, and Best Westerns," says Knip. "Once in a while you run into places that are not homogenized yet, and that's kind of cool." In West Texas, he stopped at a restaurant "where the waitress was busy, so she asked me if I would pour coffee for the next people that came in. That was nice. Real hometown-y kind of people." Louisiana also had its own flavor. "The canals with boats on them, the non-standard English. But pretty much the whole US is the same kind of people. Walmarts everywhere."

How has traveling down America's highways and byways changed the field crew's sense of the country?

"I always thought we were one large metropolitan area," says Knip. "But there's really lots of open spaces—except all the open spaces are cornfields or cattle ranches… There is not much of that Yellowstone-like [wilderness] of buffalo and grizzly bear. Most of the US is cultivated."

Peavey agrees with Knip that the United States is fairly homogenous. "I don't think the cultural and political differences are as great as I had been led to believe as a kid growing up in Yankee Land," says Peavey. "People up north can be pretty provincial too. I can't claim to avoid that. I'm guilty of it too."

The field crew did, however, observe extremes of poverty. "Down in Florida, like in Naples, the homes are castles. They are monuments to opulence," says Knip. "You sort of get the idea that everybody in America is really wealthy, and then you see really crushing poverty… I've seen guys living in paper shack houses that would make you think of the Appalachians in the 1850s." He says, "I would rethink capitalism after seeing the US."

Some of the field engineers encountered narrow-mindedness and racist attitudes. Anthony Kim, an Asian field technician who removes TA stations at the end of their two-year deployment, recalls being ignored by an Alabaman who assumed that Kim's Caucasian temp workers were in charge. "He blew right past me, goes up to my temps and is like, 'Who's the boss here?'" Kim says. "Obviously pretty prejudiced… But for every one of those, there were landowners who were like, 'C'mon in. Are you guys hungry?' And they'd get a sandwich for you."

"People have been kind at levels that you'd be surprised," says Knip. In fact, he couldn't believe how few people became suspicious when they saw him parked along some road or opening a landowner's fence. Only once, in "either Florida or Texas, I can't remember which," Knip was stopped by police while fixing a station on the grounds of a state park. "They said that the area was filled with drug traffickers bringing drugs and dropping them on the coast, and that the police officers did not trust anyone not to be associated with the cartels." Knip showed the officers his TA reconnaissance report, documents containing permission to work on the station. Forty-five minutes later, after questioning him at length and listening to an explanation of the Transportable Array project, they let him go.

Doan Nguyen installing Station K15A while the landowner's dogs look on. *Photo credit: Graylan Vincent*

Ultimately, the TA has depended on the kindness of strangers who were willing to spare a corner of land to host a seismic sensor. Landowners have trusted the field engineers to work freely on their properties and have invited them into their homes, offered them coffee, struck up conversations, and taken them shooting. Sometimes, landowners can be downright insistent; one woman in Texas refused to let field engineer Dean Lashway and his construction team leave without sampling her homemade tortillas.

In exchange for the hospitality, the crew occasionally fills a few holes or pulls out shrubs with the backhoe if landowners request it. They also trade knowledge, providing pamphlets and pointing landowners to websites that show what kinds of scientific research have come out of the TA's earthquake recordings as a result of their generosity.

"TA has succeeded because the continental US has good transportation and communication infrastructure," says Peavey. "[We] have been able to flit around the array and concentrate on the task du jour, not the elements of human existence."

The TA's next phase, seismic stations laid out in an evenly spaced grid across Alaska, will face a challenging wilderness with "virtually no infrastructure," Peavey says. "Few roads. No communication system… The project has to move people, equipment, information, food, shelter, and safety with diesel or turbine fuel." It will be a test of the TA field crew's ingenuity and hardiness as the they pit themselves against Alaska's uncolonized and unforgiving landscape.

More TA Field Crew Adventures

"People thought I was telling big tall tales," says Daniel Knip. "They wouldn't believe me. Now you're in New York, now you're in Niagara Falls, in Quebec, now you're in Ontario, oh look, now you're in Florida, now you're in Alabama. Dean [Lashway] told me to start posting pictures [online] so friends would realize that there are really people who have been *everywhere* in the US."

