# earthscope

## FACILITY OPERATION & MAINTENANCE

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# EarthScope Facility Operation and Maintenance

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## Volume II – EarthScope Facilities Technical Summaries

# Project Summary

EarthScope is a broad-based earth science initiative that is taking a multidisciplinary approach to studying the structure and evolution of the North American continent and the physical processes responsible for earthquakes and volcanic eruptions. The integrated observing systems that comprise the EarthScope Facility can be used to address fundamental questions at all scales—from the active nucleation zone of earthquakes, to individual faults and volcanoes, to the deformation along the plate boundary, to the structure of the continent and planet. EarthScope data will be openly available to maximize participation from the national and international scientific community and to provide ongoing educational outreach to students and the public.

The **intellectual merit** of the EarthScope Facility is derived from its link to the support of fundamental research throughout the earth sciences. Through an ambitious data collection scheme and broad geographic coverage, the EarthScope Facility will provide the observational resources to encourage cross-disciplinary investigations and stimulate the next generation of research scientists. The design and implementation plan for EarthScope was developed through extensive, decade-long engagement with the scientific and educational communities. Through numerous workshops and working groups, the research community, along with federal and state partners, defined the data and tools required for geoscience to take the next step in exploring the fundamental processes that shape the structure and evolution of our continents. As the MREFC-supported construction stage for the EarthScope Facility nears completion, exciting results are already emerging from the analysis of new EarthScope data, confirming the enhanced resolution provided by this powerful new suite of observational tools.

The **broader impacts** of EarthScope will be achieved through an integrated education and outreach program and applications in hazard assessment, land use, and resource management. While EarthScope is a national program, it is being operated and maintained at local levels through interactions with hundreds of universities, schools, and organizations across the nation. As EarthScope collects data and makes it available, students and the public will be introduced to key unanswered scientific questions and the role that their region or discipline plays in understanding the evolution of the North American continent and the active processes driving deformation and volcanic activity. Improved understanding of the natural environment is the first step toward improved land use, environmentally sound development, and resiliency to natural hazards. With over 3,000 geographical locations, the broad distribution of EarthScope facilities will engage traditionally under-represented groups, particularly students in rural areas that have under-resourced schools and Native Americans on tribal lands (where some of the EarthScope stations will be installed). EarthScope will provide a unique opportunity for students and the public to observe geological processes in real time and to measure geological change within the time frame of an academic school year. EarthScope is providing the public with practical examples of how science advances, as they see new data being collected and watch new theories being formulated and tested.

# Volume II


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# 1. PBO Facilities Overview

## Introduction

UNAVCO is constructing, operating, and maintaining the Plate Boundary Observatory (PBO) component of EarthScope though a cooperative agreement with the National Science Foundation (NSF). UNAVCO is a consortium of research institutions whose mission is to support and promote earth science by advancing high-precision techniques for the measurement and understanding of deformation. The Global Positioning System (GPS) has been the primary tool supported by UNAVCO; however, through the EarthScope, UNAVCO now supports other techniques useful for studying deformation. Borehole strainmeters and seismometers, long-baseline laser strainmeters, interferometric synthetic aperture radar (InSAR), and light detection and ranging (LiDAR), are expanding the spatial and temporal signals that the UNAVCO community can investigate. At the same time, GPS data are being applied in a frequency range that used to be the sole provenance of seismology, as GPS moves from one solution per day to one solution per second. These enhancements are part of a conscious strategy to meet the future needs of the scientific community supported by UNAVCO.

UNAVCO has staff and facilities in six locations, with the majority of the staff located in Boulder, CO. The UNAVCO organization is composed of three primary components: the **UNAVCO Facility**, the **PBO project**, and **UNAVCO Education and Outreach**. The UNAVCO Facility in Boulder is the primary operational arm of UNAVCO for non-PBO-related activities. The UNAVCO Facility supports NSF-funded, project investigators, the NASA-funded GPS Global Network, and projects funded through the NSF Office of Polar Programs. In addition, the Facility is the NSF-funded geodetic archive for distributing and archiving GPS data and data products. The mission of UNAVCO's Education and Outreach (E&O) Program is to promote a broader understanding of earth science through the scientific methods, data, and results of the of the UNAVCO community's scientific research.

*Figure 1.1. Students from the Pathfinder Ranch Science & Outdoor Education Program get a tour of the BSM uphole electronics.*

UNAVCO, in collaboration with the EarthScope E&O Program, is increasing the understanding and public appreciation of geodynamics, Earth deformation processes, and their relevance to society through public outreach, regional and station-specific curriculum development, and a program to employ students in the construction and operations and maintenance of PBO. To increase the diversity within solid earth sciences, UNAVCO E&O hosts the Research Experience in Solid Earth Science for Students (RESESS) program, which combines structured mentoring, ongoing research internships, and a supported learning community for undergraduates from underrepresented groups (Figure 1.1).

## The Plate Boundary Observatory

The PBO component of EarthScope is managed by UNAVCO out of Boulder CO, with construction activities based in five regional offices located in Riverside, CA; Richmond, CA; Ellensburg, WA; Anchorage, AK; and Salt Lake City, UT.

The core of the PBO is a permanent geodetic observatory consisting of an integrated network of borehole and long-baseline strainmeters and GPS receivers (Figure 1.2) constructed under the EarthScope Major Research and Facilities Construction (MREFC) project. The strainmeters are well suited for recovering transient deformation from seconds to a month. Consequently, they play a central role in observing phenomena that precede and accompany earthquakes and volcanic eruptions. GPS is well suited for capturing deformation occurring at time scales greater than a month, such as that associated with viscoelastic relaxation following an

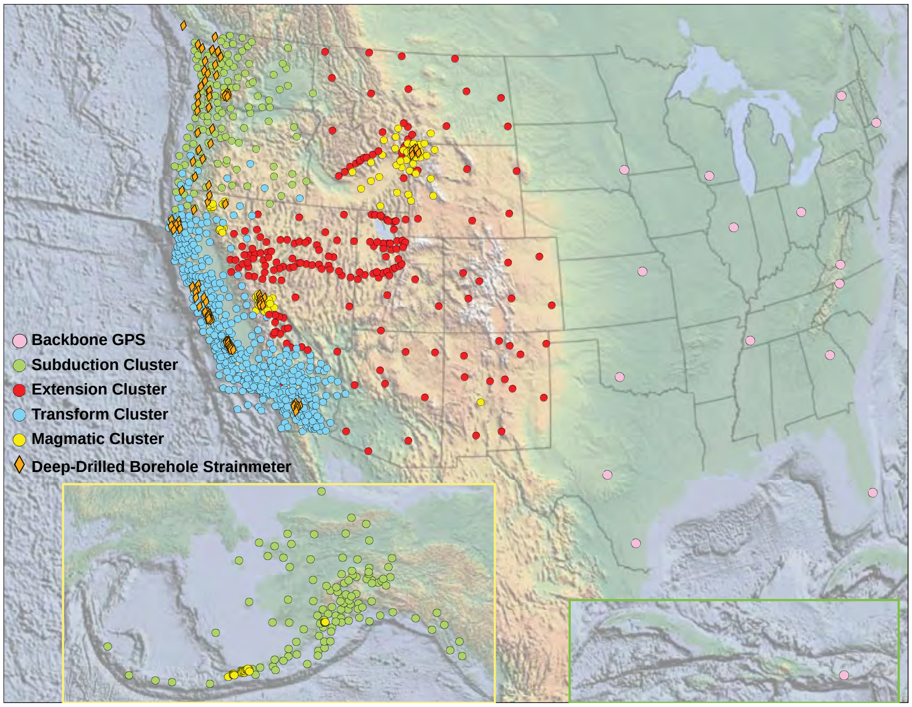


*Figure 1.2. Plate Boundary Observatory Network. Colored dots represent CGPS stations and diamonds BSM stations installed during the MREFC project.*

The PBO is ahead of schedule and under budget with 20 months left in the five-year construction phase. As of March 2007, PBO has installed 533 CGPS stations, upgraded 165 Nucleus CGPS stations, installed 28 borehole strainmeters and 27 borehole seismometers, and installed three LSMs. PBO instrumentation has produced over 350 GB of data and delivered over 1.5 TB of raw GPS, strain, and seismic data and products, all of which are freely available to research, survey, and education and outreach communities from the EarthScope and UNAVCO Web sites. In the following sections we discuss the capabilities of the PBO Facility and instrumentation and the data and data products produced.

earthquake, and decadal estimates of strain accumulation and plate motion and their spatial variations. By using both techniques, the PBO also better observes phenomena, such as transient deformation due to slow or silent earthquakes, that occur on time scales ranging from weeks to months. A core scientific goal for EarthScope is to understand the physics that govern these phenomena.

When complete, PBO will be the most accurate spatial reference system in U.S. history. It will be actively used by researchers and students in geodesy, geosciences, upper atmosphere and ionosphere science, and hydrology and geomorphology, as well as by surveyors, engineers, and others for land-control surveys and infrastructure monitoring. The PBO component of the EarthScope MREFC facility will operate and maintain 1100 permanently installed CGPS stations. Of these 1100 stations, 875 are located throughout the contiguous western United States and Alaska, 16 are permanently installed in the eastern United States, and 209 are existing stations upgraded to PBO standards as part of a separate proposal (PBO Nucleus). PBO will also operate and maintain 103 borehole strainmeter and seismometer stations and six long-baseline laser strainmeters (LSM) in the western United States. Other equipment purchased under the MREFC that will require O&M funds includes a pool of 100 portable GPS receivers for temporary ("campaign") deployments and rapid-response activities.

## GPS Capabilities

For the MREFC, the PBO footprint was divided into installation regions where each regional office is held to a specific number of installations per month. The installation activities are subdivided into natural work packages that include station siting and reconnaissance, land-use permitting, GPS monument installation, power and data communications installation, and site commissioning and data flow. To keep on schedule and budget, PBO measures project performance using Earned Value Management (EVM), a methodology used to measure and communicate the real physical progress of a project taking into account the work completed, the time taken, and the costs incurred to complete that work. We also use an equivalent station metric, which measures work progress, allowing tasks to be combined to enable data delivery to the community.

### Permanent GPS Installations

Prior to MREFC funding, community-based science committees defined GPS station locations based on transform, subduction, extension, and magmatic system tectonic provenance. Because the committees could not completely account for the practical realities of locating a station, siting tolerance buffers were assigned to each station based on a nearest neighbor algorithm. Stations were assigned to each region for siting, reconnaissance, permitting, and installation.

The ideal GPS site is located in bedrock with a 360° sky view. Prospective sites must be accessible and secure, preferably with existing power and data communications infrastructure. Geographical Information Systems (GIS) are used extensively to focus site selection personnel for stations with suitable access, sky view, and data communications coverage (Figure 1.3). Once station targets are identified, field crews visit the sites to contact land owners, ground truth for sky view, power, and data communications, and choose a monument location.

Once a site is located, PBO starts the permitting process with the land owner. For private lands, PBO has the land owner sign a standard permit form, allowing field crews access for construction activities and 15 years of operations and maintenance visits. Our average cost for 15-year private land sites is $2000. Federal and state permitting activities follow compliance regulations of the individual agency. The regulations imposed by federal agencies range from minimal to extreme and include state historic preservation (SHPO) assessment, biological and archeological surveys, and extensive public comment periods. Once the land-use permit is completed, installation crews are scheduled, equipment is ordered from the Boulder warehouse, and data communications equipment is commissioned and shipped to the regional offices.

Installation of geodetic monuments starts with drilling and installing a deep-drilled braced monument. The deep-drilled braced GPS monument (DDBM) is designed to create a highly rigid and immobile structure isolated from surface soil movement when it is cemented in place at depth. The monument consists of five legs (stainless steel pipes) placed into drilled holes, and welded together above the surface to create a "tripod" frame. Of the five legs, the center leg is vertical and the four other legs are installed at angles to brace the vertical leg (Figure 1.4). A choke ring GPS antenna with a radome is secured to the top of the monument. An equipment enclosure houses a Trimble NetRS GPS receiver, a radio or VSAT modem, sufficient batteries to operate the site, and solar panels to charge the batteries. Ninety-one percent of the PBO GPS stations installed to date run off of DC power (Figure 1.5).


