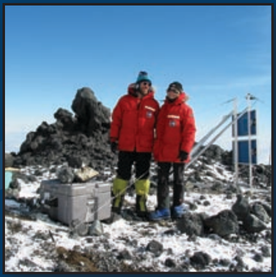
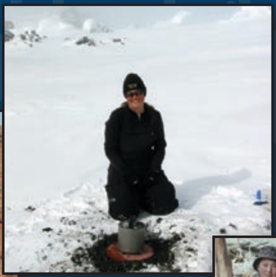





IRIS PASSCAL

PROGRAM FOR ARRAY SEISMIC STUDIES OF THE CONTINENTAL LITHOSPHERE



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OF THE CONTINENTAL LITHOSPHERE

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INTRODUCTION

WHEN IT WAS ESTABLISHED IN 1984, the Program for Array Seismic Studies of the Continental Lithosphere (PASSCAL) represented a fundamentally new direction for multi-user facilities in the earth sciences. At that time, the National Science Foundation (NSF) was encouraging exploration of new modes of collaboration in the development of community-based facilities to support fundamental research. The US seismology community organized a new consortium—the Incorporated Research Institutions for Seismology (IRIS)—to present to NSF a coordinated plan defining the instrumentation, data collection, and management structure to support a broad range of research activities in seismology. PASSCAL, along with the Global Seismographic Network (GSN) and Data Management System (DMS), were the initial core programs presented to NSF. In 1997, IRIS added an Education and Outreach (E&O) program, and in 2003, NSF expanded IRIS's responsibilities to include the USArray component of EarthScope.

PASSCAL provides and supports a range of portable seismographic instrumentation and expertise to diverse scientific and educational communities. Scientific data collected with PASSCAL instruments are required to be archived at the open-access IRIS Data Management Center (DMC). These two basic IRIS PASSCAL concepts—access to professionally supported, state-of-the art equipment and archived, standardized data—revolutionized the way in which seismological research that incorporates temporary instrumentation is practiced at US research institutions. By integrating planning, logistical, instrumentation, and engineering services, and supporting these efforts with full-time professional staff, PASSCAL has enabled the seismology community to mount hundreds of large-scale experiments throughout the United States and around the globe at scales far exceeding the capabilities of individual research groups. Individual scientists and project teams can now focus on optimizing science productivity, rather than supporting basic technology and engineering. Small departments and institutions can now compete with large ones on an equal footing in instrumentation capabilities. Scientists working outside of traditional seismological subfields now have the ability to undertake new and multidisciplinary investigations. Standardized equipment and data formats greatly advanced long-term data archiving and data re-use for novel purposes.

PASSCAL has also influenced academic seismology in all parts of the world explored by US seismologists, and the program has on many occasions provided significant instrumentation to spur or augment international collaborations. Many of the standards and facilities pioneered by IRIS for instrumentation and data collection, archival, and open exchange have been adopted by other groups in the United States (such as permanent networks) and by seismological networks and organizations worldwide. This open-data culture has been embraced by other US data collection groups (seismological and nonseismological), and obligatory data archival requirements and standards have increasingly been stipulated by federal agencies. Internationally, similar portable seismograph facilities have patterned their operations on the PASSCAL model, although comprehensive international open data policies have not yet been universally adopted.

This document summarizes the scientific research supported by the PASSCAL facility, reviews the history and management of the PASSCAL program, and describes the breadth of PASSCAL facilities and operations, focusing largely on the PASSCAL Instrument Center at New Mexico Tech in Socorro, New Mexico. PASSCAL and other IRIS core programs are funded by the NSF Earth Sciences Instrumentation and Facilities Program (David Lambert, Program Director). This report is part of a review of the IRIS PASSCAL facility required as part of the five-year (2006–2011) cooperative agreement (EAR-0552316) between NSF and the IRIS Consortium. The report reflects inputs from the PASSCAL Program Manager, Deputy Program Manager, Standing Committee Chair, PASSCAL Instrument Center PI, Director, and staff at New Mexico Tech, and IRIS community sources, including the PASSCAL Standing Committee, 2005 PASSCAL strategic planning workshop participants, and 2007 Tucson PASSCAL Review Workshop participants.

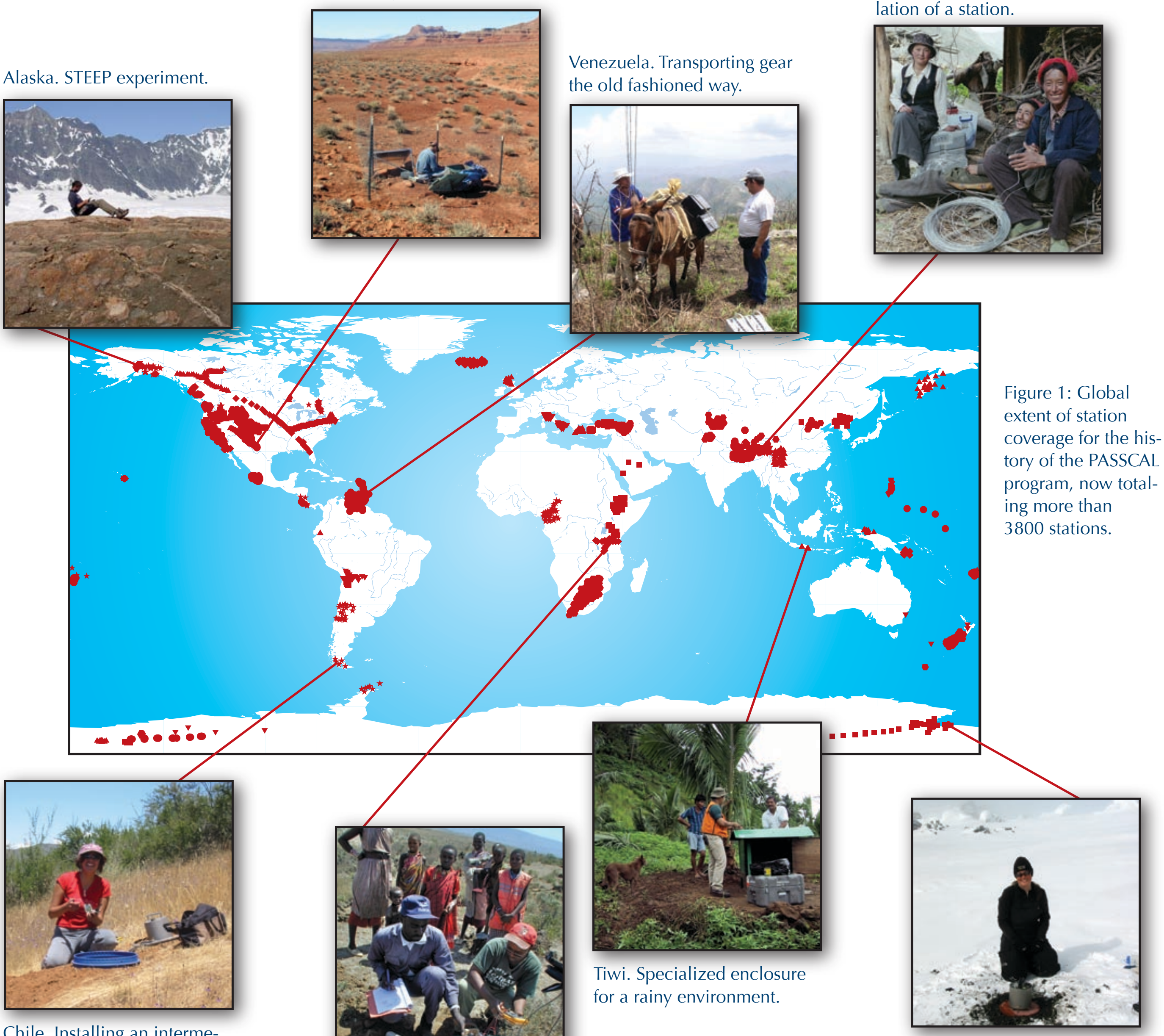
SCIENTIFIC IMPACT

EXPLORING THE EARTH

Since its inception, PASSCAL has provided instrumentation for field investigations in remote corners of the globe (Figure 1), with seismologists exploring Earth's deep interior by mounting expeditions similar in spirit to the classic scientific expeditions of the eighteenth, nineteenth, and early twentieth centuries. Among the earliest PASSCAL controlled-source experiments were investigations in Iceland and Arctic Alaska. Subsequent controlled- and natural-source investigations examined the evolution of Earth's great orogenic plateaus and mountain systems: the Himalayan-Alpine chain, the Andes, and the North American cordillera and orogenic plateau. In Asia, PASSCAL investigators have conducted a series of large-scale seismic investigations throughout the Himalayas and across the Tibetan plateau, in the Tien Shan mountains, and other parts of the Alpine-Himalayan chain. In Latin America, investigations have extended from Tierra del Fuego through Chile, Argentina, and Boliva, to the Caribbean margin of Venezuela and on many Caribbean islands. In Central America, US seismologists have investigated the volcanoes and subduction zones of Costa Rica and Nicaragua. In North America, a large number of projects have been fielded from Mexico to the northern tip of Alaska, the Aleutian Islands, and the Bering and Chuckchi Seas. PASSCAL experiments have covered the great rift system of east Africa, from Tanzania to Ethiopia, and a number of the African cratonic provinces, notably the Kaapvaal. Elsewhere, US seismologists have deployed PASSCAL instruments from the Kola Peninsula in western Russia to the Kamchatka Peninsula in far eastern Siberia, and from Greenland to the South Shetland Islands. This tradition continues today with large projects on every continent and novel investigations in Antarctica utilizing recently developed special polar equipment.

Unlike the typical laboratory investigations of many sciences, the seismologist's laboratory is the Earth, which makes seismic fieldwork both exciting, and also logistically and physically challenging (and sometimes dangerous). PASSCAL instruments have been deployed from almost every means of conveyance available, from ships, light aircraft, and helicopters; to light water craft and four-wheel-drive vehicles; to horses, donkeys, and backpacks. Instruments have been deployed in locations ranging from mountaintops to fjords, from the slopes of volcanoes to ice sheets and glaciers, and in tropical rain forests and deserts, and on desert islands. PASSCAL instruments have been damaged from excessive heat and cold, flooding, vehicle wrecks, landslides, mudslides, volcanic ejecta, and local wildlife (notably bears). Instruments have been stolen, deliberately shot, investigated by the local law enforcement agencies of several countries, paved over by road construction crews, and in one instance, destroyed by a native spear.