Knip is a service technician for the USArray Transportable Array (TA), an extensive network of seismometers that records ground vibrations from Earth's surface. After constructing, installing, maintaining, and removing more than 1700 seismic stations deployed every 70 kilometers in a grid across the United States, Knip and the rest of the field crew have logged tens of thousands of hours traveling and have collected a lot of stories. Many of the miles and seismic stations blur together, but a few stick in their memories. Field engineer Bob Pierce can still recall sites he installed a thousand stations ago: "Some of them are unique."

Getting to a snowed-in station by Snowcat. Photo credit: Graylan Vincent

Traveling the country as a TA field engineer holds little glamour, but it does involve a good dose of adventure. Dean Lashway was a city guy who got his first glimpse of the Milky Way while working on the TA. He was helping Pierce install a site in Colorado, far from the sky-haze of light pollution. But it wasn't only the galaxies that glowed.

"It got dark and I got surrounded by coyotes," Lashway recalls. "Bob said, 'As long as you see the red eyes, it's ok. It's when you see the green eyes that you got a problem.' I was like, 'Why, what are green eyes?' He said, 'Those are the big cats.'

Mike Couch, who worked on the installation team, tells about a legendary black wolf: "Golden eyes, black fur with snow sticking on." He had driven into a wintry station. "If I'd been hiking, I would've been dead."

Knip once stumbled across a gargantuan rattlesnake hanging above the door in a convenience store in Wyoming. "It was half again as tall as me, and huge, bigger than the size of my thigh." The snake apparently hailed from Texas, where the taxidermist had stretched it a bit beyond its true size for dramatic effect. "I thought, if I saw one of those out working, I would quit," says Knip.

A snake next to a Transportable Array vault lid. *Photo credit: Dan Knipp*

The snakes he has met sleeping around the lids of the buried seismic stations usually slink away without bothering him. "I've seen some awfully big spiders—big enough to pay rent if they were in your hotel room. Size of your hand, 10 centimeters or something. Just ugly."

"I've encountered deer, turkeys, tarantulas, scorpions, bears, wolves, and mountain lions," says Pierce. "But the bugs are the worst. Chiggers, leaving itchy red spots."

At one site, Knip says, the landowners had domesticated a deer that lived in the woods by their house. When he started petting the family dog, the deer nosed up to him demanding some petting as well.

The true menace, Knip says, are cows, who like to crowd around and rubber-neck while he fiddles with wires in the underground vault that contains the seismic equipment. "You don't want to be working in a hole in the ground when a 700-kilogram stupid animal walks over and falls down on you." He once pepper-sprayed a cow to keep it out of his hair. "It worked pretty good."

"I've never been attacked by a cougar or eaten by a bear… I suspect the most dangerous part of the job is driving. Being killed by a semi," says Knip. "I've been up adding extensions to the communication antenna and 110-kilometer-per-hour winds blow my jacket off while I'm hanging from a steel pipe 4.5 meters up in the air. I've been at stations that are struck by lightning, so that as you are adding steel pipe mast and the storm is brewing, you can see the lightning strikes."

Knip once fixed a station that had been hit by a lightning strike so powerful that it melted the solar panel, snaked inside the vault via the wires connecting the buried station to the solar panel, and exploded the plastic in the vault. "Plastic can conduct electricity at one million volts. I didn't know that."

"I replaced everything. Everything was broken," he says. "Lightning is evil. If you had been in the vault, we would have gotten your parents a new child. One million volts coming down? Holy buckets."

Solar panels busted up by teenagers. *Photo credit: Dan Knip*

Sometimes human visitors, not animals or foul weather, interrupt the field crew's work. Knip and his fellow service technician Howard Peavey were so exasperated with teenagers repeatedly throwing rocks at the solar panels powering Station 457A in Yulee, Florida that they put up a sign asking the kids to desist so they wouldn't have to keep returning with replacement panels. (It worked.)

Early in the project, installers Pierce and Mike Couch were driving along a forest road in the Umpqua National Forest in Oregon when a man popped out of the trees with a clipboard and demanded to know what they were doing. He wasn't wearing a ranger's uniform, however. "He was a conspiracy theorist. Government killed his friend, supposedly," says Pierce drily. The man camped in a large military tent in the National Forest with a span of mules that he had bought in Canada and was trekking down to Mexico to sell.

Pierce and Couch left him and began work constructing the seismic station when a gunshot blasted between them, luckily missing both. The man was standing at the edge of their clearing. He nodded in greeting and said, "It's ok, just signaling my wife to get water."