*Figure 1.4. UNAVCO personnel installing a deep-drilled braced CGPS monument at Flat Top Peak in Southern California.*

*Figure 1.5. Completed GPS station near Delta Utah and the Wasatch Fault Zone. DDBM with radome housing GPS antenna is on the right. Enclosure housing GPS receiver and cellular modem is on the left. Security fence prevents equipment damage by livestock.*

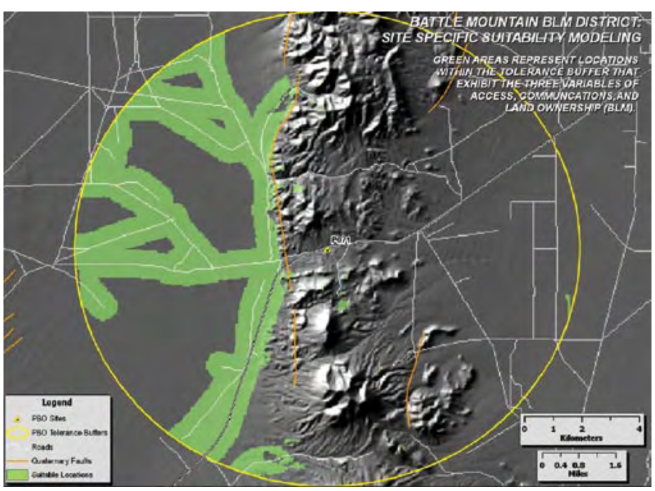


*Figure 1.3. Triangle indicates the GPS station location chosen by siting committee. Yellow circle shows stations siting buffer. Green shading indicates suitable station location based on station access, land ownership, and cellular modem coverage. Station was built due south of triangle.*

These stations record data every 15 seconds in files that are download on an hourly or daily basis. Automated processing routines reduce the data to precise station positions and inter-station distances. The daily estimates of position and distances create an interlocking, three-dimensional deformation-monitoring web so that any tectonic perturbation resulting in ground deformation, such as a large earthquake or volcanic eruption, can be detected, monitored, and modeled.

## Campaign GPS

Campaign-style GPS observations involve a PI installing receivers for a few weeks to a few years. To facilitate such operations, UNAVCO purchased and configured 100 sets of campaign GPS equipment as part of the EarthScope MREFC. The campaign systems consist of a Topcon GB-1000 GPS

*Figure 1.6. University of Colorado and UNAVCO personnel installing a campaign GPS stations near Silverton, Colorado. This station will be used to measure long-term deformation rates across the Rio Grande Rift.*

receiver and antenna, a portable GPS antenna mount, solar panels, and batteries (Figure 1.6).

These receivers are used for GPS-based PI-funded proposals within the EarthScope footprint. PBO has supported both long- and short-term projects with the campaign pool. Notably, PBO supported short-term campaign observations associated with the 2005 and 2006 Cascadia episodic tremor and slip (ETS) events and long-term support for the precise deformation measurements across the Rio Grande Rift. The Rio Grande Rift project is aimed at kinematically imaging extension in the Rio Grande Rift to address what controls extension within "narrow" continental rifts and to determine how extension is related to lithospheric heterogeneity.

## Borehole Strainmeters and Seismometers

As part of the MREFC, PBO committed to install 103 borehole strainmeters (BSMs) and seismometers. As with the continuous GPS program, BSM installation activities are subdivided into work packages that include station siting and reconnaissance; land use permitting; borehole drilling; instrumentation, power, and data communications installation; site commissioning; and data flow. The BSM effort is managed in a similar fashion to the GPS activities using EVM, equivalent stations, and total number of completed holes and data delivery metrics. Installation targets were chosen by planning committees prior to funding of the MREFC. The PBO Standing Committee provides additional siting and instrumentation deployment advice as required by the project. Overall management, station siting, and reconnaissance activities are managed out of UNAVCO Boulder. All construction activities are conducted out of the UNAVCO Ellensburg, WA office.

### Borehole Strainmeters

The ideal strainmeter site has competent, unfractured bedrock at the target depth, sufficient access for drill rigs and installation trucks, and suitable power and data communications infrastructure. PBO contractors drill boreholes to depths of about 150 m and case them using a steel pipe. They then drill the final 50 m and PBO crews run geophysical logs to determine a suitable installation zone. When suitable rock is found, the final section is rotary drilled, cored, or reamed, the bottom 4 m filled with expansive grout, and the strainmeter is lowered into the grout; we use expansive grout to couple the strainmeter to the borehole walls because it does not shrink as it hardens. A three-component seismometer, a pore pressure monitor and, in volcanic regions, a two-component tiltmeter are also installed in the borehole. The seismometer is installed 6 m above the strainmeter and cemented in place. The depth of the pore pressure monitor varies from site to site based on hydrologic characteristics. The borehole is filled with cement to within 50 m of the surface and, if required, a tiltmeter is installed. The electronics that control the strainmeter, environmental sensors, and power supply and telemetry system are housed in an enclosure on the surface. If suitable sky view exists, a GPS antenna is mounted to the top of the borehole casing (Figure 1.7).

Mini-clusters of strainmeters are installed at some sites. These involve drilling two or more strainmeter boreholes within 100 m of each other and installing one strainmeter in each hole. This system allows scientists to validate strainmeter signals and study how closely located strainmeters respond to a geophysical signal, and will allow discrimination of locally-generated signals from tectonic signals.

*Figure 1.7. A PBO borehole strainmeter/seismometer installation along the San Andreas Fault near Parkfield, California. Engineer in the foreground is spooling out strainmeter cable as the instrument is being lowered into the borehole using the derrick lift in the background.*

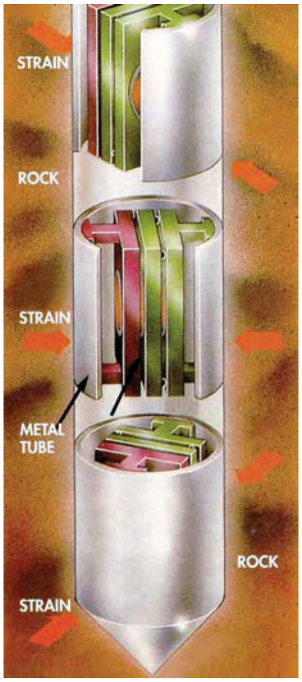


*Figure 1.8. Schematic representation of a GTSM tensor strainmeter. The two green plates are a fixed distance apart. The red plate moves relative to the green plates as the borehole deforms.*

GTSM Technologies of Brisbane, Australia supplies all of the PBO borehole strainmeters. A GTSM strainmeter measures the change of diameter of a borehole in three directions at 120° from each other. The instrument is grouted into the borehole using an expansive grout to ensure it is always under compression. Areal strains are characterized by observations which are equal on all gauges. Shear strains are identified by examining the differences between gauge responses. GTSM strainmeters also have a fourth gauge included in a different orientation to allow redundancy checks on strain measurement. A single unit of measurement (called counts) for GTSM gauges represents 4 picometers of diameter change or a strain of about 0.05 nanostrain. Short-term signals (such as seismic waves) are measured to about 0.1 nanostrain. The GTSM system uses three steel plates acting as capacitors (Figure 1.8). Two of the plates (green) are a fixed distance apart mounted on one end of the sensing diameter, and the third (red) mounted on the other end of the same diameter moves as the diameter of the borehole changes. Changes in capacitance are measured as the single plate moves; from these changes the ratio of the separation between the two plate pairs can be found.

## Seismometers

As part of the borehole strainmeter network, PBO is installing a three-component seismometer package coupled to a Quanterra Q330 data logger sampling at 100 samples per second and transmitted to Boulder using the Antelope software from BRTT. The seismometers are manufactured by SONDI and Consultants and are designed for deep borehole installations. The outer casing is made of stainless steel and the package is cemented into the borehole. The three sensors in the package are Geo Space HS-1-LT geophones with a natural corner frequency of 2 Hz and are arranged in a traditional X, Y, and Z configuration. Each geophone is mounted in gimbals with 11° of movement to handle any deviation from vertical. The inside of the package is filled with a silicone oil to help dampen the movement of the gimbals during deployment and to help weight the package for deployment. The packages are deployed using a 2-in PVC tube that also provides coupling for the pore pressure sensor. An 800-ft multi-conductor, Kevlar-reinforced, gel-filled, heavy-duty cable is used to transfer signals from the sensors to the data logger at the top of the boreholes and is taped every 10 ft to the 2-in PVC (Figure 1.9).

## Long Baseline Laser Strainmeters

The long-baseline laser strainmeter (LSM; Figure 1.10) is an example of an extensometer, which measures the change in length (strain) along a line. A laser strainmeter measures the relative displacement between two end-piers separated by several hundred meters, by directing laser light through a straight, evacuated pipe. Mounted on one of the end-piers is a laser interferometer, at the other is a reflector. The interferometer records any changes in the distance separating the two piers in terms of the wavelength of light from a wavelength-stabilized laser. An evacuated pipe is employed to suppress the variations in the index of refraction of the air that would otherwise disturb the optical path-length measurement. Two LSM instru-

*Figure 1.9. UNAVCO engineer installing a three-component seismometer in a PBO borehole.*

*Figure 1.10. Long baseline laser strainmeter DH2 on the west side of the Salton Sea. The cargo container houses electronics and laser and a pad for the deep optical anchors. The long tube to the right is a vacuum tube through which the laser beam travels to a retro-reflector approximately 500-m away.*

ments are generally installed at 90° to each other. PBO will install five LSM instruments and take over the operations and maintenance of the GVS1 instrument in Verdugo Canyon. All construction and operations and maintenance activities for the LSM program are conducted through a subaward to the University of California, San Diego. The first instrument, DHL2, is located at Durmid Hill, California, next to the eastern side of the Salton Sea and within 2 km of the southeastern terminus of the San Andreas Fault. Two instruments, SCS1 and SCS2, are on the western side of the Salton Sea near the historically seismogenic San Jacinto Fault, and one instrument is at Glendale, CA, next to the San Gabriel Mountains and near Los Angeles basin blind-thrust faults. Two additional instruments will be at Cholame, CA, near the posited initiation point of the 1857 San Andreas Fault earthquake.

## Data and Data Products

PBO's primary mission is to provide high-quality geodetic data products to the scientific community. PBO serves a wide range of users, from those who analyze raw GPS data to others who want to start with geodetic time series and other derived products. One thing that ties all these users together is that they want timely, reliable access to PBO data. UNAVCO meets this need with a robust, distributed management system through which all PBO data flow from the remote station to our users, including redundant centers that analyze PBO data with independent systems, multiple archives to manage PBO data, and several different mechanisms through which users may access PBO data.

To meet the scientific goals of EarthScope, PBO generates a suite of freely available data products, outlined in Tables 1.1 and 1.2 and described here. Level 0 data are raw data collected at each instrument as well as site metadata. All CGPS stations collect data at a rate of 15 seconds/sample (15-sec) and 5 sample/sec (5-sps); all 15-sec data are routinely downloaded, while 5-sps data are only downloaded following a large earthquake or similar event. BSM stations collect 100-sps seismic data; 20-sps, 1-sps, and 10-min strain data; and auxiliary channels at 1-sps and 300-sec. LSM stations collect data at 1-sps. Level 1 data products are primarily quality-controlled GPS data in RINEX format.