The experiment-planning stage for instrument deployments everywhere in the world is becoming increasingly difficult and lengthy in nearly all environments, as seismologists and support staff are faced with ever-increasing numbers of permits to obtain, often from a variety of different agencies, and as experiments continue to grow in numbers of instruments. Global urbanization is posing new and challenging problems; cities are high-seismic-noise, densely packed, theft-prone environments. An example of careful planning in the urban environment is the successful series of controlled-source experiments conducted in the Los Angeles basin by the US Geological Survey and a team of university collaborators. Fielding over 1000 seismographs, these experiments deployed instruments in the backyards of residents throughout the greater metropolitan area, and detonated explosives in drillholes on public lands that included national forests, military facilities, watershed and flood-control lands, and even on school grounds.



Alaska. STEEP experiment.

La RISTRA, New Mexico.

Venezuela. Transporting gear the old fashioned way.

Tibet. Locals help with installation of a station.

Figure 1: Global extent of station coverage for the history of the PASSCAL program, now totaling more than 3800 stations.

Chile. Installing an intermediate period sensor.

Kenya. A short period station being serviced while local Masai look on.

Tiwi. Specialized enclosure for a rainy environment.

Mt. Erebus. An intermediate period sensor is installed directly onto the bedrock flanking the volcano.

INNOVATION IN DATA ACQUISITION AND ANALYSIS

The initial desire for a single multi-use PASSCAL instrument proved to be excessively restrictive for community needs, and the instrument pool has evolved today into a small suite of specialized equipment packages, with many investigations making use of multiple instrumentation types and associated methodologies during a single project. For most earthquake-recording applications, PASSCAL stations are self-contained. Installations include solar and battery power, independent GPS clocks, large data-storage capabilities, usually broadband (120 s) or intermediate (30 s) period instruments and, if available, communication links facilitated by satellite, line-of-sight radio, and Internet or telephone networks. In contrast, crustal-scale, controlled-source experiments require rapid deployment and recovery of large numbers of instruments that have lower storage capacities and power requirements. These community needs led to the development of the RT125 (“TEXAN”) instrument. Many tens of these instruments can be deployed or recovered by a single team in a day. Demand for high-resolution reflection imaging of the shallow (< 1 km) subsurface required purchase and support of commercially available cable reflection systems.

The availability of large numbers of each instrument type has followed or encouraged development of new analysis techniques that are either theoretically impossible or practically inconceivable for small numbers of instruments and low data volumes. For example, large aperture, increasingly dense, and increasingly two-dimensional arrays of broadband seismographs allow the identification and removal of multipath interference in surface wave measurements (Forsyth and Li, 2005), a longstanding problem in surface wave analysis. Cross correlation of the microseism noise field to estimate surface wave Green’s functions between stations in large, dense arrays has opened a whole new field of investigation of the crust and upper mantle with surface waves in the 5–40 s band (Shapiro et al., 2005). Similarly, large-aperture, dense arrays make correcting for Fresnel zone phenomena in body wave tomography possible, removing the ray-theoretical assumptions inherent in travel time methods, and providing improved images of the subsurface (Dahlen et al., 2000; Dahlen and Baig, 2002; Nolet et al., 2005). Anisotropy measurements made from shear-wave splitting across large dense arrays can reveal systematic variations in orientation that can be related to asthenospheric flow directions, often associated with plate edges, subduction zones, and mantle upwellings (e.g., Savage and Sheehan, 2000; Fischer et al., 2005; Walker et al., 2005; Zandt and Humphreys, in press). The seeming chaos of splitting directions observed across a coarse array can be geodynamically meaningful when viewed across a dense array.

The densest broadband arrays now provide spatially unaliased recordings of teleseismic signals to relatively high frequencies (0.5–1 Hz). Such data sets permit advanced wavefield imaging using P-to-S and S-to-P scattered waves from teleseismic sources, and multiply reflected P-wave signals, and provide structural velocity and impedance images with roughly an order of magnitude greater resolution than comparable transmission tomography (e.g., Bostock et al., 2001, Rondenay et al., 2001). These methods provide, for the first time, images of the upper mantle with resolution comparable to crustal images using controlled-source methods. Even common conversion point stacking (Dueker and Sheehan, 1997), which is less sensitive to spatial aliasing, can provide remarkably detailed images of crustal structure from teleseismic signals (Figure 2), although increasingly, single or multimode migration methods and/or scattering inversions are being pursued (e.g., Bostock et al., 2002; Wilson and Aster, 2005) (Figure 3).

In controlled-source seismology, PASSCAL instruments have long been used for traditional two-dimensional refraction and reflection profiles, but the growing number of University of Texas, El Paso (UTEP), PASSCAL, and EarthScope TEXAN instruments now permits three-dimensional surveys across relatively large areas. The crustal tomography community has been developing three-dimen-

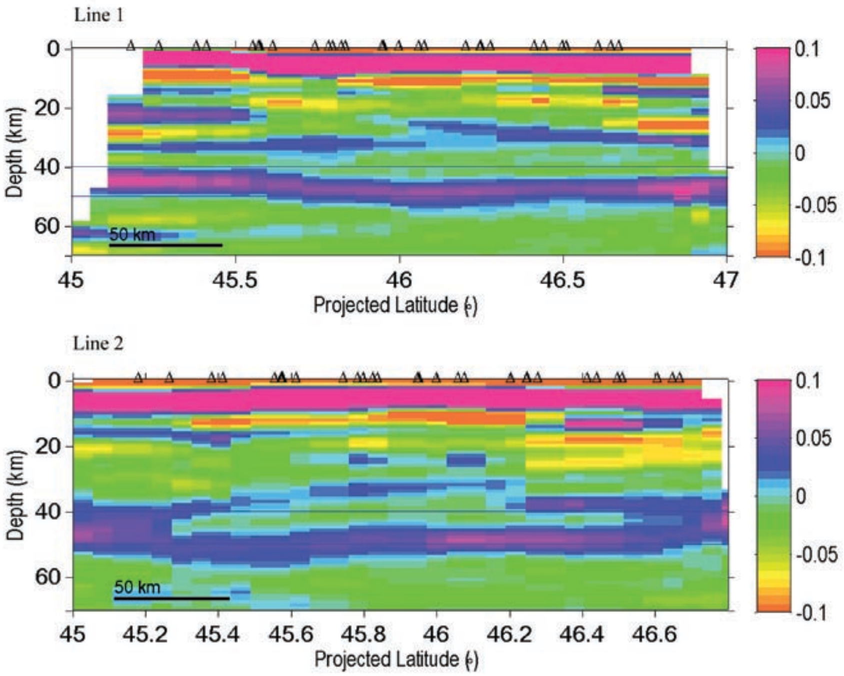


Figure 2 Common conversion point (CCP) stacked receiver function image from an aereal array of broadband seismographs in Montana showing details of crustal structure. The thick lower crustal layer was first identified in a complementary PASSCAL controlled-source experiment deployed in the same region. (From Yuan et al., 2006)

sional travel time tomography methods for about the last 10 years and can easily exploit the expanded instrument base (e.g., Hole, 1992; Zelt and Barton, 1998).

Theoretical developments and advances in computational capabilities, coupled with several community efforts in methodological exploration, and in software standardization and dissemination (e.g., Computational Infrastructure for Geophysics [CIG] and Seismic wave Propagation and Imaging in Complex media [SPICE]) are facilitating the increased application of waveform tomography (i.e., full wavefield inversion) to two-dimensional, controlled-source land, marine, and onshore-offshore investigations to provide extremely high-resolution images of velocity and density variations in crust. Although still a computational challenge, three-dimensional waveform inversion of large data sets for controlled and natural sources is within sight.

Enhanced experimental developments, well-sampled teleseismic wavefields, and three-dimensional active-source arrays, coupled with theoretical and data processing advances, are significantly advancing geological and geodynamic insight into Earth history and processes. Increasingly detailed seismic structural imaging now permits interpretation of chemical- and phase-change boundaries, and more useful inferences on the presence or absence of free fluids or hydrated materials. This advance, in turn, allows the seismological community and an increasing diversity of collaborators in geology, geodynamics, and geochemistry to advance understanding of fundamental Earth processes.

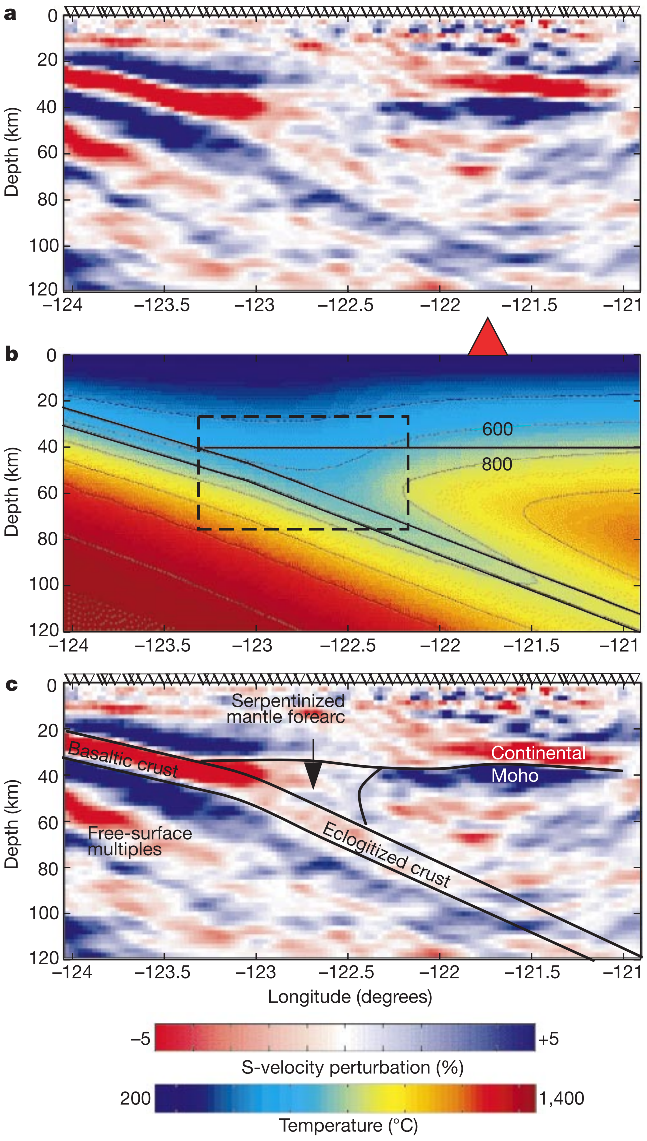


Figure 3. Scattered wave image made using a generalized Radon Transform inversion of P-to-S converted waves from a dense broadband array across the Oregon Cascadia subduction zone, superimposed on a thermal model of the subduction zone, and an interpretation of the image. The loss of signal from the continental Moho in the mantle forearc is attributed to mantle serpentinization by fluids released from the subducting plate. (From Bostock et al., 2002. Field experiment described in Nabelek et al., 1993.)