Pierce sighs. "That was the first real nutjob."

One landowner, who the field crew affectionately dubbed “Photovoltaic” or “PV” Potts, lived near Mt. St. Helens in an off-the-grid, mostly solar-powered home built out of an old school bus. Don Lippert, who first visited Potts’ property, describes him as a “retired hippie.”

“Ahhh, Mr. Potts… You pulled into the road that went to his place and it looked like the Grateful Dead graveyard for vehicles.” Potts negotiated with Lippert to get two solar panels in exchange for hosting the station. When Doan Nguyen arrived several weeks later to install the station, Lippert says, “old Mr. Potts said, “Hey, I was promised two solar panels.” So Doan said, “Okay, I’ll give you two and that’s it.” But anytime anybody came back to service the station, he was always conning people into some more solar panels.”

“Each of us agreed, expecting the other panels to be collected,” recalls TA manager Bob Busby. When Potts ended up with several solar panels, “that twisted Busby’s knickers,” says Peavey, who fixed the station on Potts’ property a few times.

Some of the field crew ended up connecting with the landowners they met during their travels. Peavey used to keep tabs on a veteran who lived in a tarpaper shack next door to a station in western New Mexico. “He’s one of those displaced Vietnam vets who has not found his way into society again… He lives out there because he can’t deal with civilization, but he has a tiny little television and an antenna. He could get one station out of Albuquerque. He was much more aware of world events than I am,” says Peavey. “Since he was the one watching the station and making sure nobody ran off with any of the important equipment, I made several trips out there. When I was going anyway, I made sure that I had things—food, different sorts of things I thought he may need. He was as close to a subsistence person as I know.” Peavey says he hasn’t returned to visit the veteran since the station was removed several years ago. “I don’t know what became of him.”

If you look at a map showing the entire TA network rolled out across North America, the stations are arranged in rows and columns labeled with letters and numbers. “The top row is the A’s, then the B’s, then the C’s. It starts on the West Coast at one and goes sequentially into the fifties over on the East Coast,” says Knip. “I talk with people about the US in terms of the D row. Right now I am on the Y row. I don’t know what city I’m in without looking at my phone, but I know what row.”

“The stations all blur together,” sighs Knip. “As we slow down, I look back and I wish I’d kept a journal: I went to this city, I went to that city, I did this.”

USArray Data Have Helped Launch Careers

Miaki Ishii and Maureen Long are two young geophysicists whose early careers have been minted by the USArray data set. The USArray Transportable Array is an extensive network of seismometers deployed across North America that records ground vibrations from earthquakes. Ishii, Long, and other scientists and students can freely access those recordings in order to study a multitude of questions about the structures at and beneath Earth's surface.

Ishii and Long utilize the same USArray data set; however, they study very different processes. Ishii's research at Harvard University uses USArray's earthquake recordings to create back-projections of what occurred at an earthquake's epicenter. Long teaches at Yale University, where she uses USArray seismograms to study the mantle, the thick viscous layer directly beneath Earth's crust.

Long knew she wanted to be a geophysicist back in 8th grade. "I took Earth Sciences," she says. "We did a unit on plate tectonics and started mapping out that earthquakes and volcanoes happen on plate boundaries. I just thought it was the coolest thing I had ever heard in my life. I thought, "This is what I want to be when I grow up." I was twelve years old."

Her current research focuses on the dynamics of Earth's mantle. "Right now we're sitting here on continental crust, which is 35–40 kilometers thick," she explains. "The mantle makes up about 80% of the volume of the Earth… If you look at a cross section of Earth, the crust is like the skin on an apple, and the mantle is everything else."

"We want to know what's going on down there because it turns out that processes in the mantle actually control a lot of what we see at the surface," says Long. "We still don't understand very well how continents are formed, why Earth has continents as part of its plate tectonics systems, and what processes led to the formation of the continental crust."

The more scientists can learn about how the mantle interacts with tectonic plates, the more informed they can be about how, why, and when earthquakes occur. Those insights not only teach us about Earth's geologic history, they may also help us prepare for earthquake hazards and prevent humanitarian disasters. "All of the plate tectonics we see at the surface, which affect natural hazards—we can't understand that system unless we understand what's going on in the deep Earth," Long says.