Initial GPS Level 2 derived data products, produced by each of two GPS Analysis Centers, include GPS station position estimates in SINEX or similar format and input and auxiliary output files from GPS processing codes. "Rapid" Level 2 products are available within 24 hours of the arrival of data at PBO GPS Analysis Centers, with "final" products available about 15 days later. The delay between rapid and final products is based on the availability of precise orbit files for GPS processing. The highest quality GPS Level 2 products, produced by the GPS Analysis Center coordinator by combining the initial Level 2 products, include combined

**TABLE 1.1.**

| TYPE | PRODUCT | FORMAT | FREQUENCY |
|---|---|---|---|
| GPS | 15-sec raw | T00, RINEX | Daily |
| | 5-sps raw | T00, RINEX | Hourly* |
| | Survey mode raw | Varies | Varies |
| Strain | BSM raw | Bottle, miniSEED | Hourly |
| | BSM SOH, enviro | Bottle, miniSEED | Daily |
| | LSM raw | Ice9, miniSEED | Daily |
| | LSM SOH, enviro | Ice9, miniSEED | Daily |
| | BSM logging | Varies | Each install |
| Seismic | 100-sps raw | SEED | Streaming |
| | 200-sps raw | SEED | Streaming |
| Pore pressure | 10-sec raw | BINEX, ASCII | Hourly |
| Tiltmeter | 1-min raw | BINEX, ASCII | Hourly |

**TABLE 1.2.**

| TYPE | PRODUCT | FORMAT | LATENCY |
|---|---|---|---|
| GPS | Position time series | ASCII | 1- & 15-day, 3-month |
| | Velocity solutions | ASCII | Varies |
| | Network solutions | SINEX | 1- & 15-day, 3-month |
| | Coseismic offsets | ASCII | Varies |
| Strain | Cleaned strain series | XML, ASCII | 2-week, 4-month |
| | Clean enviro series | XML, ASCII | 2-week, 4-month |
| | Station notebooks | PDF | Varies |

GPS station position time series and network solutions; periodic estimates of long-term GPS station velocity; and coseismic offsets estimated following significant earthquakes in or near the PBO network.

Level 2 strainmeter data products include fully corrected and scaled tensor and linear strain time series (Figure 1.11) and ancillary series produced with no more than two weeks' latency by the PBO strain analysis centers in Socorro, NM (for BSM products) and at UC San Diego (for LSM products). In addition, every four months, these analysis centers reprocess all data from a given strainmeter to produce strain series with all known problems corrected. Other data products provided by PBO will include access to all GeoEarthScope LiDAR and InSAR data sets and pre-processed images.

Multiple independent organizations archive PBO data products in order to provide data security and access even in the event of failure at any one center. The UNAVCO Facility in Boulder archives and distributes all PBO GPS raw data and derived data products and runs a secondary archive offsite; to date, these centers hold more than 2.3 TB of GPS products. The Northern California Earthquake Data Center at the University of California, Berkeley and the IRIS Data Management Center in Seattle archive and distribute all PBO

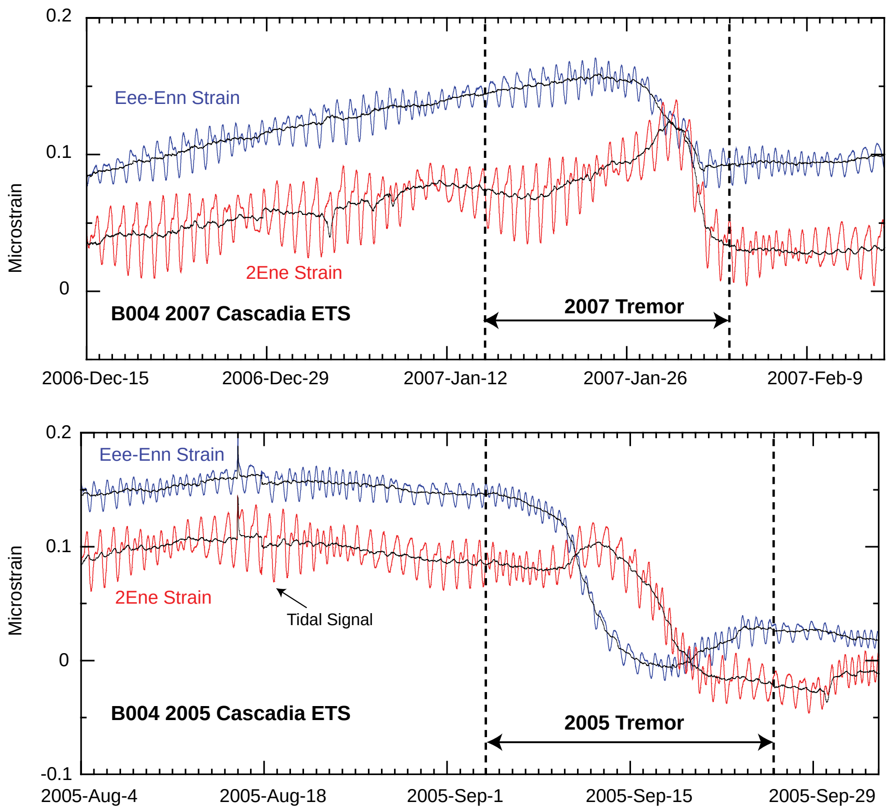


*Figure 1.11. Example of strain data products produced by the BSM Analysis Center. Both subfigures show time series of shear strain from PBO borehole strainmeter station B004, which was installed on the Olympic Peninsula in June 2005. This station, the first installed in the PBO network, recorded strain transients associated with the 2005 (bottom) and 2007 (top) episodic tremor and slip events in the Cascadia subduction zone. Red and blue lines in both figures show shear strain with solid Earth tides, while black lines show the same series with solid Earth tides removed. The data have been detrended and the atmospheric pressure effect removed. Values in both cases are in microstrain (one part per million), and both figures span approximately two months of data.*

strainmeter data products, and IRIS archives all PBO seismic data products; all told, more than 160 GB of strain and seismic data products are available from these archives. These same two centers also archive all other EarthScope seismic and strain data, which makes it much simpler for users to access EarthScope products from a unified set of centers.

PBO and EarthScope data products may be accessed using a variety of tools for the individual centers. The PBO Web site (http://pboweb.unavco.org) provides centralized access to PBO products stored in our distributed archives. For example, GPS products may be accessed from http://pboweb.unavco.org/gps_data and strain data products from http://pboweb.unavco.org/strain_data. In addition, the individual archives have client Web-based tools to provide access to their holdings, both for PBO and other networks, which allows users to retrieve data from multiple discipline-specific sources.

Early in the construction phase, PBO established data and data product metrics for all deliverables. For GPS data we measure the latency required to bring standard data files to Boulder and successfully archive the data. Table 1.3 shows at the 95% confidence level all data are archived within less than 24 hours. Another quality metric is the comparison of PBO GPS station position uncertainties relative to other networks. PBO Results from PBO indicate that station position uncertainties are similar to those in other large networks. Another metric is multipath at a GPS site. Multipath is interference between directly arriving GPS signals and reflected/refracted/scattered signals. The interference can come from reflections off of vegetation and buildings and lower values of multipath are an indicator of high station quality. The network is considered high quality if the overall L1 and L2 frequency multipath values have a median of < 0.35 m and 90% of stations are < 0.50 m. The PBO network passes both these tests.

Quality-control standards for borehole strainmeters include the following questions: Are the stations accumulating strain? Are the instruments tracking tides? Are at least three strain gauges in compression? Borehole strainmeters are doing well with the exception that some of the gauges not going into compression. This indicates poor coupling between the borehole and the instrument and could be due to poor grouting of the instrument and fractures near the borehole wall. As the boreholes reequilibrate to the environment following drilling and installation, we anticipate that over 90% of the gauges will be in compression.

**TABLE 1.3.**

| STATIONS | N | E | UP | # STATIONS |
|---|---|---|---|---|
| PBO | 1.0 | 1.5 | 4.0 | 498 |
| Nucleus & Others | 1.2 | 1.5 | 4.0 | 299 |

| METRIC | SATISFACTORY | UNSATISFACTORY |
|---|---|---|
| Accumulating Strain | 100% | 0% |
| Gauges in Compression | 77% | 23% |

# 2. USArray Facilities Overview

USArray is a continental-scale seismic observatory designed to provide a foundation for integrated studies of earthquakes and the structure of the continental lithosphere and deep Earth over a wide range of scales.

Each USArray seismic station includes the instrumentation necessary to sense, record, and transmit ground motions from a wide range of transient seismic sources, including local and distant earthquakes, artificial explosions, and volcanic eruptions. Because most USArray stations record continuously, it is also possible to collect data on Earth's background "noise," which is primarily generated through coupling of the solid Earth with the oceans and atmosphere. As early results from USArray show, studies of these continuous Earth vibrations can complement the traditional analysis of earthquake sources in revealing deep Earth structure.

Specialized sensor, signal conditioning, and timing systems with high sensitivity, wide dynamic range, and high precision are used to detect and record the low-level ground motions of interest to research seismology. The nested components of USArray sample overlapping spatial and frequency scales. At high frequency and resolution, the Flexible Array includes systems for "active source" studies, using explosions or vibrators that cover the frequency range above 1 Hz and are used for high-resolution studies of the crust. At an intermediate scale, the Transportable Array and the "passive source" instruments of the Flexible Array employ sensors that cover the band from hundreds of seconds to a few hertz and are used to record body and surface waves from regional and global events in studies of earthquake sources or the structure of the lithosphere and deep Earth. The Reference Network spans the entire continent, linking together the temporary observations of the Transportable Array. It includes instruments at selected stations that have long-period response extending to thousands of seconds. USArray also includes both permanent and transportable electromagnetic recording systems, which are used to probe the conductivity structure of the crust and lithosphere.

USArray is being implemented as a component of EarthScope within the management structure and facilities established for IRIS core programs. All USArray components draw heavily on the more than 20 years of technical and operational experience that IRIS has developed in providing support for seismological data collection and distribution.

- The field systems and technical services for the *Flexible Array* are closely integrated with the IRIS *PASSCAL* program. An Array Operations Facility (AOF) has been established at the PASSCAL Instrument Center at New Mexico Tech in Socorro, NM to maintain the Flexible Array instruments and provide training and support for users of these field systems. Through a subaward to New Mexico Tech, the Flexible Array supports 7 FTEs, approximately 24% of the Instrument Center staff.
- The *Reference Network* builds on long-standing collaboration between IRIS and the USGS in operations of both the *Global Seismographic Network* (GSN) and the Advanced National Seismic System. EarthScope-supported augmentations to the ANSS Backbone were completed in the third quarter of 2006 under the direction of USGS personnel from the Albuquerque Seismological Laboratory and Golden, CO. Operation of these stations has now been turned over to the USGS, which is responsible for field service, quality control, and delivery of all ANSS Backbone data to the IRIS Data Management Center (DMC).
- All USArray data will be archived and distributed through the IRIS *Data Management System (DMS)*, incorporating infrastructure and protocols that are well established and familiar to the research community. The primary operating node and archive of the DMS are at the IRIS DMC in Seattle, WA. USArray supports 9.6 FTEs or approximately 40% of the DMC staff. This includes six data technicians for quality control and servicing data requests and two programmers for software development.
- *Siting Outreach* draws upon the resources of the IRIS *Education and Outreach Program* to assist in identifying sites for the Transportable Array and to encourage involvement of undergraduate students in EarthScope. USArray supports 1.5 FTEs for Siting Outreach, including an outreach specialist and partial support for publications specialists.

The Transportable Array, magnetotelluric arrays, and overall USArray management also draw on IRIS experience, but, because of differences in technology or scope, have required the development of new capabilities during the MREFC stage of EarthScope.