DISCOVERY

Over 85 institutions contributed "one-pager" research summaries, attributed to PASSCAL instrumentation, to the 2005 IRIS proposal. These summaries provide a representative overview of the variety of seismic experiments currently being fielded that is more comprehensive than space allows in this review. Here, we note a few key themes that are shaping current scientific discussions about Earth processes. Because seismic exploration of the Earth has never before been undertaken at the spatial and temporal scales of the GSN and the aggregate of PASSCAL experiments, serendipitous discoveries are quite common.

Subduction and Whole-Mantle Convection

The cover graphic on the April 1997 issue of *GSA Today,* showing the subducted Farallon plate beneath North America in P and S wave global tomograms (Grand et al., 1997), helped to forever change the debate in the earth science community about whole mantle versus layered mantle convection (Figure 4). Although primarily a result of measurements made on observatory seismographs, global tomographers are increasingly including data from the great number of PASSCAL broadband deployments around the globe to enhance resolution in their studies. This data use has driven a new policy that every PASSCAL broadband experiment is now required to declare one station open to the larger community as soon as it is installed. Note that all data become available after a maximum two-year period. Tomographers are providing ever more accurate images of the global plate circulation system at depth throughout the world. Dozens of PASSCAL experiments have been fielded with the goal of examining the primary convection system, and an increasing number are being undertaken to investigate the secondary convective processes that modulate the whole mantle system and that often drive regional tectonics.

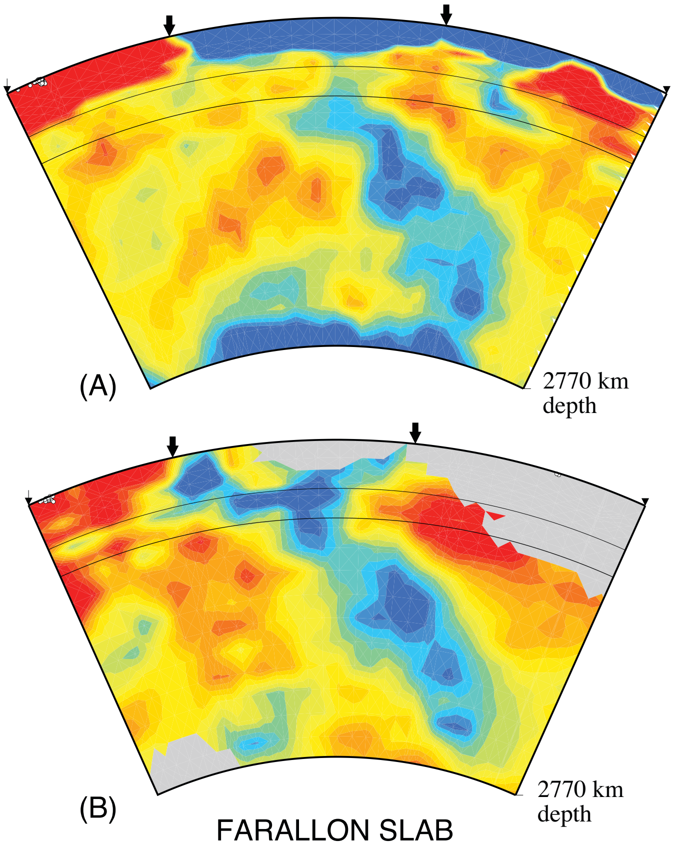


Figure 4. Cover graphic from *GSA Today* showing the subducted Farallon plate beneath North America. (From Grand et al., 1997)

PASSCAL experiments have been designed to provide structural images and infer processes in a wide range of subduction zones, the most obvious manifestation of the primary convection system. In northern China, a PASSCAL experiment will measure the spatial extent, and therefore length of time, the subducted Pacific slab rests on the 660-km phase transition beneath northern China before descending into the deeper mantle as the Japan trenches roll back. A series of passive- and controlled-source seismic experiments are examining the complex arc-continent collision of the Eurasian and Philippine plates that formed Taiwan, and the accretion of Taiwan to the Asian mainland. The controlled-source experiment is designed to relate surface structures in the Taiwan crust to the mantle deformation field. Combined land and marine experiments have investigated the structure of the backarc and slab of the Tonga-Fiji and Marianas trench systems, with complementary controlled-source experiment to examine evolution of oceanic island arc crust and back arc crust. Combined land-marine passive- and controlled-source experiments are examining the complex southeastern Caribbean plate boundary where the Atlantic-South America plate forms a slab tear edge propagator fault (STEP fault; Govers and Wortel, 2004) as the Atlantic subducts beneath the Caribbean plate. Simultaneous tearing and deformation of the South American lithosphere control mountain building and basin development along the northern South American margin. The causes and tectonic consequences of trench rollback in the Adriatic and Hellenic arcs are being determined by projects in the central and eastern Mediterranean. Other subduction zone experiments have examined the consequences of tears in or terminations of subducting plates in Mexico and the northwest Pacific, and the hydration state of slabs in Central America.

The Andes mountains and Altiplano-Puna plateaus are being investigated because they form one of Earth's great mountain chains and orogenic plateaus, and also because they are viewed by many as an analog to the western United States ~ 40–50 million years earlier in its history. These regions thus shed light on the complex Cenozoic history of western North America. For example, basement rooted, Laramide-style uplifts occurring in South America are similar to those found in the Southern Rockies that formed ~ 55 Ma. Andean studies provide a natural laboratory for contrasting lithospheric deformation and volcanic patterns. These patterns range between flat-slab subduction near 30°S, which is producing a volcanic gap with characteristic basement-rooted, Laramide-style uplifts, to steep slab subduction at 36°S, where a normal volcanic arc exists.

Active and passive seismic experiments employing land and ocean bottom seismographs have probed subduction-related processes in the accretionary wedge, the seismogenic zone, the oceanic crust, and mantle wedge in a variety of trenches, including those in Central American, Cascadia, Alaska, and the western Pacific (Figure 5). In Cascadia and Alaska, high-resolution scattered wave and tomographic images of the descending plate and the mantle wedge have been used to identify zones of hydration and serpentinization in the mantle wedge, and track dehydration and eclogization of subducting oceanic crust.

The Indian-Asian plate collision zone has produced Earth's most extreme topography as ocean-continent subduction evolved into continent-continent collision. A large number of recent PASSCAL-supported controlled- and natural-source experiments have produced a much greater understanding of large-scale orogenesis and its structural underpinnings. In the early investigations in Tibet, for example, combined controlled- and passive-source investigations identified a wide-spread midcrustal low-velocity zone beneath the Tibetan plateau that is topped by seismic bright spots. These observations have been interpreted as a plateau-wide partial melt zone, capped by either lenses of melt and/or melt-derived fluids. A similar widespread zone of partial melt was subsequently identified under the Altiplano of the Andes. More recent experiments have examined mantle flow fields created adjacent to the edges of collision zone, as Eurasia deforms in response to the collision. The seismologic database in Tibet and the Himalayas have led to several models of lithospheric descent under the Tibetan plateau; debate still exists as to whether the lithosphere consumption is one-sided or two-sided (i.e, whether the Indian mantle lithosphere is subducting alone, or both Indian and the Eurasian mantle lithosphere are descending into the mantle).

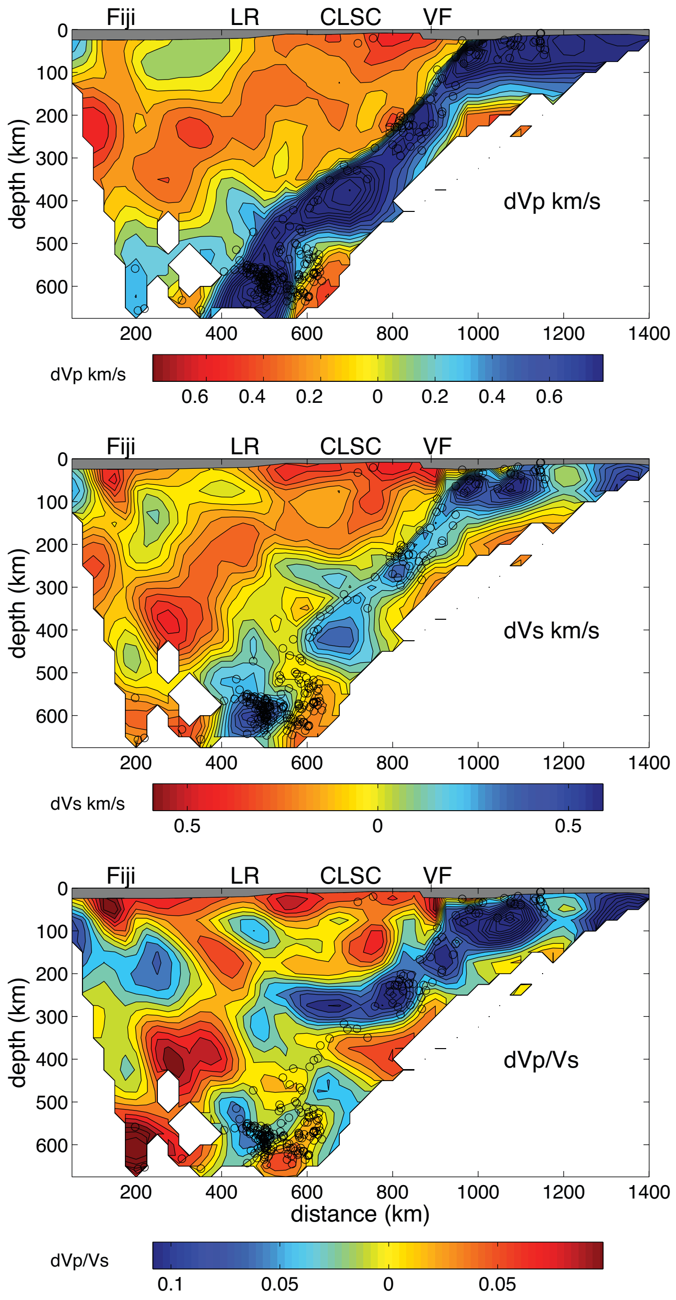


Figure 5. Mantle seismic velocity structure of the Tonga subduction zone and Lau back arc basin as determined by broadband ocean bottom seismometers and PASSCAL instruments. Crustal structure is constrained by seismic refraction results. The figure shows (a) dVp, (b) dVs, and (c) d(Vp/Vs) anomalies relative to the IASP91 velocity model, contoured at 0.08 km/s for Vp, 0.06 km/s for Vs, and 0.012 units for Vp/Vs. Earthquake hypocenters are shown as black circles. The central Lau spreading center (CLSC) shows a large dVp/Vs anomaly in the uppermost mantle extending to ~100 km depth, with an anomaly amplitude larger than expected from thermal effects alone, suggesting a wide zone of melt production. (From Condor and Wiens, 2006)

Hotspots and Plumes

Source-region depths for Earth's hotspots, which have topographic, geothermal, and magmatically distinct signatures at Earth's surface, have been seriously debated since before the theory of plate tectonics was proposed. Most recent discussion has focused upon whether they originate near the core-mantle boundary or in the upper mantle (or perhaps both). Global tomography with improved imaging capabilities, in some cases augmented with archived PASSCAL data is gradually determining that some source zones may indeed be at the core-mantle boundary, whereas others arise at shallower levels. A number of PASSCAL experiments have been carried out in recent years explicitly to address this debate.