It is too difficult to drill down and observe the mantle firsthand, so scientists like Long and Ishii rely on remote sensing techniques from the field of seismology. They image the deep Earth using seismic waves from earthquakes in the same way that a doctor examines an X-ray to find out what's going on in a patient's body. "The fact that we can get such a crisp and detailed view of Earth's interior from seismic waves, I just think is really cool," says Long.

Earth's mantle consists of rocks and minerals were compressed at such high temperatures and pressures that, at certain depths within Eath, they can flow like a viscous liquid. Using a technique called seismic anisotropy, Long can look at the different speeds of seismic waves recorded by USArray seismic stations in order to map out where the mantle flows faster or slower and in what directions it oozes.

Maps showing the topographies of mountain ranges and watershed systems of rivers already exist for the surface of North America. Long wants to map the shapes and flows of the *underside* of North America. "Now, with the continent-wide view of the mantle structure that we get from USArray, we can really ask how the deep structures and processes that we infer from seismology connect to the surface geology, and what that tells us about the evolution of the whole North American continent."

Ishii studied physics as an undergraduate at the University of Toronto. Her first-year instructor, Jerry Mitrovica, was "probably one of the most entertaining people in the world… He basically told me, 'Go be a geophysicist.'" She found that seismology combined the theoretical techniques she loved from physics with real-world applications.

Different kinds of earthquakes at different depths allow Ishii to look at different segments of the core, mantle, and crust. "I really need a deep, big earthquake to give me all the nice information about the deep inner core." Non-scientists are often shocked when she tells them that earthquakes can be a useful tool. "I try to explain that we are not looking for disasters. My ideal earthquake is a magnitude 7.0 at 700 kilometers' depth. People won't feel too much at the surface unless they are sitting right on top of it."

Ishii explains that the USArray is a particularly powerful seismic network for doing tomography—imaging Earth's structure using seismic waves. The USArray Transportable Array seismic stations, densely packed every 70 kilometers across the surface of the United States, provide a very high-resolution image of a wavefront vibrating outward from an earthquake event.

“The earth is not homogenous,” says Ishii. “We have continents and oceans at the surface. So waves passing through the continents are distorted differently than waves going through the ocean… Having dense stations [with the USArray] allows us to correct for that distortion.”

One of Ishii’s main projects using USArray data by aligning signals from earthquakes recorded at different stations in order to form a detailed visualization of how ruptures occurred. “That was something we didn’t think we could do, and it turned out to be very successful,” she says. “Now we are starting to see earthquakes that are actually not detected by conventional techniques.”

Imaging deep Earth structure using seismic tomography and doing back-projection analysis to “rewind” and visualize how faults rupture can help scientists learn what to expect next time a big earthquake hits. Scientists cannot predict earthquakes, but they can look at certain types of faults to figure out what kinds of motion and aftershocks to expect. They can also extrapolate from historical data about earthquakes to determine, within a large window of time, when another quake might hit. Their hypotheses inform building codes and evacuation procedures that can save lives. Ideally, Ishii says, they could image ruptures immediately in order to send out tsunami warnings or shaking announcements. “But without understanding how earthquakes happen, that’s very difficult.”

Ishii has been in several earthquakes herself, and she draws on those experiences to teach her students about magnitude and intensity scales. She still finds it amazing that, after an earthquake, seismic waves continue to travel through and around the planet, totally invisible to human senses. “When you have a big earthquake, it’s like hitting a bell. The earth rings,” she says.

The USArray first started making data freely available online just as Long and Ishii were finishing their graduate and postdoctoral studies. Long says, “It has been really formative for me and my contemporaries. Just as we were establishing our independent scientific careers, along comes this data set, this opportunity.”

“It completely changed the game,” she says. “It’s like if you had been an astronomer and all you had was a pair of binoculars looking up at the sky, and then somebody gave you this amazing telescope. All of a sudden you’re able to see so much more than before. That’s really what the USArray data set has done for seismology, specifically for looking at the structure beneath North America. It changed what we can do, what kind of imaging we can do, what kind of questions we can ask and answer."

She and Ishii access USArray data sets, data products, and teaching tools on a daily and weekly basis through the website for the Incorporated Research Institutions for Seismology (IRIS). They can also borrow seismic stations from USArray to set up "flexible arrays," small seismic networks for temporary experiments. Long has a Flexible Array study underway now in the Appalachians. "Before USArray," says Long, "if you wanted to have data from a particular place, you had to do it yourself. As an individual scientist, you could never do something on the scale of USArray."