- The Transportable Array is the largest component of USArray and is being implemented with direct IRIS responsibility for all aspects of array development, deployment, and data collection. This differs from past experience with PASSCAL (where individual PIs are largely responsible for field operations) or with the GSN (where operations have been carried out through collaboration with the USGS and UC San Diego). A flexible and scalable mode of operation for the Transportable Array has been developed that is managed by a small group of IRIS staff, with key activities linked to PASSCAL-related facilities at Socorro and San Diego and mobile field operations carried out by specialized crews under contract to

IRIS. The IRIS staff of FTEs includes the Transportable Array Manager, a Deputy Manager, a half-time Project Associate, and two field engineers. At the Array Operations Facility in Socorro, the Transportable Array supports 7 FTEs for receiving, maintenance, and shipping of Transportable Array equipment, and a specialized Transportable Array Coordination Office (TACO) with 4 FTEs for coordination of field operations and permitting. The Array Network Facility (ANF), supported under a subaward to UC San Diego, includes 6 FTEs for monitoring and maintenance of communications channels, metadata collection, and initial quality control for the entire Transportable Array.

- The instrumentation and data management requirements for time-series data collection from magnetotelluric instruments are similar to those for seismological data; some aspects of the magnetotelluric array operations have benefited from IRIS experience, especially in data collection and archiving. However, the unique site requirements for deployment of sensitive magnetometers and electrical sensors necessitates a separate deployment strategy. Contract crews are being used for the short-term deployment of magnetotelluric instruments for regional surveys. The permanent magnetotelluric stations are being operated and installed through a subaward to the University of Oregon.

## Reference Network

As an integrated resource both for EarthScope science and seismic monitoring, the Reference Network was designed in close collaboration with the USGS. It serves as a reference for the continental-scale imaging being performed by USArray's moveable components. Each of the Transportable Array "footprints" and focused Flexible Array experiments will ultimately be connected through the Reference Network. As of early 2007, the Reference Network or ANSS Backbone (Figure 2.1) consists of: 59 stations operated by the USGS (of which 35 were funded under USArray); 17 stations from the Global Seismographic Network; eight stations operated cooperatively with partner networks with some support provided by the ANSS; and 11 contributed or "backbone affiliate" stations.

The sensors selected for the Reference Network sites meet ANSS design goals for the USGS National Seismic Network (NSN) stations, with a broadband (CMG 3-T or STS-2, 100 sec to 15 Hz) seismometer augmented with a low-gain sensor for recording strong ground motion (up to 2 g) on scale without clipping. A uniformly distributed subset of 13 sites of the Reference Network meet the more demanding GSN standards, which includes ultra-long-period (to 1,000 sec) sensors at extra-quiet locations (STS-1 surface or KS54000 borehole). Except for the central part of the United States, the NSN-quality component of the Reference Network has nearly uniform coverage at a scale of about 300 km. USArray and IRIS will continue to work with the USGS to seek opportunities, possibly through the early deployment of Transportable Array-type stations, to fill some remaining gaps in a swath from the Dakotas to Texas, and in some parts of the Southeast, to complete uniform coverage of the Reference Network during the lifetime of EarthScope. The GSN-quality component of the Reference Network has coverage at the 1000-km scale to augment global GSN coverage (about 2000-km spacing). The resulting array focuses progressively from global to national scale, and then merges at the regional and local scales with the Transportable and Flexible Arrays.

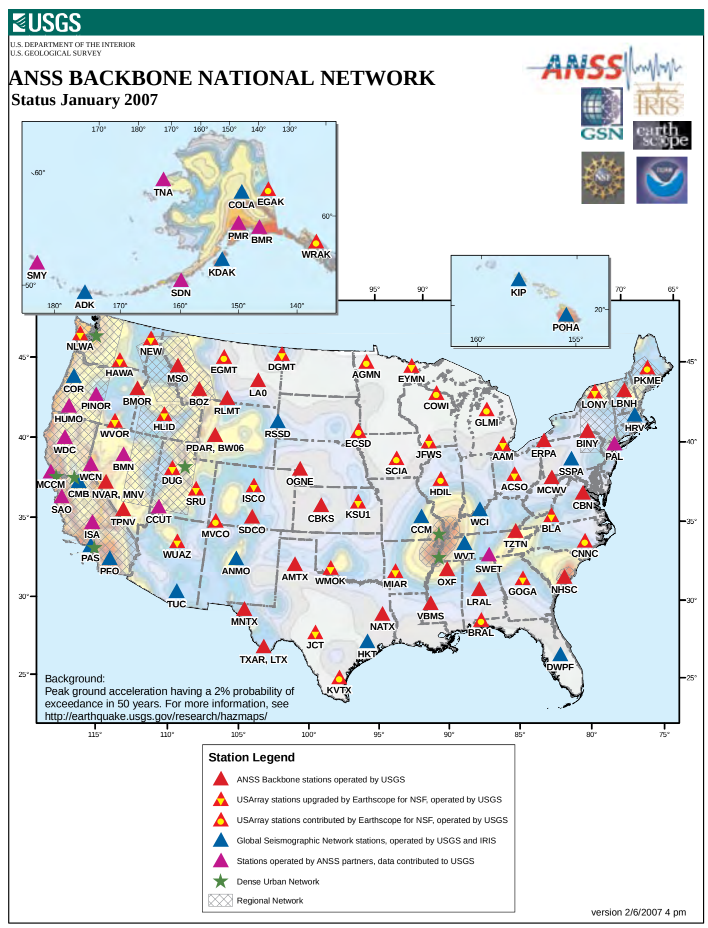


*Figure 2.1. The ANSS Backbone as of January 2007. Stations with yellow centers were contributed by USArray. EarthScope will continue to work with the USGS to fill the remaining gaps in the central United States to complete the Reference Network.*

# Transportable Array

By early 2008, the first deployment of the Transportable Array will consist of 400 new broadband seismic stations and approximately 65 pre-existing stations from regional networks that are cooperating with USArray (Figure 2.2). In areas where there are regional networks for earthquake monitoring, USArray collaborates closely with regional network operators in site selection and installation; the regional networks have high-priority access to all data.

The seismic systems used in the Transportable Array are based on standardized instrumentation configurations developed under the IRIS PASSCAL program and used by regional networks. The primary sensors are the Streckeisen STS-2, Guralp CMG-3T and Nanometrics Trillium 240 (120 sec to 15 Hz); data are acquired using Quanterra Q330 systems. A variety of telemetry modes, depending on local conditions, are used for continuous data transmission. Most of the remote stations use either cellular modem or VSAT. A standardized vault has been developed especially for Transportable Array installation (Figure 2.3), which involves burial of a 42-in diameter plastic pipe with the seismometer placed on concrete at a depth of 6 ft.

The Array Operations Facility at New Mexico Tech is responsible for most aspects of purchasing, delivery, check out, and final integration of Transportable Array equipment. A Transportable Array Coordination Office (TACO), also located at the PASSCAL Instrument Center, is responsible for coordination of field operations, site selection, and permitting. Full-time professional contract crews, managed by the Transportable Array Manager and coordinated with the TACO, carry out the separate task of Transportable Array site construction and installation.

Overall supervision of station deployment is managed by the Transportable Array Manager. Supporting the Manager is a Deputy Manager, Construction Supervisor and several Station Specialists, and Reconnaissance Specialists. A Reconnaissance Specialist is responsible for obtaining and maintaining the information on permits. The Station Specialists are field service personnel who maintain the operating stations to keep data return high.

Installation of a Transportable Array station means emplacing the sensor, connecting the power supply elements, interconnecting the station components, configuring station information, exercising the telemetry capabilities, collecting metadata, and confirming station operation.

An Array Network Facility (ANF) has been established at Scripps Institution of Oceanography at the University of California, San Diego to collect the real-time data from the Transportable Array and performs both preliminary and advanced data-quality inspections that provide feed-

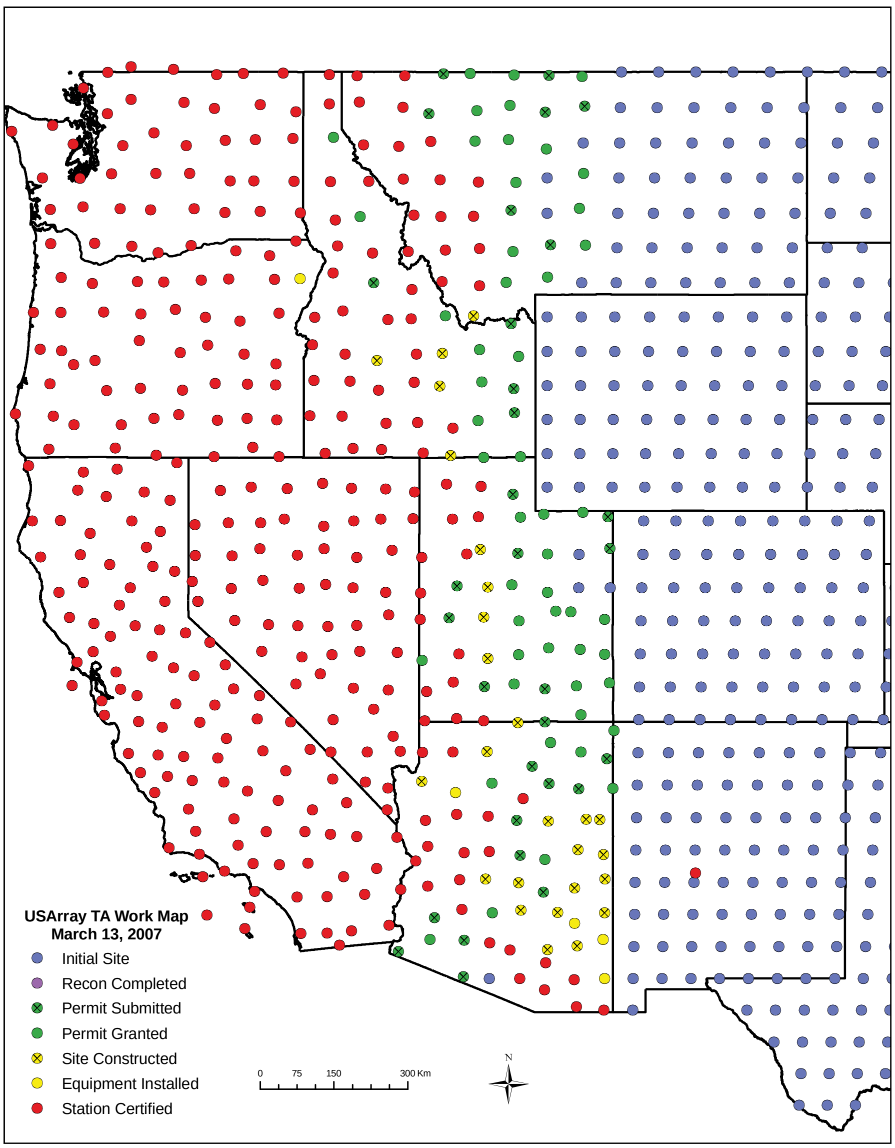


*Figure 2.2. Status of Transportable Array installations as of March 13, 2007.*

*Figure 2.3. A typical Transportable Array station showing the relationship of the equipment inside the enclosure and the solar panel.*

back to array operations in the field, and collects metadata so that the IRIS DMC can distribute array data in real time. Real-time data feeds are available to all interested scientists through the DMC.

A typical site for the Transportable Array occupies approximately 100 square meters of land. The seismic sensor and the rest of the equipment are housed in a weather-tight, subsurface enclosure. All cables are buried underground in conduits and the mounting structures for the antennas and solar panels are located as far from the sensor vault as practical to reduce noise from wind-buffeted structures. The most visible surface features are a solar panel and communications antennas. Seismic stations require sites that are quiet, secure, and relatively accessible. A quiet seismic site is one that is distant from noise sources—both natural (e.g., wind and rivers) and cultural (e.g., traffic, railroads, and heavy industry). Selecting and permitting good sites is a significant part of the USArray effort and requires close interaction among operators, outreach specialists, private landowners, and federal and state agencies.