The Yellowstone caldera and hotspot have been the target of multiple PASSCAL experiments that identified low crustal velocities associated with surface thermal anomalies. Deeper imaging revealed a low-velocity pipe to the north-northwest of Yellowstone that is associated with a downward-deflecting 410-km discontinuity and extends at least as deep as the 660-km discontinuity, although it does not appear to penetrate the bottom of the transition zone. A related PASSCAL experiment across the Snake River plain to the southwest identified a high-velocity lower crust, interpreted as a frozen, plume-derived basalt intrusion atop a low-velocity upper mantle. Seismic velocity and anisotropy interpretations ascribe the upper mantle anomaly to the flow of a plume head, flattened and stretched by the overriding North American plate.

Iceland has also been the site of several recent PASSCAL experiments (e.g., Figure 6). Integrated tomography and receiver-function imaging suggest that the plume extends at least to the top of the transition zone at the 410-discontinuity. Receiver functions suggest it may extend to its base, but the most recent global tomography suggests it is an upper mantle feature. This is still a very controversial topic.

Global tomography data sets have been complemented by data from a number of PASSCAL experiments in the quest for plume sources. For example, data from the Kaapvaal PASSCAL seismic array has helped quantify the large-scale low-velocity zone at the core-mantle boundary under the southern Atlantic that extends under East Africa, the site of a developing continental rift system. A variety of PASSCAL active- and passive-source seismic experiments examined the details of the East African rift system from Tanzania through Ethiopia, finding large volumes of basaltic additions to the crust, and relatively narrow low-velocity zones in the mantle through upper mantle depths. Processes in the uppermost mantle directly beneath the crust are still poorly understood.

Relatively thin crust and low upper mantle velocities in the Basin and Range province have been identified by a COCORP survey at 40°N and a number of controlled-source and broadband PASSCAL experiments. Until recently, tomographic images of the Basin and Range mantle relied largely on the existing earthquake monitoring seismograph

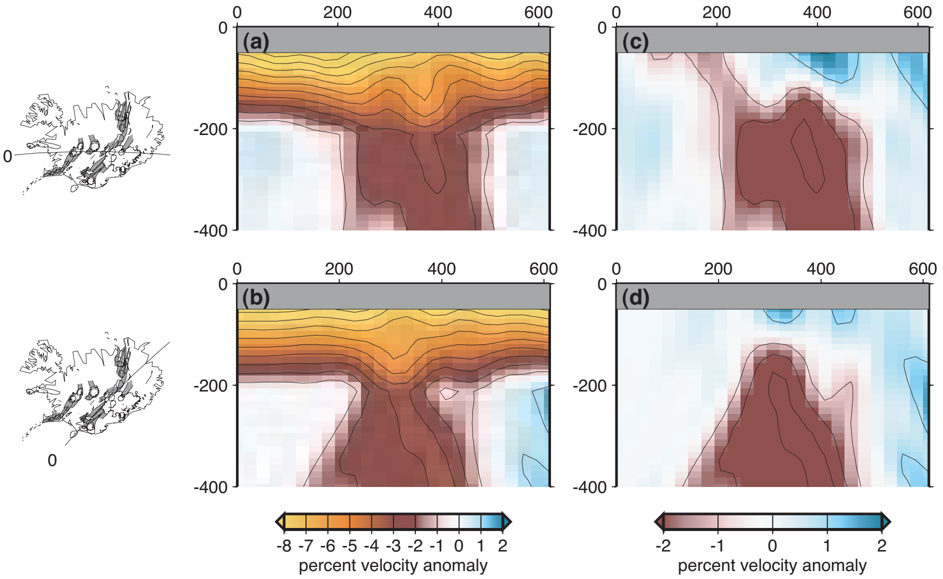


Figure 6. Tomographic images of Vs perturbation along two cross sections through Iceland showing the vertical plume conduit resolved to 200–400-km depth, and the plume head above 200 km. Anomalies are absolute velocity variations across (a) and parallel (b) to the rift zone as a percentage deviation from 4.5 km/s in the upper 210 km. Below 210 km, the percentages are relative to layer averages. Relative velocity anomalies (c and d) show velocity variations within the plume head including high velocities in the uppermost mantle above the plume core. (From Allen et al., 2002)

network, but are now being rapidly refined using data from the first USArray Transportable Array footprint. Explanations for the positive buoyancy required by the excess elevation and thin crust include "simple" orogenic collapse over an already perturbed mantle wedge following the Sevier and Laramide orogenies, a mantle plume impacting the entire region, and asthenospheric upwelling induced by Farallon plate removal. Each of these scenarios has different consequences for support of the Basin and Range lithosphere, ranging from an almost entirely thermal origin, to a mixed mode of thermal and chemical buoyancy, likely modulated by water added to the upper mantle over time by the Farallon plate. A remarkable circular anisotropy pattern in the central/northern Basin and Range has been attributed to the plume impact, or to toroidal asthenospheric flow arising beneath the edge of the descending Gorda/Juan de Fuca plate. A PASSCAL-facilitated study of the Rio Grande rift, marking the extreme eastern extent of Basin and Range-type extension, showed that it has an entirely uppermost mantle expression confined well above the 410-km discontinuity.

The Upper Mantle and Secondary Convection Phenomena

Several secondary convection mechanisms that are key to the history of Earth's continental crust have been suggested, notably Rayleigh-Taylor instabilities and delamination processes, in which negatively buoyant mantle lithosphere and sometimes mafic lower crust are recycled into the deeper mantle without being part of a larger subducting plate system. A number of these have been subsequently identified by PASSCAL-supported projects. Rayleigh-Taylor instabilities were first predicted theoretically (Houseman et al., 1981), and somewhat later delamination processes were inferred from geochemical data in the Andes (e.g., Kay and Kay, 1990, 1993). These processes heavily modulate regional tectonics and magmatism, yet the triggers of the instabilities are not observable at the surface. Their *a posteriori* surface signatures are identifiable in local or regional thermal perturbations, in the magmatic record, and in abrupt changes in elevation. Various types of seismic investigations can identify descending lithospheric drips and the unusual crustal structures that ephemerally persist following delamination. Active- and passive-source PASSCAL experiments have examined probable mantle drips (1) in the Sierra Nevada, where a lithospheric keel is thought to have foundered from the batholith base, producing a characteristic suite of surface volcanics, (2) in the Wallowa Mountains, where a bull's-eye uplift of a granitic pluton is associated temporally and spatially with the Columbia River flood basalts, (3) across the Rio Grande Rift and Colorado Plateau, and (4) in the Vrancea zone, Romania, where intermediate-depth seismicity and a mantle slab have been identified far from a typical subduction zone.

Ancient Boundaries and Modern Processes

Southwestern North America was assembled in Paleo-proterozoic times by successive accretion of island arcs to the Archean Wyoming protocontinent over some 600 million years. A suite of active and passive seismic experiments across the terrane boundaries separating these ancient island arcs in the southern Rocky Mountains show that the modern upper mantle has a fabric parallel to the northeastern trend of the Precambrian fabric, rather than the more north-south trend of the modern plate boundaries. These seismic data led to the insight that ancient lithosphere-scale mantle structure persists and controls much of modern tectonics in the western United States not directly affected by Farallon subduction. Upper mantle seismic velocities are low along northeasterly trends beneath a number of the terrane boundaries. One such feature is along the Jemez lineament, a trend of Cenozoic volcanics following the southeastern flank of the Colorado Plateau into the Great Plains, and crossing the east-west rifting of the Rio Grande. Combined controlled- and passive-source PASSCAL experiments such as CD-ROM and RISTRA identified a thinned crust and a mantle source for recently erupted basalts in northern New Mexico and showed dramatic and largely unanticipated uppermost mantle velocity contrasts associated with ongoing interactions between the Proterozoic boundaries, Laramide compressional, and Cenozoic extensional structures. A prominent and presently enigmatic mantle feature, which probably has a similar mixed provenance related to the interactions of ancient structures and recent tectonics, is in the Aspen Anomaly region of central Colorado. This structure underlies the highest topography of the present-day Rocky Mountains, and is now being investigated in a continental dynamics experiment embedded within the EarthScope USArray Transportable Array.

The Cratons

The Archean cratons of Africa and North America have been extensively studied in PASSCAL-supported experiments. Four notable experiments are the Trans-Hudson, MOMA, Abitibi experiments in North America, and the Kaapvaal experiment in South Africa. The TransHudson experiment provided the first data to suggest that the anisotropy field beneath the cratons was related to absolute plate motions and resultant mantle shear strain, which was subsequently supported by observations in many other locations. The MOMA experiment identified the southern edge of the Canadian shield, showing distinct structures north and south of the array. The Kaapvaal experiment identified small positive velocity anomalies that have been interpreted as a tectonospheric root extending up to ~ 300 km (Figure 7). The Abitibi experiment data were used to make scattered wave images of apparent Grenville age subduction structures along the southeastern flank of the Superior province, contributing to our understanding of cratonic evolution and deformation (Figure 8).