Ishii hopes that, in the future, seismologists will be able to deploy a permanent observatory like the USArray Transportable Array for long-term earthquake monitoring. "We've seen how much the data set can do in advancing our studies and results. It definitely makes us think, how many things are we missing without having the TA [around permanently]?"

Long praises USArray for setting an example with its philosophy of open data access. "That's really important for the geophysical community and particularly important for early career scientists." She also thinks that "the USArray data set has pushed us seismologists to work in a more interdisciplinary and collaborative way."

"I was not around when USArray was being conceived and planned," she says. "At the time, people thought it was nuts, that it was too big. Whereas for me and people my age, we've grown up with this being a reality. You almost take it for granted that *of course* it's possible to go out and collect a data set like USArray. So I think it has enabled people to think even bigger… Like, wow, if we can pull off USArray, what are the next crazy ideas that might turn out to actually be doable and pay off with amazing scientific rewards?"

Appendix E. List of USArray Media Exposure

Date	Title	Source
2009	Salesmen for Science	Texas A&M Alumni Magazine
7-Apr-09	Listening to the Earth's deepest secrets	New Scientist Magazine
2-Jun-09	Geophysics Team Participates in Continent-Wide Seismic Probe	Univ Arkansas at Little Rock
12-Jun-09	Earthquake recording stations to be located in Missouri	Missouri S&T News
12-Jun-09	Scientists Placing Earthquake Stations in Missouri	KSPR (Missouri) News
9-Jul-09	Team participates in project to explore Earth's interior	The Northern Iowan
14-Jul-09	Scientists seek local help in studying New Madrid fault	Daily American Republic (Missouri)
17-Aug-09	Newby farm chosen for EarthScope seismic study	The Pratt (KS) Tribune
8-Sep-09	EarthScope Advances Quake Prediction	VOA (Voice of America) News
24-Sep-09	Scoping Out Unseen Forces Shaping North America	Science
30-Sep-09	EarthScope GPS and Seismic Stations Find ETS Phenomenon in Cascade Region That Could Help Predict Mega Earthquake	KCPQ-TV (Q13Fox, Seattle)
5-Nov-09	Subtle Underground Movements: National Seismic Experiment Coming to Lewis County	The Chronicle (Centralia, WA)
15-Apr-10	Seismometers Installed to Gather Data on Oklahoma Earthquakes	KOTV (Oklahoma)
4-May-10	South Dakota is shaking up earthquake research	Capital Journal
Summer 2010	National Earthquake Study Comes to Illinois	Northwestern Univ (video)
10-Jun-10	Northwestern researcher probes Earth for its secrets	Medill Reports
22-Jun-10	Undergraduates train at Purdue for national earthquake program	Purdue Univ News Service
26-Jun-10	Scientists measure seismic activity in Gage County	Beatrice Sun (Nebraska)
27-Jun-10	Seismometers buried in Neb. to measure earth moves	Associated Press
14-Jul-10	Quake monitor installation nears completion	Associated Press (North Dakota)
19-Jul-10	Quake Monitor Installation Nears Completion in North Dakota	Insurance Journal
22-Jul-10	Auburn University, University of Alabama join forces on earthquaketracking project	The Birmingham News (Alabama)
23-Jul-10	State prepared for seismic snapshot	Tuscaloosa News (Alabama)
2-Aug-10	Students Size Up Seismic Sensor Sites	Univ Wisconsin-Madison News
3-Aug-10	AU, UA Students Team with National Initiative to Study Earth’s Interior	The Crimson White
5-Aug-10	Nationwide Seismic Network Underway	Internet Evolution
10-Aug-10	Seismic system for detecting earthquakes is installed in Kindred	WDAY-TV (North Dakota)
10-Aug-10	Slow-moving 'earthquake' under Olympic Peninsula will be well recorded	Univ Washington News
18-Aug-10	EarthScope makes its way to Walsh County; Seismic Monitoring Station installed rural Park River	Walsh County Press (North Dakota)
24-Aug-10	Project Seeks a Better Image Inside Earth	Michigan Tech News
7-Sep-10	Yellowstone Detectives Find Underground Column of Molten Rock	OurAmazingPlanet
13-Oct-10	Seismic station installed on Clever property	Christian County Headliner (Missouri)
20-Oct-10	Unearthing secrets; Seismograph station being installed on area farm as part of EarthScope project	El Dorado News (Arkansas)
1-Nov-10	Ein Kontinent wird eingescannt (in German)	GEO Magazine
3-Dec-10	EarthScope, IRIS plant seismograph near Nelson, Mo.	Marshall Democrat-News (Missouri)
2011	X-Ray Earth (2-hr documentary includes segment on TA)	National Geographic
11-Mar-11	Japan Earthquake Makes Waves Across the U.S.	ScienceInsider
12-Mar-11	Minnesota need not fret 'The Big One'	Twin Cities Pioneer Press (Minnesota)