## Siting Outreach

Siting Outreach supports Transportable Array siting and deployment by assisting in finding potential sites, providing USArray information and data to local communities, and providing a legacy for the local community after relocation of the Transportable Array. This effort is closely linked to Transportable Array deployment. It will also be closely coordinated with, and will provide support for, the broader Education and Outreach efforts to be undertaken by the new EarthScope National Office. The value of these investments in site selection has already been proven to be extremely valuable during implementation of the initial footprint of the Transportable Array. Siting Outreach is designed to precede and be integrated with the permitting process, creating community awareness and interest as the Transportable Array arrives. A key element is the involvement of students from local universities in the siting process, particularly in states were there is not a regional seismic network. This engages the wider earth science community, makes use of local knowledge of potential sites, and provides students with an opportunity to engage in a continental-scale scientific experiment.

Information on Transportable Array activities is provided to landowners and the public in a number of ways. The quarterly *OnSite* newsletter is distributed to landowners and other EarthScope hosts sites as a way to keep the landowners informed about both the EarthScope facility that their station is part of and the scientific results that depend on EarthScope data. A wider audience is reached via regular updating of information on the EarthScope Web site. Simple data access for the public is provided via newly developed tools, including the USArray Station Monitor and the Rapid Earthquake Viewer via a collaboration with the University of South Carolina. Another audience will be reached via simple, near-real-time museum displays, especially at sites that are located at or near national parks or museums. The Active Earth Display has recently been developed primarily with core IRIS funding and has been designed to be used in small museums and visitor centers. The content is customizable for each display via a Web interface that resides at the IRIS DMC. Siting Outreach will develop new EarthScope content in collaboration with other groups that will highlight EarthScope data and results.

Simple educational seismographs and classroom activities are provided to schools that host a Transportable Array site. The schools become part of an existing educational seismology network of over 120 schools. Teachers receive training in seismograph use and the students are able to compare data from their seismograph to the nearby Transportable Array station. The educational seismograph remains after the Transportable Array is removed, allowing the school to remain part of the network.

# Flexible Array

As the name implies, the Flexible Array is deployed in a variety of sizes, station geometries, and implementation modes. Data collection varies significantly from one experiment to another and is largely defined by the needs of the individual experiment and the PI. Data from the Flexible Array are sometimes telemetered and in other experiments are locally recorded at the station site.

The Flexible Array consists of 120 short-period and 291 broadband seismographs and 1700 single-channel, high-frequency recorders for active- and passive-source studies that can be deployed using flexible source-receiver geometries. These additional portable instruments will permit high-density, short-term observations of key targets to complement the larger Transportable Array in studies using both natural and active sources. The systems are based on standardized instrumentation configurations developed under the PASSCAL program for use in temporary deployments for earthquake studies and short-term active source (explosion) experiments. The broadband sensors used are CMG-3T (100 sec to 15 Hz) and the short-period sensors are CMG-40T (1 Hz). Both the broadband and short-period systems use Reftek RT130 data acquisition systems. The systems for high-frequency, active-source experiments use Reftek Texan single-channel recorders with conventional high-frequency geophones.

The flexible pool of instruments operates in a mode similar to the current PASSCAL operations. Investigators propose special experiments, via standard NSF grant procedures, to use the Flexible Array instruments in special high-resolution studies (Figure 2.4). The majority of experiments aim to enhance data gathered by the Transportable Array while it is located in a specific area. In this mode of operation, the PI will furnish the bulk of the crew for operations, as is now done for PASSCAL experiments.

All equipment used in Flexible Array experiments is tested at the AOF before it is shipped to the field. Once the equipment arrives in the field, AOF personnel who are assisting the experiment conduct further tests to verify the operation of the sensors and recorders. The AOF personnel maintain the equipment to ensure it is operational. The AOF furnishes training, logistical support, and initial quality-control and data-formatting support.

In telemetry mode, the data flow to the AOF, where quality control and reformatting take place, and are forwarded to both the IRIS DMC and the PIs. At the DMC, these data flow through DMC quality-assurance tools and then are archived with the other DMC data.

In experiments where on-site recording is used, the resources and tools developed at the DMC for quality control and data assimilation are used to ensure uniform data quality. It is the responsibility of the AOF working together with the PI to provide final data products for archiving at the DMC. The involvement of additional USArray resources for data collection and during the experiment, and the mode of delivery to the DMC archive, will be defined during the planning stage for each experiment. The guidelines for how experiments are defined and selected, and the data policy for Flexible Array experiments, have been established by NSF through solicitations and program announcements related to the overall EarthScope program.

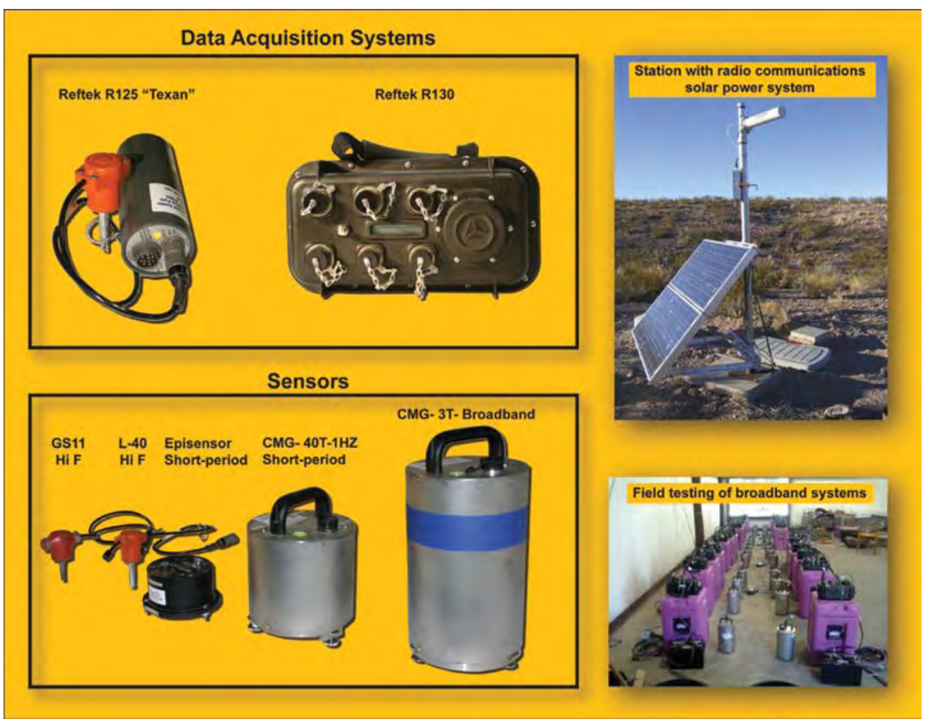


*Figure 2.4. Shown here are the major components that constitute the equipment for the Flexible Array. The single-channel Reftek R125 "Texan" data acquisition system is paired with a 4.5 Hz GS11 or 40 Hz L40 vertical sensor. The three-channel Reftek R130 data acquisition system can be used with either the CMG 40T-1Hz short-period sensor or the CMG 3T broadband sensor. Many Flexible Array stations are equipped with radio communications equipment that can be arranged into a real-time seismic network. Solar power systems, enclosures, sensor vaults, and shipping cases comprise the ancillary equipment for a Flexible Array station.*

# Magnetotellurics

USArray, in conjunction with the EMSOC Consortium (ElectroMagnetic Studies Of the Continent), is installing magnetotellurics (MT) stations as part of EarthScope. Seven stations are being installed at permanent sites through a subaward to Oregon State University. Twenty transportable systems are being acquired that will be deployed by commercial field crews, under contract to IRIS, for field campaigns (Figure 2.5) of approximately one-month duration.

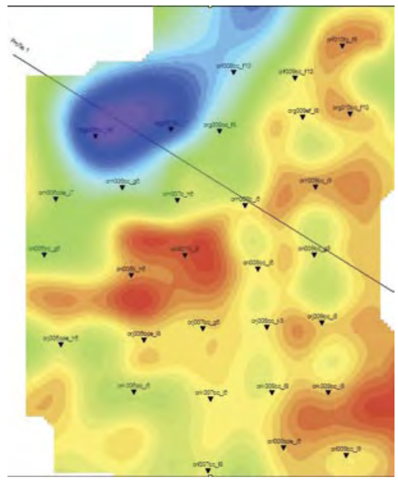

*Figure 2.5. A preliminary 3-D inversion of data from the transportable MT pilot experiment in Oregon in 2006. Stations (at approximately 70-km spacing) are shown as triangles. The map shows the inversion for a cross section at depth of 30 km. Resistivity values range from 5 ohm-meters (red) to 5000 ohm-meters (blue). The "Klamath-Blue Mountain Lineament" is seen trending NE-SW and is thought to be a feature that was once oriented N-S (older back-arc line of volcanics?) that has rotated clockwise. Inversion and figure courtesy of Randall Mackie, GSY-USA Inc.*

The instruments used in EarthScope MT stations are built by Narod Geophysics, Ltd. These systems are designed to record magnetic field variations from DC to 0.5 sec and electric field variations from 30,000 sec to 0.5 sec. The system includes three orthogonal magnetic sensors in a single housing and a data-acquisition box with two electric field channels. The long-period MT site consists of three components. For magnetic observations, the system includes a fluxgate ring core magnetometer unit that is buried in the ground in a hole 30-cm in diameter and about 1-m deep. This unit measures three components of the magnetic field and is connected back to the recording instrument via a 5-m-long cable. This cable will be buried in a shallow (15 cm) trench. For the complementary electrical measurements, an orthogonal array of either four electric field lines in a cross array or two electric field lines in an "L" array is installed, depending on local site logistics. Total dipole length is at least 100 m in most locations and at least 50 m in areas where surface resistivities are over 1000 ohm (such as in mountains). Each line is terminated with a PbCl2 electric field sensor, and a grounding rod is buried at the recording instrument. Each of these sensors is installed in a hole about 30-cm deep in a slurry of bentonite mud and saltwater. The on-site recording instrument and batteries are wrapped in plastic and a space blanket and then buried so that the entire installation is below the ground surface. Data are sampled at 1 Hz and stored on flash card memory. Data are collected, quality controlled, and re-formatted before being sent to the IRIS DMC for archiving and distribution through the same request channels used for seismic data.

# Data Management

The fundamental principles underlying the collection and distribution of EarthScope/USArray data include:

- All data will be freely and openly available to all interested parties
- Wherever possible, data will be collected and distributed in near real time
- Data (including both time series from sensors and associated metadata) will be reviewed to ensure quality
- All data will be archived at the IRIS DMC
- All data will be distributed by the IRIS DMC using both the traditional and newer Data Handling Interface (DHI)-based data distribution methods and the EarthScope Data Portal
- Data will be protected in an offsite Active Backup System

In the same way that many of the technical standards underlying the USArray field systems have emerged from the PASSCAL and GSN programs, the collection, distribution, and archiving of USArray data are based on procedures developed by the IRIS DMS. Hardware and software systems now in use for handling PASSCAL and GSN data have been augmented and expanded to incorporate USArray data. In addition to leveraging investments already made by NSF in developing the DMS, this also ensures that users will be able to merge USArray data with existing data resources in a simple manner, and access to USArray data will be via familiar and well-tested procedures and tools

The aggregate data flow rate from the seismic systems of EarthScope is estimated to be 4.2 terabytes per year, which represents roughly one-third of the total current data input to the DMC. Because of the modular hardware configuration and highly automated procedures established at the DMC, this increase in data flow has been incorporated with relatively minor increases in staffing and hardware.

For operational, backup, and data security reasons, the IRIS DMC makes five copies of each sample of waveform data. Data are stored in an Isilon RAID system with a capacity on the order of 100 terabytes in 2007. In a tape-based backup system at the DMC, data are stored in a time and station sorted order to optimize servicing of data requests, and two copies of the data are stored off-site at the Active Backup facility collocated at the PASSCAL Instrumentation Center in Socorro. These safeguards effectively increase the archiving requirement by a factor of five, making our mass storage system requirement 25 terabytes per year. The current mass store system at the DMC has an installed capacity of 100 terabytes and with modular expansion can be increased to several petabytes. The Powderhorn tape-based system currently has a capacity of 1.2 petabytes, sufficient to service all USArray data in addition to existing data sources.