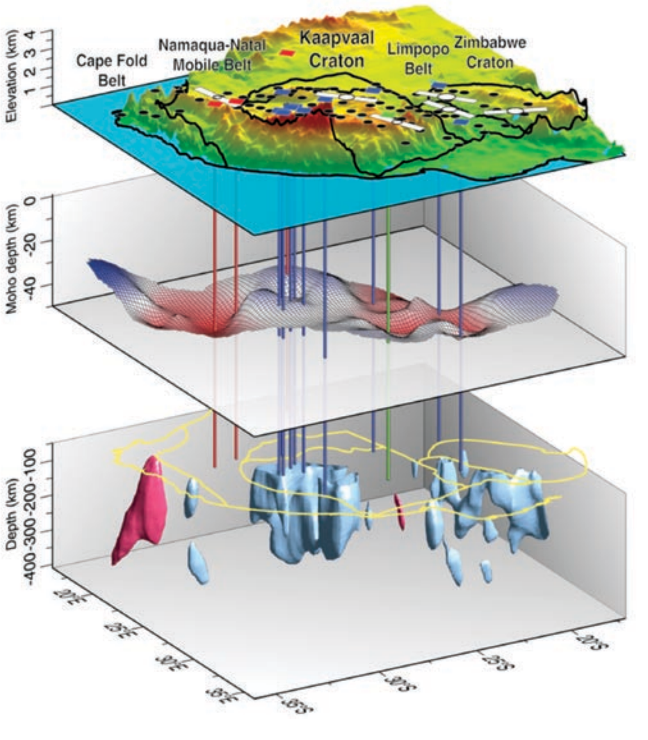


Figure 7. Summary figure from the Kaapvaal project in southern Africa showing geological provinces (top) with PASSCAL broadband seismograph stations (black dots). Kimberlite pipes are shown schematically from diamondiferous kimberlite localities showing their relationship to crustal and mantle seismic structure. The Moho is shown as a gridded surface at center. At the bottom are Vp velocity perturbations in the upper mantle, shown as a constant blue for anomalies > 0.45% and constant red for anomalies < -0.7. Inferred tectospheric roots of the Kaapvaal and Zimbabwe cratons are outlined in blue. (From James et al., 2001)

The Continental Crust

The processes by which continental crust and underlying lithosphere forms and persists for up to gigayears has been a longstanding geological problem with fundamental implications for continental evolution and the history of plate tectonics. There appears to be no direct differentiation path from fertile mantle to bulk continental crust. Some intermediate differentiation processes must occur to produce a crust with the chemical properties recorded in sediments and also inferred from seismic data (~ 62% $Si0_2$). Field evidence suggests cratonic crust is an aggregation of island arcs; however, seismic evidence suggests that modern island arcs are too basaltic (< 50% $Si0_2$) to form what could be considered average continental crust. A number of different hypotheses have been put forward, including a marked change in plate tectonics since the early Archean, and various forms of chemical refining in island arcs or in continental arcs such as the Andes and Sierra Nevada, followed by delamination of a restite layer from the base of the crust along with mantle lithosphere. In addition to direct studies of the cratons, a number of experiments are examining formation and evolution of the continental crust as an arc process. These projects include controlled- and passive-source experiments in several island arc settings, including the Marianas, the southeastern Caribbean, and the Aleutians, complemented by studies of the continental arc process in the Andes and

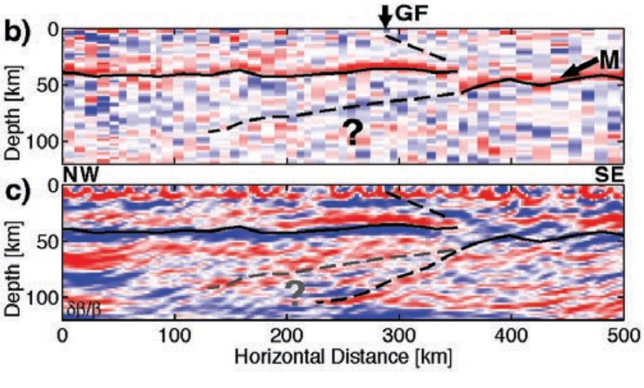


Figure 8. (top) CCP stacked receiver function image of the Proterozoic Abitibi-Grenville boundary showing an offset Moho. (bottom) Scattered wave inversion of the same data set show velocity perturbations and more clearly delineate subduction-collision structures in the Moho. (From Rondenay et al., 2005)

Sierra Nevada. Suspected delamination phenomena have been investigated by several PASSCAL-supported experiments, including in Arctic Alaska, the Sierra Nevada, the Wallowa Mountains, the eastern Rio Grande rift, and the Vrancea zone, Romania.

The Core

Improved global coverage afforded by PASSCAL experiments has proven important for core studies, giving seismologists new vantage points for viewing core phases across relatively dense seismograph arrays. Data from the Kaapvaal craton were used to discover that the edges of South African deep mantle low-velocity anomalies are very sharp, leading to a consensus that they arise from a combination of thermal and chemical perturbations. Data from the PASSCAL MOMA, FLED, RISTRA, and other US arrays have led to identification of core-mantle boundary anomalies under the western Caribbean plate that have various interpretations, including D" "slab graveyard" sites. As an example of serendipitous discovery, data from the BOLIVAR array in Venezuela displayed a previously undetected retrograde seismic phase, PKIIKP2, indicating that Earth's center has a unique seismic structure (Niu and Chen, in review; Figure 9).

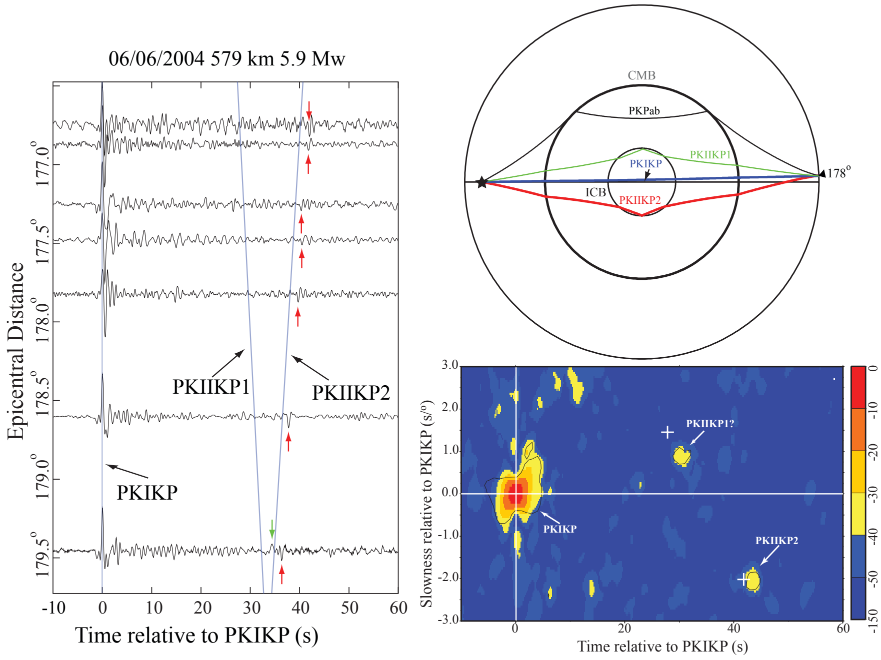


Figure 9. (left) Bolivar array recording of an earthquake from the antipode displaying the major arc phase PKIIKP2. (top right) Ray paths for the minor arc phase PKIIKP1 and major arc phases PKIIKP2. Slowness-time stack for all antipode earthquakes recorded by the Bolivar array showing the PKIIKP phases. (From Niu and Chen, in review)

Currently and recently deployed PASSCAL arrays in Antarctica (see Polar Efforts section) are expected to provide valuable information on inner core anisotropy by providing the first set of dense measurements made along paths nearly parallel to Earth's rotational axis. These measurements are key to deciphering the anisotropic structure of the inner core, and its pronounced east-west hemispherical asymmetry.

HIGH-RESOLUTION SEISMOLOGY

In contrast to large-scale experiments that commonly pursue the great themes of Earth evolution, many high-resolution seismology projects have more pragmatic motivations. For instance, high-resolution seismology is an important tool for assessing groundwater resources as we grapple with locating, characterizing, and protecting water sources for an increasingly urbanized society. Seismic investigations have proven particularly valuable in the arid southwestern United States where deep aquifers, often occupying tectonically controlled basins, are a crucial source of drinking, agricultural, and industrial water. Aquifer assessment commonly requires signal penetration of no more than 1–2 km.

High-resolution seismology has proven to be one of several useful tools for delineating likely locations of contaminants deliberately or inadvertently lost to the subsurface. Away from the pollution-discharge point, seismic imaging can identify channels along which contaminants migrate and traps in which they pond. Such subsurface characterization of contaminant traps is critical information for the hydrologists and engineers designing successful surfactant flooding and pump-and-treat remediation programs. Surveying for contaminants frequently requires ultra-high-resolution seismology (sampling rates ~1 kHz or more), with targets often found as shallow as 10 m and resolution required at scales of tens of centimeters. PASSCAL multichannel systems and TEXAN instruments have been deployed in this manner for two- and three-dimensional surveys at a number of contaminant sites.

PASSCAL high-resolution equipment also has an important educational use. High-resolution reflection and refraction experiments are ideally suited for teaching seismology fundamentals in exercises that are inexpensive and easy to conduct with student assistance. PASSCAL equipment has seen enormous class use for field geophysics classes, exploration geophysics courses, and has also been used by the NSF Research Experience for Undergraduates IRIS Internship Program and by the Summer of Applied Geophysical Experience (SAGE) geophysical field camp coordinated with Department of Energy and other partners. High-resolution instrumentation can be used to introduce and reinforce a number of important seismology concepts, including basic principles of wave propagation (reflection, refraction, surface waves); the power of seismic arrays for detecting weak signals; the strengths, limitations, and differences between imaging Earth structure with scattered waves and transmitted waves; and the importance of record keeping and quality control during data acquisition to successfully process seismic data.

EARTHQUAKES AND EARTHQUAKE HAZARDS

PASSCAL instrumentation has been used extensively for the study of earthquake sources and for earthquake hazards research and assessment in urban areas. Earthquake source studies using PASSCAL instrumentation include RAMP (Rapid Array Mobilization Program) deployments for determining aftershocks, controlled-source experiments and fault zone guided-wave studies to understand the structure of fault zones, and recent array studies of episodic tremor and slip (ETS) in Cascadia.

PASSCAL RAMP consists of 10 six-channel instruments with strong-motion-capable sensors, reserved for rapid mobilization to record seismicity following an earthquake or associated with a volcanic eruption. RAMP instruments were used to monitor aftershocks following major shocks in: 1989 at Loma Prieta, CA; 1992 at Little Skull Mountain, NV; 1992 at Landers and Mendocino, CA; New Guinea in 1996; Pennsylvania in 1998; Ohio and Nisqually, WA in 2001; Mexico in 2001; and Puerto Plata, Dominican Republic in 2003.