12-Mar-11	Japan quake recorded at Noonan	Minot Daily News (North Dakota)
15-Mar-11	Aftershocks of Japan quake being recorded in N.D.	Minot Daily News (North Dakota)
31-Mar-11	EarthScope Seismic Sensors Head East of the Mississippi	NSF Press Release
27-Apr-11	Rice University geologist leads team effort to solve mystery of the Colorado Plateau	Rice Univ News & Media
28-May-11	Going seismic: Local farmers to help map tectonic shifts	Winona Daily News (Minnesota)
1-Jun-11	Scientists to Explore Midcontinent Rift in Northern Ontario	Wawa News (Ontario, Canada)
30-Jun-11	UF students help with project to measure seismic activity across U.S.	Univ Florida News
11-Jul-11	Big Science: The Universe's Ten Most Epic Projects	Popular Science
19-Jul-11	Scientists Study Earthquakes in Southern Illinois	WSIL TV (Illinois)
19-Jul-11	Students ID Remote Michigan Sites for Earth Imaging	Michigan State Univ News
20-Jul-11	'Seising' up Southern Illinois	The Southern (Illinois)
24-Jul-11	MSU students scout sites for EarthScope monitors	Associated Press
1-Aug-11	Researchers at UI taking part in $1.3 million geology project	The News-Gazette (Illinois)
1-Aug-11	Looking for mantle plumes	Physics Today
8-Aug-11	Local Farmer Provides Place To Study Earthquakes	Trenton Republican-Times (Missouri)
23-Aug-11	Why Virginia Quake Shook Entire Coast	LiveScience.com
19-Sep-11	Seismograph to be installed at Ryerson Woods	Daily Herald (Illinois)
6-Oct-11	Watching a continental split	The Why Files
7-Oct-11	Earthquake Mapping Project Digs Into Northeast Wisconsin	WBAY-TV (Green Bay, Wisconsin)
13-Nov-11	Tracking tremors: Nationwide earthquake-detection system will uncover seismological secrets	The Columbus Dispatch (Ohio)
18-Nov-11	Scientists to place new earthquake monitors in Georgia, Alabama	Associated Press
25-Nov-11	USArray Headed To Maryland To Monitor East Coast Earthquake Activity...	WJZ (Baltimore)
8-Dec-11	AGU: Twenty Thousand Geeks by the Sea	KQED QUEST
16-Dec-11	New Madrid anniversary: First of catastrophic earthquakes hit 200 years ago today	Hearld Times (Indiana)
7-Feb-12	EarthScope: A Seismic Shift in Data Gathering	Miller-McCune
12-Feb-12	First EarthScope 'Transportable Array' Seismic Station Reaches U.S. East Coast	NSF Press Release
8-Mar-12	Scientists detect seismic signals from tornado	Indiana Univ
13-Mar-12	Correlation between tornadoes and seismic activity?	EarthSky.org
22-Mar-12	The mystery is solved' - Clintonville felt several small earthquakes (note: did not mention ES/USArray by name, but references IRIS and 6 stns)	Shawano Leader (Wisconsin)
23-Mar-12	USGS: Micro-quake near Wis. city bothered by booms (note: did not mention ES/USArray by name, but references 6 stns)	Associated Press
26-Mar-12	EarthScope Workshop Kicks Off at JMU	WHSV (Harrisonburg, VA)
23-Apr-12	Eastanollee gets seismic station	The Toccoa Record (Georgia)
1-May-12	W.Va. getting seismic monitors for 2-year project	Associated Press (WV Public Broadcasting)
1-May-12	EarthScope - Seismic Station Volunteer Program	WV Public Radio (audio)
1-Jun-12	EarthScope’s Transportable Array Plans Deployment in Alaska Beginning Late 2013	arcus.org
7-Jun-12	Students Help to Measure Seismic Activity Across the U.S.	College of Charleston News
12-Jun-12	UNH Geologists to Instrument Northern N.E. With Seismometers	Univ New Hampshire News
12-Jun-12	UNH putting seismometers (earthquake sensors) around New England	Nashua Telegraph
13-Jun-12	UNH geologists to help with earthquake research in northern New England	Associated Press
15-Jun-12	EarthScope national seismic monitoring project arrives in Upstate New York	Syracuse Univ News