Data from the Transportable Array are sent from the field in real time using TCP/IP communications protocols. The Transportable Array data flow through the Antelope system and flow in parallel to the ANF at UC San Diego and the IRIS DMC in Seattle. In most cases, data flow first to an ORB at the ANF and are transferred with minimal delay to the IRIS DMC. In the event of a failure at the ANF, a redundant system in place at the IRIS DMC can assume primary data collection.

At the DMC, the data are managed in a parallel system, dedicated to the management of USArray data. The data flow into a Buffer for Uniform Data (BUD) system, similar to that used currently for reception of various data streams into the DMC. The data can then be made available through the BUD real-time data access methods and other standard DMC data access tools. IRIS has developed methods to automatically implement routine procedures to check data quality (QUACK). Data from the BUD system flows through these quality assurance tools and into the primary DMC archive.

In response to the increased use of real-time data collection in the GSN and PASSCAL programs, and in anticipation of the USArray portion of EarthScope, the IRIS DMS began the development of the BUD system to ingest and manage large amounts of real-time data. Real-time data from seismic stations and networks can arrive in a variety of formats and via various communication protocols. The BUD converts these data into a standard format for use internally within the DMC and to provide a standardized interface to provide external users with access to real-time data. The BUD system has been functioning since 2001. IRIS now has a reliable and dependable system that receives the real-time data from USArray. Not only can the IRIS DMS draw upon BUD for data reception, but a series of tools have been developed that can distribute data in real time as well. All of the systems that have been developed are scalable—as new data streams are added and as demand warrants, additional processors, and RAID disk subsystems can be added to handle the increased load in a straightforward manner.

For non-real-time access to data, the powerful set of standard IRIS user tools is available to access data from the archive (Figure 2.6). We project that the centralized node of the IRIS DMC should be able to continue servicing these requests directly through the existing DMC systems. As demand warrants, additional resources can be installed at the DMC to scale the capabilities to meet user demands.

The DMC systems for data archiving and distribution are relatively mature and have been shown to serve well the needs of the seismology research community. As USArray has grown, the emphasis has been on scaling the existing systems to handle the increased data flow rather than the development of new technologies for data distribution or for integrating activities. During the final year of the MREFC phase of EarthScope, a centralized data portal will be built in collaboration with UNAVCO and SAFOD to provide a parallel pathway for integrated access to all EarthScope data. The portal will consist of a central site operated by UNAVCO in conjunction with the EarthScope Web site and "portlets" developed by and operating at the IRIS DMC, UNAVCO, and SAFOD that will link and serve data to the central site.

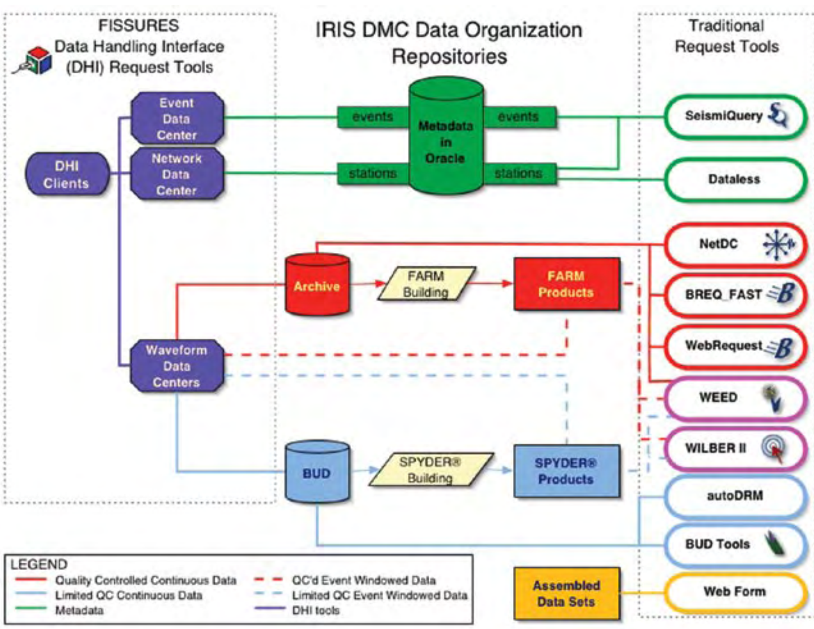


*Figure 2.6. Request mechanisms and data repositories at the IRIS Data Management Center. Seismic waveforms and metadata are stored in the real-time and archival repositories shown in the center part of the figure. All EarthScope seismic data are available through the standard DMC request tools (right side) and the Data Handling Interface (DHI) (left side).*

# 3. SAFOD Facilities Overview

## Introduction

SAFOD is being carried out in three distinct phases. Phase 1 was carried out during the summer of 2004 and involved drilling a vertical hole starting 1.8 km away from the surface trace of the San Andreas Fault, which was then directionally drilled to within a few hundred meters of small-magnitude earthquakes occurring along the fault at depth (see Figure 3.11 in Volume I). During Phase 2 (summer of 2005) we successfully drilled through the San Andreas Fault, reaching a true vertical depth of 3.1 km. Phase 3, scheduled for the summer of 2007, will involve several multilateral core holes drilled off of the main hole to obtain continuous core within the San Andreas Fault Zone. A pilot hole was drilled at the SAFOD site in 2002 with financial support from the International Continental Scientific Drilling Program (ICDP) and NSF. Twenty papers were published in Geophysical Research Letters describing the results of that work and related SAFOD site characterization studies (*Geophysical Research Letters*, v. 31, numbers 12 and 15, 28 June and 15 August, 2004).

A wide array of data and physical samples were obtained during SAFOD Phases 1 and 2. In addition to the core, cuttings, and fluid samples described in Volume I, comprehensive geophysical logs were acquired along the entire length of the drill hole (see Figure 3.13 in Volume I), continuous measurements were made of the composition of gases dissolved in the drilling mud, and various other downhole measurements and instrument deployments were carried out. All of the downhole measurement data and information about samples can be accessed via the ICDP Drilling Information Drilling Information Web site (http://www.icdp-online.de/contenido/icdp/). All of these data will be made available through the EarthScope portal. Seismic recordings obtained in the boreholes are available at the IRIS Data Management Center (DMC) and/or the Northern California Earthquake Data Center (NCEDC). Preliminary results from SAFOD Phases 1 and 2 were presented in two special sessions at the 2005 Annual Meeting of the American Geophysical Union and numerous papers describing this work are now either in print or in review.

SAFOD is located in central California at the transition between the creeping segment of the San Andreas Fault and the Parkfield segment, a section of the fault where seven moderate (~M6) earthquakes have occurred since 1857, most recently on September 28, 2004 (Figure 3.1). The Parkfield segment of the San Andreas Fault is the most densely instrumented fault segment in the world. Seismic and deformation data from SAFOD are an integral part of the Parkfield Earthquake Experiment, which the USGS is committed to continuing as the fault prepares for the next Parkfield earthquake (see http://earthquake.usgs.gov/research/parkfield/). Hence, a wide variety of seismological, geodetic, and related geophysical data will be coming from the Parkfield area for many years to come.

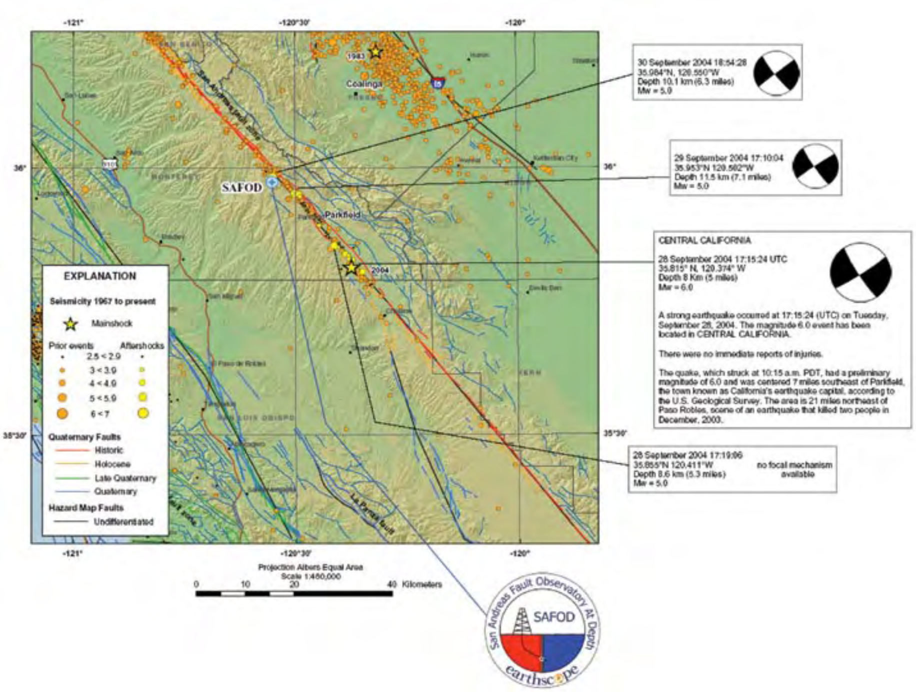


*Figure 3.1. The location of the SAFOD site and seismicity along the San Andreas Fault and in the surrounding region. Epicenters of the 2004 Parkfield main shock and the two largest aftershocks are shown.*

As discussed in Volume I, the unique capability to monitor repeating microearthquakes with near-field instrumentation at depth defines many of the key components of the SAFOD observatory. However, as illustrated in Figure 3.1, the observatory instrumentation will also have the opportunity to monitor at depth the moderate earthquakes frequently occurring throughout the region. This will make it possible to detect changes in the behavior of the San Andreas Fault that might occur in response to these regional earthquakes, including changes in microseismicity, aseismic deformation, and changes in pore fluid pressure. As discussed below, SAFOD is also an excellent site for monitoring nonvolcanic tremors occurring on the San Andreas Fault near the base of the seismogenic zone immediately to the southeast, near the nucleation zone of the great 1857 Fort Tejon earthquake.

The SAFOD site has been the location of intense study for many years. These studies have yielded unprecedented high-resolution images of the physical properties and geophysical and geologic setting of the crustal volume surrounding the San Andreas Fault in the vicinity of SAFOD. Figure 3.2 illustrates some of the geophysical studies that have been carried out in the region immediately surrounding SAFOD:

- Upper left – Extensive aeromagnetic and ground magnetic data (not shown) have been obtained in the vicinity of the SAFOD site. These data are particularly helpful for studying the configuration of basement rocks as well as the location of highly magnetic serpentinite bodies at depth. Investigators include Darcy McPhee and Robert Jachens (USGS).
- Upper right – Detailed gravity data have been obtained in the region surrounding the drill site, and also help define basement lithology, topography and structure. Investigators include Darcy McPhee and Robert Jachens (USGS) and Peter Malin (Duke University).
- Lower left – Numerous seismic lines have been collected through the SAFOD site at a variety of scales, which involved recording of both P- and S-waves. The most extensive of these seismic experiments was conducted in the fall of 2003, as shown here and described in more detail on the Web (see http://earthquake.usgs.gov/research/parkfield/2003site.php). Investigators include John Hole (Virginia Tech), Trond Ryberg (GFZ, Potsdam) and Gary Fuis, Rufus Catchings and Mike Rymer (USGS). Map of seismic deployments surrounding the SAFOD site from October–November 2003. This map only shows the central part of the seismic line acquired by John Hole and Trond Ryberg (brown line), which extends for 50 km from Camp Roberts on the southwest to Coalinga on the northeast.
- Lower right – From 2000 through 2006, a dense network of seismometers has been used for determination of crustal structure and earthquake locations by passive recording of microseismicity surface calibration shots. These Parkfield Area Seismic Observatory (PASO) deployments were principally the work of Cliff Thurber (U. of Wisconsin) and Steve Roecker (Rensselaer Polytechnic Institute) working in collaboration with Bob Nadeau and his colleagues (UC Berkeley) and seismologists at the USGS.