A frequent use of PASSCAL's high-resolution seismic equipment has been for imaging the shallow structure of active faults (Figure 10). Motivated by improving hazard awareness, such studies have been progres-

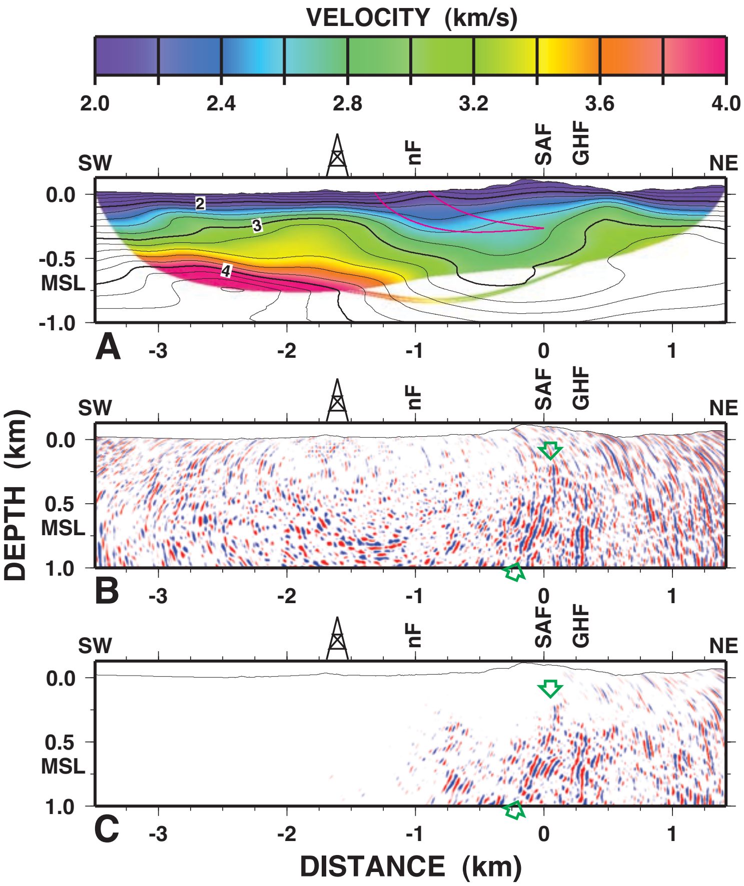


Figure 10: Tomographic and seismic reflection image of the near-vertical San Andreas and Gold Hill faults near the SAFOD drill hole (derrick) at Parkfield, CA. The acquisition used 840 channels of high-resolution seismic equipment, including the PASSCAL multichannel systems. (After Hole et al., 2001)

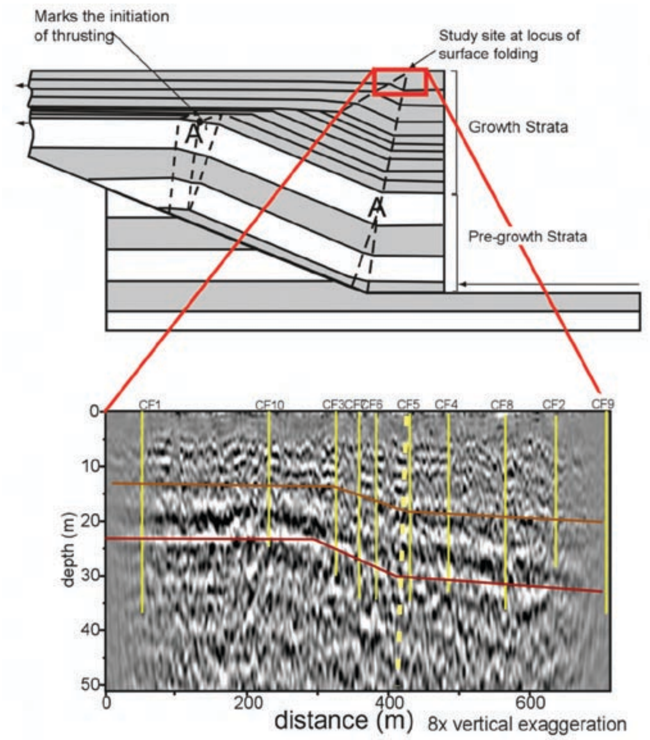


Figure 11: High-resolution seismic reflection profile from urban Los Angeles showing shallow folding above the backlimb of the Compton blind thrust fault. The profile shows a narrow "kink band" above the location where a thrust ramp leaves a horizontal basal fault. Kinematic model is shown at top. Yellow lines show the locations of cores used to obtain ages and measure the thickness of the shallow strata, from which slip rates can be estimated. (Modified from Leon et al., submitted)

sively moving into more urbanized areas as the number of available channels and quality of shallow seismic sources has increased. In addition to imaging the faults themselves, these studies have been imaging the shallow folds above deep "blind" thrust faults that lie kilometers below the surface, helping assess risks from faults which do not have a surface rupture (Figure 11).

The availability of large numbers of instruments allows determination of the spatial distribution of strong-motion amplification and duration caused by the excitation of shallow sedimentary basins and deeper structures during earthquakes. In the Puget Sound region, for example, large numbers of PASSCAL sensors have been used to monitor ground shaking created by teleseismic and local earthquakes, large blasts, and even during the demolition of the King Dome sports stadium (Snelson et al., 2007; Figure 12). Similar studies have been carried out in Anchorage, Alaska, and Hawaii to map seismic amplification beneath urban areas.

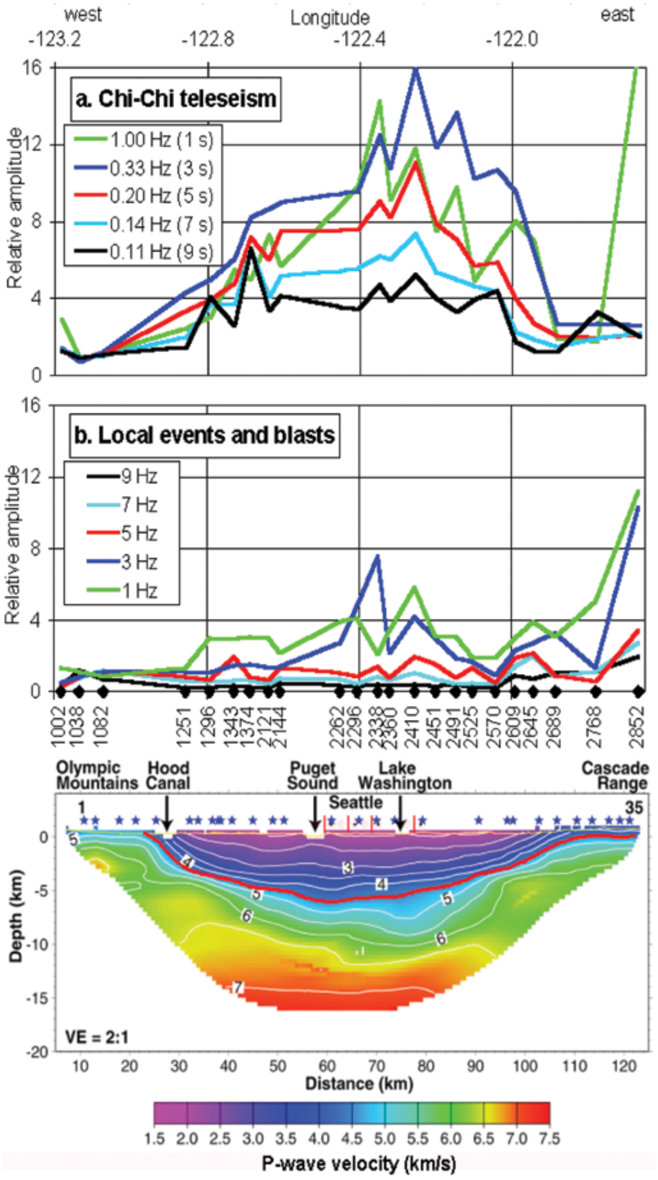


Figure 12. Ground shaking over the sediment-filled Seattle basin resulting from teleseismic signals from the 1999 Chi-Chi, Taiwan, earthquake, and during local earthquakes and blasts, as measured using PASSCAL instruments. The tomographic image of the basin was made using over 1000 seismometers that recorded large blasts. (Figure from Pratt et al., 2003 and Snelson et al., 2007)

PASSCAL high-resolution seismic equipment also is used for geotechnical studies to characterize the shallow subsurface. In particular, measurements of the shallow S-wave velocity structure, either through small-scale refraction profiles or measurement of surface wave speeds via ambient noise analysis, are used to determine amplification factors to estimate damage likelihoods from shear waves during earthquakes. For example, one recent study mapped the shallow S-wave velocities along profiles in the Reno and Las Vegas, Nevada, urban areas, and in Los Angeles.

NUCLEAR EXPLOSION SEISMOLOGY

Nuclear explosion monitoring research is focused on low-magnitude events ($m_b \leq 4.0$) over broad areas, particularly in Eurasia. Monitoring normally requires observations of events at regional distances (< 1500 km) where signals are best observed at relatively high frequencies (0.05–10 Hz). Propagation through the heterogeneous crust and upper mantle has a strong impact on these signals, and requires calibration to account for path-specific seismic observables (e.g., travel times, amplitudes, surface wave dispersion, and regional phase propagation characteristics). The PASSCAL facility provides instrumentation for research experiments related to nuclear monitoring, as well as an archived global data set that indirectly supports nuclear explosion monitoring research by constraining crust-mantle structural models, particularly in the critical Eurasian region, and by improving empirical calibration methods. Specific experiments that have contributed to our knowledge of seismic structure and seismic monitoring calibration include: 1991–1992 Tibet (Owens et al., 1993), Tanzania (Nyblade et al., 1996), INDEPTH-II (Nelson et al., 1996), 1995–1997 Saudi Arabia (Vernon and Berger, 1998), Eastern Turkey Seismic Experiment (Sandvol et al., 2003), and Iraq (Ghalib et al., 2006). The value of archived PASSCAL data is illustrated here; although these experiments were generally supported to address fundamental scientific objectives, they nonetheless provide data that benefit applied seismology for nuclear monitoring.

Underground nuclear explosion monitoring is the main theme of verification research, but source phenomenology is a second important area of interest. In this vein, PASSCAL instrumentation has been used in experiments with the specific goal of improving understanding of large chemical explosions, such as the nuclear analog Non-Proliferation Experiment (Zucca, 1993; Tinker and Wallace, 1997), as well as the Source Phenomenology Experiment, which examined mining explosions (Leidig et al., 2005; Hooper et al., 2006).

POLAR EFFORTS

Seismology in polar regions is a rapidly developing component of PASSCAL-supported science. Antarctic, Greenland, and past continental ice sheets and sea ice have dramatically affected climate and sea level throughout Earth's history. Yet, great extents of these key regions are largely inaccessible to geologic study, and Antarctica remains a tectonic *terra incognita*. IRIS PASSCAL-supported seismology, principally funded by the NSF Office of Polar Programs (OPP), is enhancing fundamental understanding of basic crustal and upper mantle structure as a part of larger interdisciplinary studies, and is being used in novel studies of ice cap, glacial, and iceberg-related seismic phenomena. Facility support for these efforts requires significant new development efforts in sensor, telemetry, and station design. Currently, this effort is being accomplished through a joint IRIS PASSCAL/UNAVCO OPP Major Research Instrumentation (MRI) initiative, supplemented by a second IRIS MRI largely for equipment procurement.

The far polar regions have the poorest seismographic coverage of any region on Earth, and temporary PASSCAL deployments at high latitudes not only provide regional structure but also unique raypaths for constraining important elements of deep structure in global tomographic models. Broadband seismic recording in polar regions is uniquely useful for constraining inner core anisotropy, because the axis of inner core anisotropy is oriented approximately parallel to Earth's spin axis. The source of the anisotropy is believed to be the preferred orientation of anisotropic inner core iron crystals, but alignment mechanisms and crystallography are unclear. Improved understanding the inner core is key to understanding the evolution of the core system, core heat flow, and magnetic field throughout Earth history.