19-Jun-12	Helping seismologists see the complete picture	Lehigh Univ News
1-Jul-12	Middleboro selectmen approve installing earthquake sensor	The Enterprise (Massachusetts)
16-Jul-12	Miami part of EarthScope: Continental scale seismic observatory (Part 1)	Miami Univ of Ohio News
17-Jul-12	Professor and Student Scoping out Seismic Sites	Boston College Chronicle
26-Jul-12	Miami part of EarthScope: Continental scale seismic observatory (Part 2)	Miami Univ of Ohio News
1-Aug-12	JMU graduate helps with national seismometer grid project	James Madison Univ News
2-Aug-12	EarthScope comes to Miami University	Oxford Press (Ohio)
6-Aug-12	On fracking and seismic hazards: better data, more quakes	Nature News Blog
6-Aug-12	3 NCCU Students Join Project to Look Deep Inside the Earth	North Carolina Central Univ News
7-Aug-12	Fracking-Earthquake Connection Suggested In New Study (note: did not mention ES/USArray by name, but TA stns were used in study)	LiveScience.com
9-Aug-12	Hydrofracking wells may raise quake risk	Futurity.org
14-Aug-12	Nearly 1,000 earthquakes recorded in Arizona over three years	ASU News
14-Aug-12	About 1,000 Earthquakes Shook Arizona in Recent Three-Year Period, ASY Researchers Report	Phoenix New Times
15-Aug-12	Seismic Station Placed Near Earthquake Site	The Mechanicsville Local
20-Aug-12	2014 study of St. Helens magma system will be among world's largest (note: did not mention ES/USArray by name)	The Columbian (Washington)
31-Aug-12	Shakeout gets land of 1,000 quakes prepared	Verde Independent (Arizona)
5-Sep-12	Watch Costa Rica Quake Vibrations Hit U.S. (note: does not mention ES/USArray, but shows image of and link to GMV)	OurAmazingPlanet
1-Oct-12	North America Spills Its Guts	Discover Magazine
1-Nov-12	USArray: Geoscientists' "Earth Telescope"	EARTH Magazine
13-Nov-12	Superstorm Sandy shook U.S. like an earthquake	OurAmazingPlanet
15-Nov-12	Superstorm Sandy shook the U.S. like an earthquake	Yahoo! News
1-Feb-13	Array Unlocks Sub-Secrets	AAPG Explorer
4-Mar-13	Incoming! Then Outgoing! Waves Generated by Russian Meteor Recorded Crossing the U.S.	NSF Press Release
8-Mar-13	Siberian Meteor Spurs Dash for Data, Calls for Safeguards	Science
18-Apr-13	Superstorm Sandy Shook the U.S., Literally	Science Daily
3-May-13	Hearing the Russian meteor, in America: Sound arrived in 10 hours, lasted 10 more	Phys.org
15-May-13	Va. earthquake is aftershock of major 2011 shake (note: uses recording from TA station, but not referenced in text)	WTOP (Washington, DC)
14-Jun-13	Science writer Richard Kerr is interviewed about USArray	Science Podcast
14-Jun-13	Geophysical Exploration Linking Deep Earth and Backyard Geology	Science
10-Sep-13	Seismic device fuels drilling theories	The Daily Star (Oneonta, NY)
7-Nov-13	US seismic array eyes its final frontier	Nature
21-Nov-13	Gigant Bobler ryster jorden under os (in Danish)	Science Illustrated Denmark
1-Jan-14	Scoping out the North American continent, 10 years on	Physics Today
13-Jan-14	Scientists installing seismic stations in central Virginia for earthquake study	Richmond Times-Dispatch
9-Aug-14	New instruments monitor what's shaking beneath West Virginia	The Charleston Gazette (West Virginia)
13-Aug-14	How to Take the Planet's Pulse	BBC's Focus Magazine