Results from these investigations have been instrumental not only in designing and carrying out the SAFOD experiment, but are also in allowing scientists to "scale up" results from sampling, downhole measurements, and monitoring in SAFOD to other segments of the San Andreas Fault and faults in other tectonic settings.

The SAFOD site consists of 5 acres on private land in Monterey County, CA. It is a secure site, protected by several locked gates. Real-time cameras at the site and regular visits by the USGS operations manager for Parkfield (Andy Snyder) provide additional security. Environmental approvals and permits for drilling and long-term monitoring at SAFOD were obtained through an environmental consulting firm under the supervision of the USGS, with joint funding and legal assistance provided by NSF. The USGS signed a 20-year lease on the SAFOD property in 2002 and is covering both the initial payment and annual upkeep on this lease.

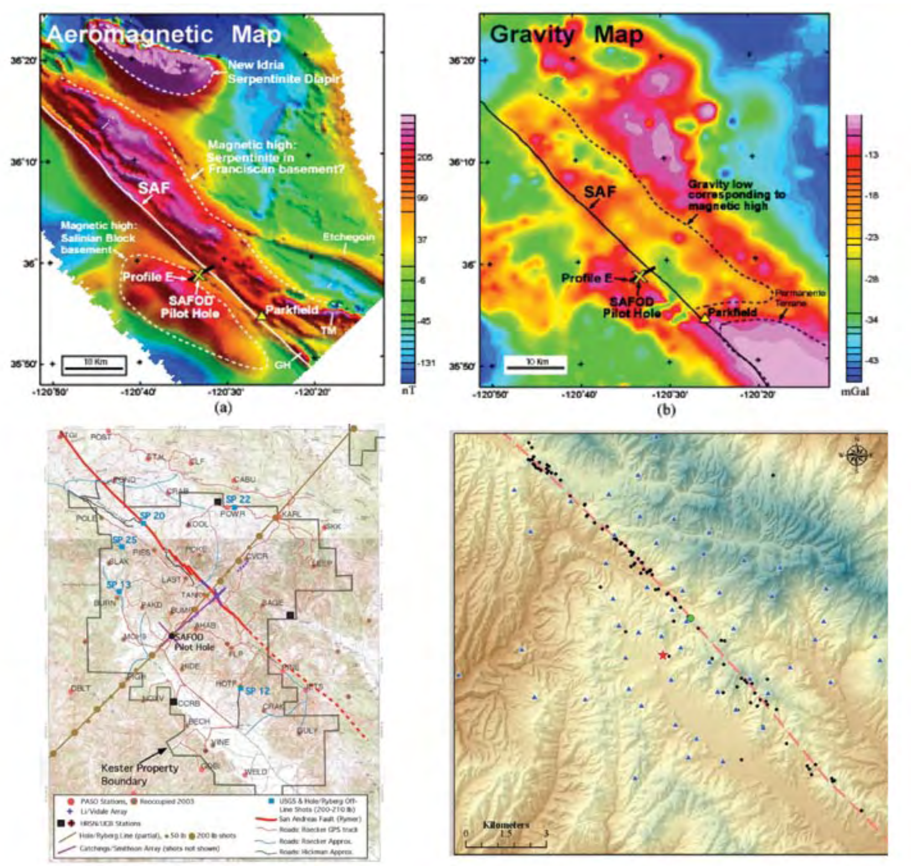


*Figure 3.2. Detailed geophysical surveys in the vicinity of the SAFOD site.*

# SAFOD Borehole Instrumentation Systems

Figure 3.3 shows a collage of photos related to deployment of prototype borehole monitoring equipment in the SAFOD borehole during 2006. Through multiple deployments designed to test critical components related to downhole sensors, telemetry, clamping, and cable terminations, it was possible to achieve a number of technical improvements in the equipment to be used in the long-term monitoring array (see Figure 4.2 in Volume 1). Personnel from Pinnacle Technologies, the instrumentation subcontractor for the SAFOD downhole monitoring array, are shown inside the instrumentation building at the site in the September photo along with USGS operations manager Andy Snyder. All of the surface instrumentation, including radio towers, telemetry systems, Internet access, site power and security systems are operated and maintained by the USGS. Andy Snyder is stationed at Parkfield and frequently assists with SAFOD instrumentation.

The collage also shows photos of two key components of the downhole monitoring system—a high-temperature, three-component seismometer manufactured by OYO Geospace (the DS-150) and the high-temperature borehole tiltmeter manufactured by Pinnacle technologies. These instruments, along with MEMS accelerometers will be deployed at three levels in the SAFOD main hole before the conclusion of the MREFC phase of EarthScope. Not shown are a quartz pressure transducer and inflatable packer to be used for monitoring pore pressure in the fault zone through perforations in the cemented casing (see Volume 1, Figure 4.2).

Figure 3.4 shows seismograms from two earthquakes, along with an illustration of the position of the seismometer at the time of the recordings. The event on the right (~M 0) occurred on November 2, 2006, when the seismometer was located at a true vertical depth of 2740 m (note the position of the sonde in the cross section). This event is located in one of the clusters of "target earthquakes" located very close to the SAFOD borehole, as indicated by the short interval of 68 msec between the P and S arrivals. It is an aftershock of the M 2.1 "S.F." target earthquake that occurred 10 minutes earlier, shown in green on the fault-parallel cross section of


*Figure 3.3. A collage of photos related to testing components of the downhole instrumentation systems and the surface facilities instrumentation facilities. A sixth grade class is shown touring the surface instrumentation building. The photo of the instrumentation rack shows the earthworm computers and LTO3 tape drives referred to in Volume I. The Geores recording system for the downhole seismometers is visible in the second rack.*

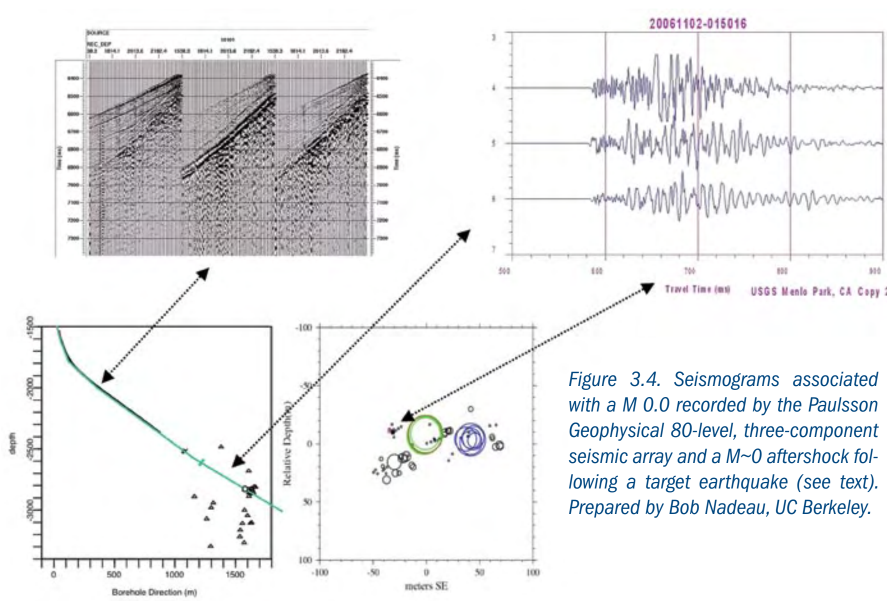


*Figure 3.4. Seismograms associated with a M 0.0 recorded by the Paulsson Geophysical 80-level, three-component seismic array and a M~0 aftershock following a target earthquake (see text). Prepared by Bob Nadeau, UC Berkeley.*

the target earthquake. The wavefield on the left was recorded by the 80-element, three-component borehole seismic array of Paulsson Geophysical Services, Inc. (PGSI). This M0 earthquake is located midway between the "S.F." earthquake and the M1.9 "L.A." earthquake (blue). Note the coherence of secondary phases across the array in the radial (left) and transverse (center and right) components of motion.

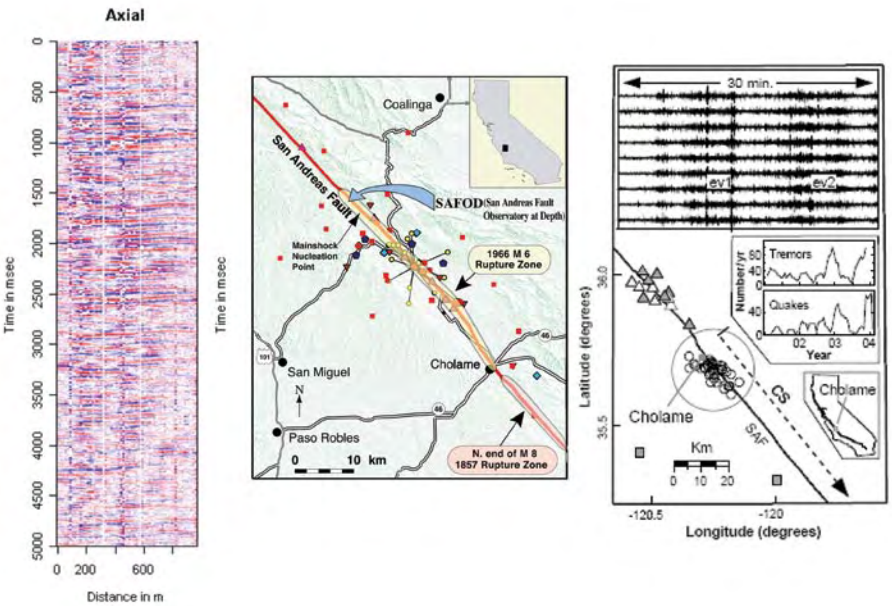


*Figure 3.5. Non-volcanic tremor recorded on the PGSI array are shown on the left. This event is associated with slip at depth in the Cholame area. The figure on the right is from Bob R. Nadeau and his colleagues.*

During the two weeks that the PGSI array was in the borehole, a nonvolcanic tremor was detected. Five seconds of tremor are shown in Figure 3.5 for the axial component of the three-component sensors, covering a measured distance in the borehole (horizontal axis) of about 1000 m. Bob Nadeau and his colleagues at UC Berkeley discovered that this tremor originated in the Cholame area, ~ 30 km from the SAFOD site (right side of Figure 3.5) below the deep seismic-aseismic transition. Because of the low signal of these events (with respect to ambient noise), it has not been possible to determine if such events occur elsewhere along the fault. However, PBO is now installing a long baseline laser strainmeter at Cholame to see if these tremor are associated with episodic deformation. By detecting such events in the ultra-low noise environment of SAFOD it will be possible to help determine if the events are more widespread along the length of the fault and to confirm the apparent correlation between tremor and changes in microearthquake activity along the fault.

Figure 3.6 illustrates several features of the fiber-optic laser interferometer installed by Mark Zumberge of UC San Diego behind the casing in the vertical section of the SAFOD main hole (the installation is schematically illustrated in upper right figure). By attaching the fiber end points to the casing at several depths (Figure 3.6, left), and then cementing the casing to the adjacent formations, it is possible to precisely measure vertical strain associated with small fault slip events. The "strainogram" shown in the lower right of Figure 3.6, indicates a maximum strain resulting from a nearby event of ±0.3 x $10^{-9}$.