A series of completed and ongoing PASSCAL experiments (e.g., **Figure 13**) is interrogating the seismic structure of the Antarctic lithosphere using specialized cold-weather instrumentation. Little has been known about the origin

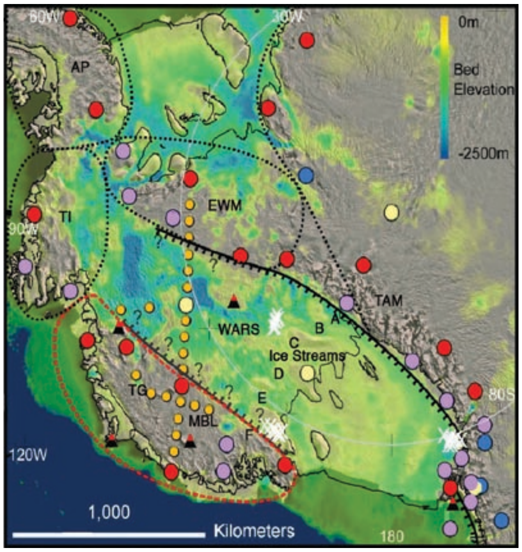
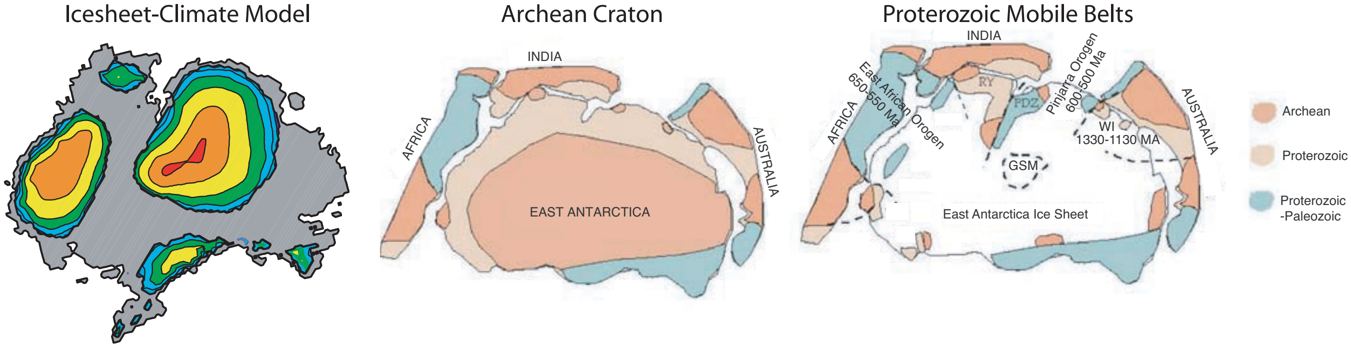


Figure 13. Ongoing POLENET PASSCAL broadband seismograph/GPS deployment relative to bedrock topography and tectonic features. WARS=West Antarctic rift system; TAM=Transantarctic Mountains. Dotted lines: crustal block boundaries (black) AP=Antarctic Peninsula; TI=Thurston Island; MBL=Marie Byrd Land; EWM=Ellsworth-Whitmore Mtns]. POLENET has been funded by NSF OPP during the International Polar Year period. POLENET, and an East Antarctica project AGAP, are initial beneficiaries of recent PASSCAL polar instrumentation developments. (From Lythe et al., 2001)

and timing of major mountain uplifts in the highlands of West Antarctica. The West Antarctic Rift System (WARS) is one of the largest regions of diffuse continental extension in the world, perhaps comparable to the western US Basin and Range, but the pattern of rifting and geologic history of WARS rift basins are virtually unknown. East Antarctica is characterized by the highest mean deglaciated elevation of any major continental region. The uplift mechanism and history of these highlands is of significant interest because the first glaciation of the Cenozoic nucleated here ~ 34 Ma. There are numerous proposed mechanisms for the origin of the highlands, including collisional tectonics, extensional tectonics, mantle plume (hotspot) processes, underplating and/or retrograde metamorphism of eclogite, dynamic support by mantle convection, and erosional isolation of an elevated region protected from denudation by resistant cap rocks. The plume hypotheses are particularly intriguing because of the potential for abnormal geothermal inputs to the bases of glaciers and ice sheets, which affect their coupling to Earth, the formation of subglacial lakes, and their long-term stability.

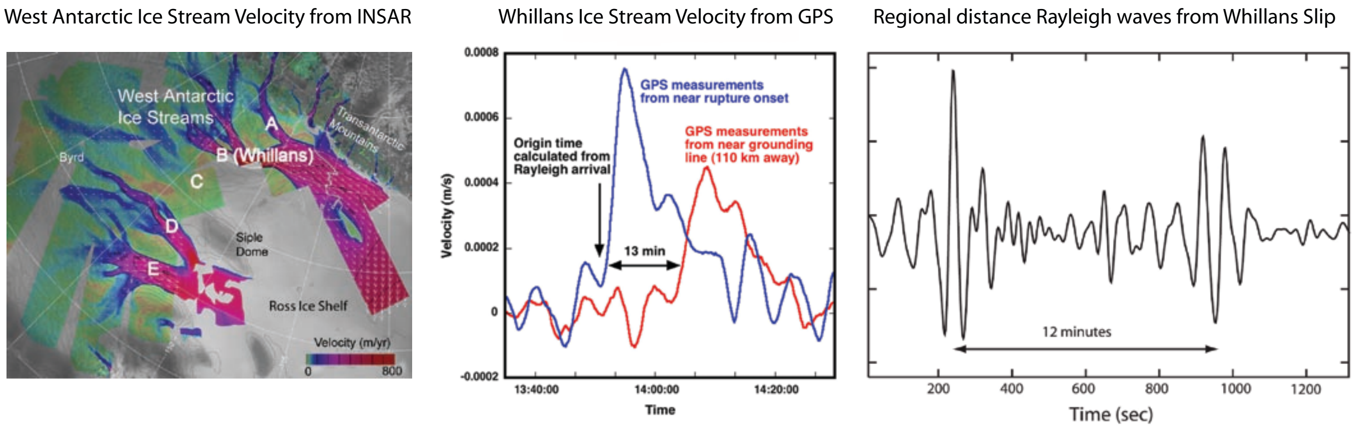
PASSCAL experiments are providing novel and important information on processes affecting glaciers, ice streams, and sea ice, frequently in consort with GPS, weather stations, ice-penetrating radar, and other glaciological instrumentation (Figure 14). For example, the dynamics of outlet glaciers, ice shelves, and ice streams are of principal importance for understanding the stability of large continental ice sheets and the impacts of possible climate change. PASSCAL-facilitated studies of seismicity associated with the flow of ice streams and some mountain glaciers have advanced understanding of, in many cases unanticipated, relationships between small external forcings (tidal, ocean swell, and possibly even smaller atmospheric pressure forcings; Figure 15) and cryosphere dynamics. PASSCAL seismographs have further been used as a principal component of multidisciplinary studies of interrelated glaciological, atmospheric, and oceanographic processes affecting giant tabular icebergs


Icesheet-Climate Model

Archean Craton

Proterozoic Mobile Belts

Figure 14. (left) Coupled ice sheet-climate model showing ice elevation 5 My following an increase in global CO_2 about 35 Ma. The first glaciation in the cooling world localize over the Gamburtsev Mountains (site of the ongoing AGAP project). (center and right) Speculative tectonic structure of Antarctica. The geology of East Antarctica is presently unknown, so the history and uplift mechanism of its internal highlands is uncertain. East Antarctica may be comprised of a single Archean craton or multiple cratons. (Figure from DeConto and Pollard, 2003)


West Antarctic Ice Stream Velocity from INSAR

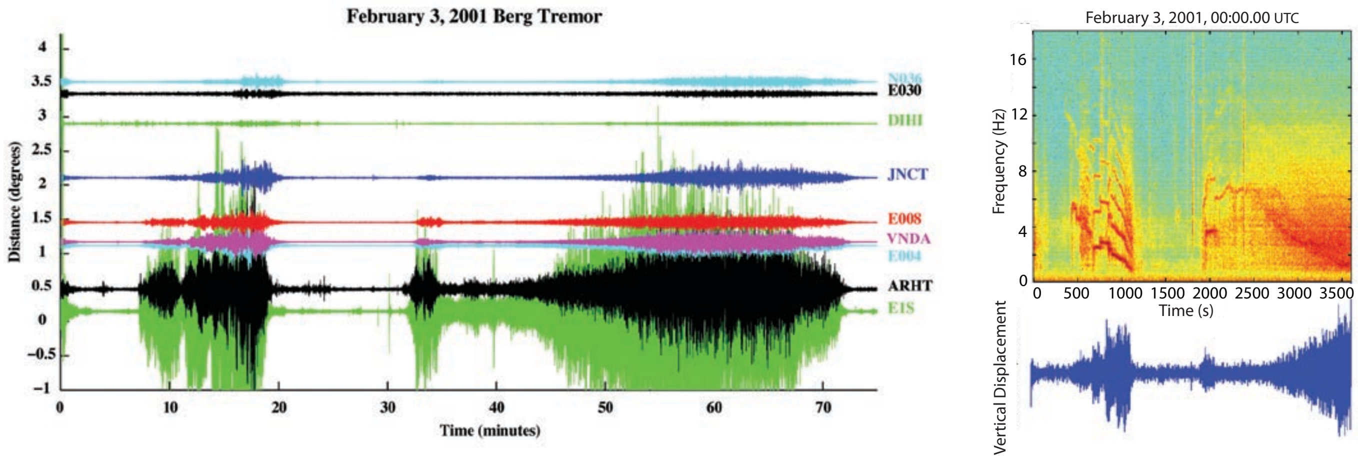
Whillans Ice Stream Velocity from GPS

Regional distance Rayleigh waves from Whillans Slip

Figure 15. (left) West Antarctic Ice Stream average velocities from INSAR (Joughin and Tulaczyk, 2002). (middle) The Whillans Ice Stream shows stick-slip behavior, with slip episodes requiring approximately 10–15 minutes to propagate from the nucleation point to the grounding line (data from the TIDES project, courtesy of S. Anandakrishnan). (right) Rayleigh waves excited by these slip events were detected—1100 km away at the PASSCAL TAMSEIS array, suggesting such behavior can be routinely monitored seismically with broadband instrumentation. (From Wiens et al., 2006)

calved from the Ross Ice Shelf since 2000, including calving, breakup, and collision mechanisms producing tremor signals visible at teleseismic distances as oceanic T phases (Figure 16). Interest in seismic recordings of glaciological processes has been substantial, and over the past several years the number of polar PASSCAL experiments related to glaciology has exceeded the number with purely solid-Earth motivations. PASSCAL and associated longer-term seismic deployments in and around Ross Island and Mount Erebus volcano, as well as on the surfaces of large, recently calved megaicebergs, have identified a host of novel seismological and acoustic ice-ice and ice-seabed collision signals associated with the birth and evolution of Earth's largest freely floating ice masses.