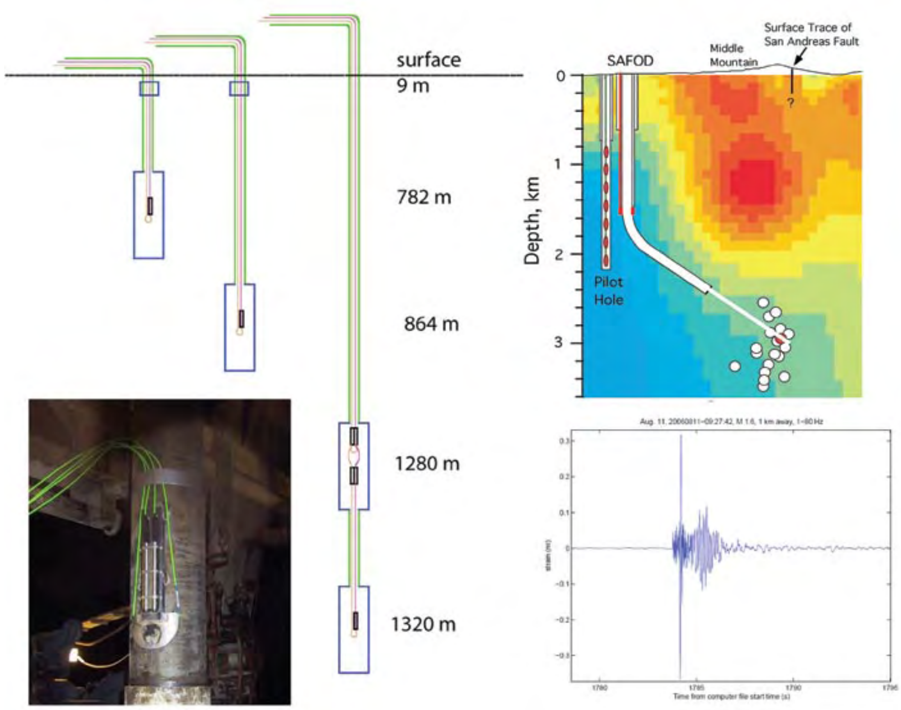


*Figure 3.6. Illustrations of the deployment of the fiber optics laser interferometer installed behind cemented casing by Mark Zumberge of University of California San Diego and an example of strain data resulting from a nearby microearthquake.*

# Core and Samples

As mentioned in Volume I, limited quantities of spot cores and fluid samples together with appreciable volumes of washed and unwashed drill cuttings were collected along the entire length of the borehole during SAFOD Phases 1 and 2. In addition, ~ 600 m of core will be collected from directly within the San Andreas Fault Zone in the summer of 2007 during Phase 3. As shown in Figure 3.7, approximately 80 scientists attended the two SAFOD sample parties held to date at the Integrated Ocean Drilling Program (IODP) Gulf Coast Repository (GCR) at Texas A&M University and the USGS in Menlo Park. As described in detail in Volume I, the GCR is serving as the long-term repository for all SAFOD core, cuttings, and fluid samples. Although most scientists obtained their subsamples from the SAFOD sample collection after they arrive at the GCR, it is also possible to collect samples at the site to study ephemeral properties. Tom Torgerson (Univ. of Connecticut) and Gisela Winckler (Lamont Doherty Earth Observatory) are shown in the lower left photo collecting a subsample at the site at the end of Phase 2 to obtain samples to study noble gas chemistry.

In accordance with the SAFOD sample policy and under the direction of the SAFOD Sample Committee (see Volume I), scientists receive core samples after evaluation of a formal request. Figure 3.8 illustrates how a number of requests for core (top) resulted in a consensus of how specific samples should be distributed (middle and bottom views). So far, SAFOD samples have been distributed to over 30 principal investigators in the United States and abroad.

As core samples are collected at the site during Phase 3, a series of steps (shown in Figure 3.9) will be taken to extract key information in the field. First, all cores will be extracted from the core barrel, cleaned, aligned and labeled by the on-site science team, who will also record important core metadata such as the locations of core breaks and rubble zones along with relevant drilling parameters. Following this initial processing, the core will be described in detail (for lithology and mesoscale structures), photographed, and passed through a GeoTek MultiSensor Core Logger. Core samples will then be hermetically sealed in shrink-wrap plastic and refrigerated on-site before being shipped to the GCR. Shown in the photo is John Firth, who is the Chief Curator at the GCR. As described in Volume I, the GCR will be responsible for long-term curation, subsampling, distribution and record keeping for the SAFOD sample collection during the EarthScope O&M phase.

Key metadata about samples are being stored in the online Web site operated by the ICDP (upper part of Figure 3.10). As shown, this Web site (which will be accessible via the EarthScope portal) contains photos of core, cuttings,

*Figure 3.7. Scientists inspecting core at sample parties and retrieving a sub-sample in the field for studying noble gases.*

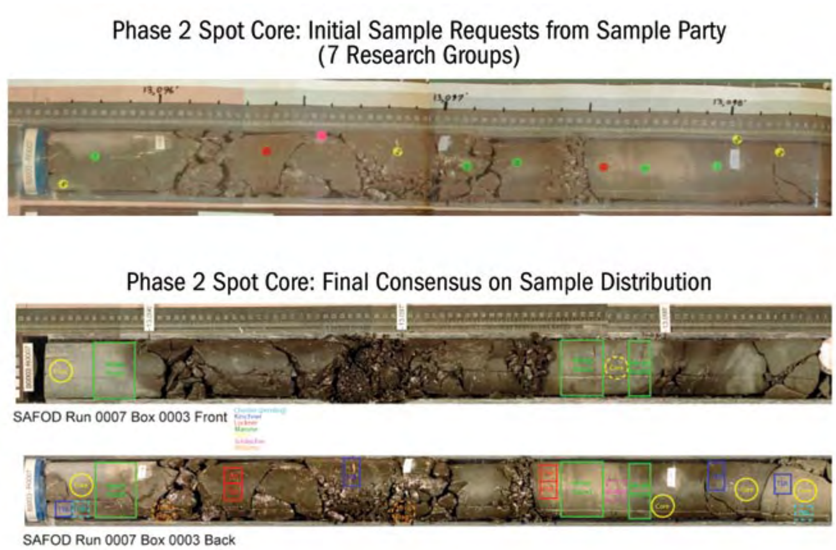


*Figure 3.8. Photos of a section of core with samples selected by scientists for laboratory study (top) and the samples eventually distributed.*

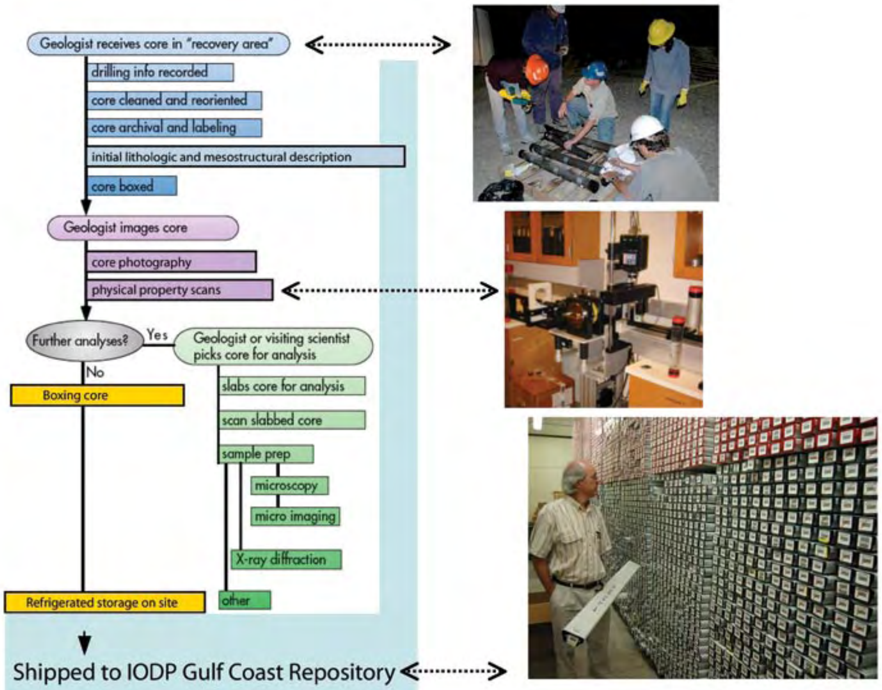


*Figure 3.9. Illustration of the sequence of steps associated with core studies in the field prior to shipment to the IODP Gulf Coast Repository.*

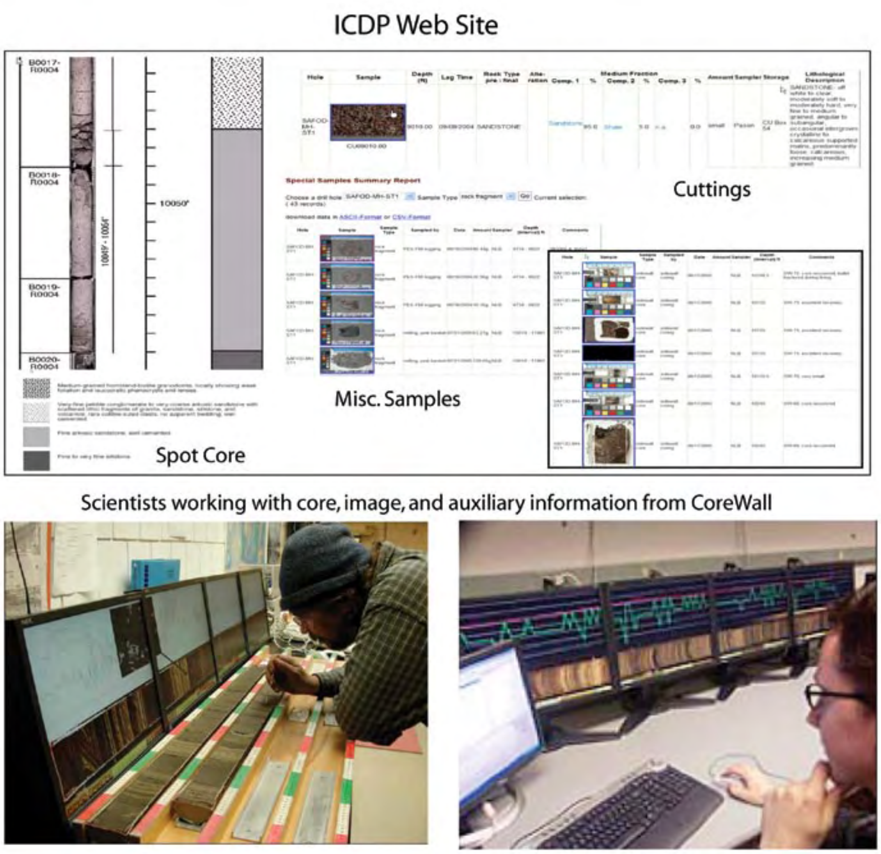


*Figure 3.10. Example of information about samples stored on the ICDP Web site and scientists working with CoreWall software that integrates core images with physical property and other measurements.*

miscellaneous samples, and other information needed by investigators potentially interested in working with SAFOD samples. This additional information includes thin section scans and photomicrographs, preliminary petrographic and structural descriptions, SEM images, spot elemental analyses, magnetic susceptibility measurements on cuttings, and spectral gamma scans of core (for U, K, Th content). The ICDP Web site also provides a useful overview for investigators to use prior to visiting the GCR to help prepare their sampling requests.

At the time of writing this proposal, the SAFOD PIs are also considering use of the CoreWall software suite for Phase 3 SAFOD core samples to supplement the data in the ICDP system. This system was developed for the Limnological Research Center LacCore Facility at the Univ. of Minnesota, with support from NSF (http://www.corewall.org/). Because CoreWall is a core visualization tool that has the ability to integrate other pieces of information (such as the GeoTek petrophysical scans, analytical measurements on core), it will likely prove to be a very effective tool for helping investigators work with SAFOD core samples and to integrate their results with the work of other PIs (see photos in Figure 3.10). We are currently discussing a number of modifications to CoreWall software with the LacCore staff and subcontractors to improve its functionality for SAFOD core analysis. In addition, a data base is being developed by SAFOD to keep track of the scientific studies being carried out on SAFOD core, cuttings, and fluid samples and to provide an archive that documents the results of those studies. We are currently working with the LacCore facility to integrate this database directly with CoreWall.