Recently, Ekstrom et al. (2003) discovered a class of large ($M_w \sim 5$) long-period seismic sources from the periphery of Greenland that generate long-period seismic waves equivalent to those produced by magnitude-5 earthquakes, but no detectable high-frequency body waves. Although similar events are observed in Alaska and Antarctica, more than 95% are associated with Greenland outlet glaciers


February 3, 2001 Berg Tremor

February 3, 2001, 00:00.00 UTC

Figure 16. Megaiceberg tremor recorded at PASSCAL TAMSEIS, GSN, and Mount Erebus seismic stations (record section at left.) Note the exceptional duration of the seismic source (over 1 hr) and its regional visibility more than 300 km into the east Antarctic plateau. The complex and evolving spectral structure of this B15 iceberg-Ross Island collision (spectrogram at right) arises from tens of thousands of repetitive stick-slip subevents occurring during ice-ice or ice-ground collisions. (From MacAyeal et al., in prep.)

(Figure 17). The seasonal signal and temporal increase apparent in these results are consistent with a dynamic response to climate warming driven by an increase in surface melting and to the supply of meltwater to the glacier base, which affects transport and calving in these very large and relatively warm glacial systems. In January 2008, IRIS and NMT submitted a proposal to the NSF MRI program, "Development of a Greenland Ice Sheet Monitoring Network (GLISN)," specifically to improve the monitoring of Greenland seismicity, with particular attention to seismicity that may be associated with climate change affecting on the icecap and its outlet glaciers.

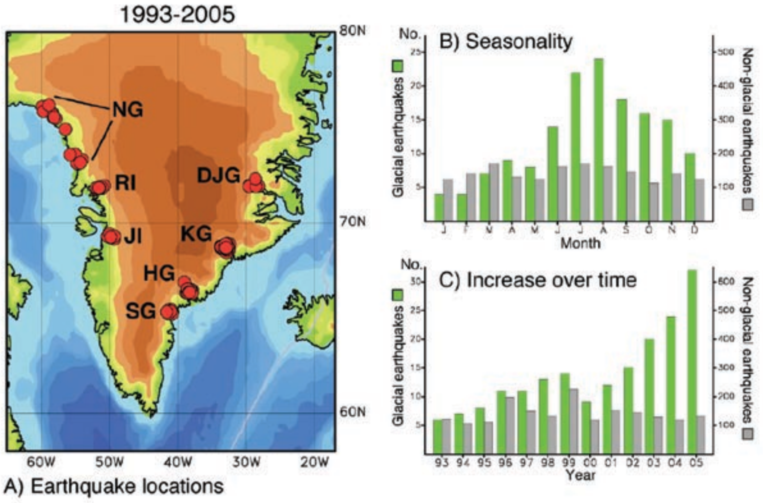


Figure 17. (A) Topographic map of Greenland with locations of 136 glacial earthquakes (red circles): DJG, Daugard Jensen Glacier; KG, Kangerdlugssuaq Glacier; HG, Helheim Glacier; SG, southeast Greenland glaciers; JI, Jakobshavn Isbrae; RI, Rinks Isbrae; NG, northwest Greenland glaciers. (B) Histogram showing seasonality of Greenland glacial earthquakes. Green bars show the number of detected glacial earthquakes in each month, and gray bars show the earthquakes of similar magnitude detected elsewhere north of 45 N. C: Histogram showing the increasing number of glacial earthquakes (green bars). (From Ekstrom et al., 2006)

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PROGRAM HISTORY

Sensors on rack in the warehouse.

PASSCAL Instrument Center, Socorro, NM.

Sensor repair bench.

Cable storage system.

Warehouse forklift and packing area.

In the early 1980s, seismologists formed the Program for Array Seismic Studies of the Continental Lithosphere to develop a portable array seismograph facility. PASSCAL was subsequently merged with another group endeavoring to develop a modern global seismic network; the resultant collaboration became the IRIS Consortium. PASSCAL's goals were to develop, acquire, and maintain a new generation of portable instruments for seismic studies of the crust and lithosphere, with an initial goal for instrumentation set at a somewhat arbitrary number of 6000 data-acquisition channels. PASSCAL formed the flexible complement (the "Mobile Array" in the 1984 IRIS proposal to NSF) to the permanent GSN observatories. During the first cooperative agreement between IRIS and NSF (1984–1990), the primary emphasis was on the careful specification of the design goals and the development and testing of what became the initial six-channel PASSCAL instruments. Three technological developments between 1985 and 1995 were critical to the success of portable array seismology: the development of low-power, portable broadband force-feedback sensors; the availability of highly accurate GPS absolute-time-base clocks; and the advent of compact, high-capacity hard disks. An initial purchase of 35 seismic systems were delivered in 1989 and maintained through the first PASSCAL Instrument Center at Lamont-Doherty Geological Observatory of Columbia University. During the second cooperative agreement (1990–1995), the PASSCAL instrument base at the Lamont facility, which focused on the broadband sensors used primarily in passive-source experiments, grew to more than 100 instruments.

In 1991, a second PASSCAL Instrument Center was established at Stanford University to support a new three-channel instrument that was designed for use in active-source experiments and for rapid deployment for earthquake aftershock studies. By 1995, almost 300 of these instruments were available at the Stanford facility. The rationale for the Stanford Instrument Center was in part driven by proximity to the USGS Menlo Park Crustal Studies Group, which was maintaining a fleet of 200 Seismic Group Recorders (SGRs) that were widely used in the controlled-source community. The SGRs were donated to Stanford by AMOCO, reconditioned for crustal studies, and maintained by the USGS with support from PASSCAL. Newer-generation TEXANs were developed by Refraction Technologies, Incorporated (REF TEK), UTEP, the University of Texas at Dallas (UTD), and Rice using funds available through the state of Texas. Initial instrument procurement began in 1999 and the aging SGRs were gradually decommissioned over a period of three years. In 1998, the instrument centers merged and moved to the current PASSCAL Instrument Center (PIC) at the New Mexico Institute of Mining and Technology in Socorro, NM (Figure 18). The consolidation and move were motivated by a number of considerations, principally: (1) the desire for greater technological synergy and coordination within the facility, (2) the cost savings of operating a single instrument center, and (3) the need for greater operational space. New Mexico Tech facilitated construction of a new, custom-

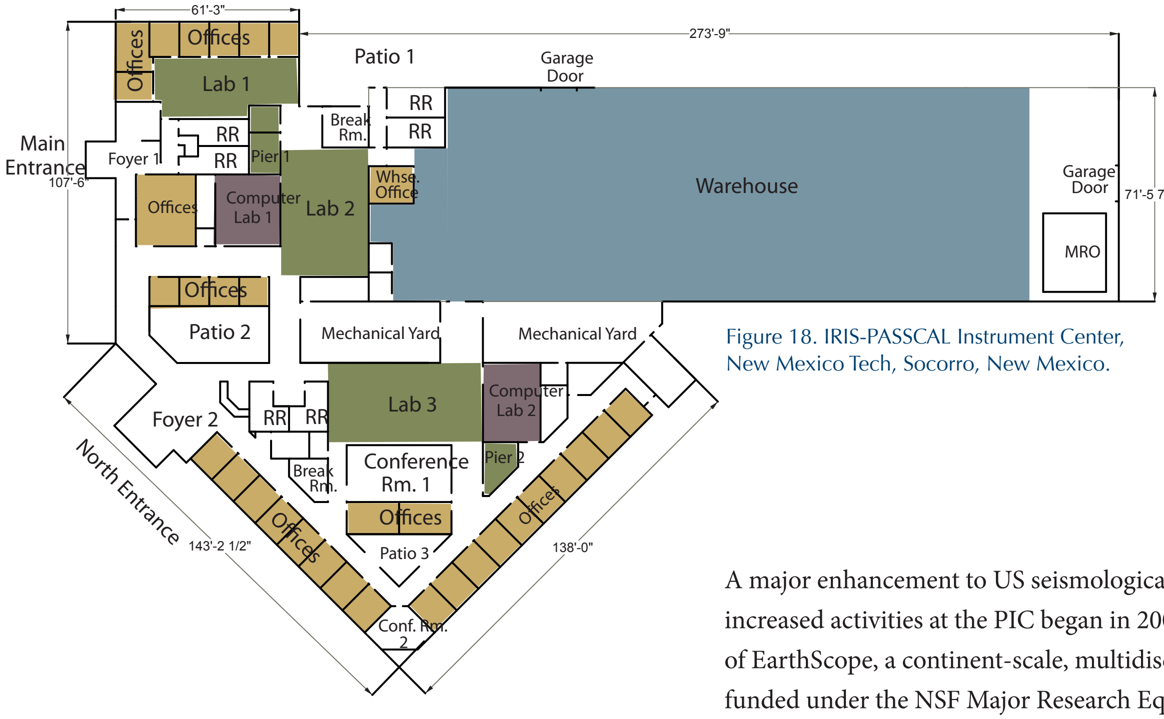


Figure 18. IRIS-PASSCAL Instrument Center, New Mexico Tech, Socorro, New Mexico.

designed facility, with 7500 sq. ft. of office and lab space and 20,000 sq. ft. of warehouse space. This complex was later expanded to accommodate USArray operations, adding an additional 11,000 sq. ft. of office and lab space. The building was designed by the PASSCAL technical staff and NMT to optimize PIC operations. Land and construction funds to build the original facility building and USArray addition were entirely provided by the state of New Mexico through the university.

Starting in 2002, the Department of Energy (DOE) provided funds to replace the original six-channel and three-channel data acquisition systems (DASs), which were becoming aged and failure prone, with modern systems. The new DASs, produced by REF TEK and Kinemetrics/Quanterra, incorporate the latest technologies from the computer industry, and as a consequence, require much less power, have higher recording capacity than the first-generation instruments, use modern memory components, and are configured to operate with a number of communication systems as either serial devices or TCPIP nodes. The preceding REF TEK 72a series recorders have been officially retired from use. However, IRIS and REF TEK are presently making these retired instruments available to international partner institutions seeking to establish or upgrade their permanent networks.

A major enhancement to US seismological resources and increased activities at the PIC began in 2003 with the start of EarthScope, a continent-scale, multidisciplinary project funded under the NSF Major Research Equipment and Facility Construction account. IRIS is responsible for the operation of USArray, the seismological component of EarthScope. With separate funding through EarthScope, a Flexible Array, providing both broadband and high-frequency instruments for individual PI experiments, operates out of the PASSCAL instrument Center. Most Flexible Array operational needs and procedures closely parallel those of the core PASSCAL program. The largest part of USArray, the 400-element Transportable Array that will gradually cross the conterminous United States and Alaska continent over a 15-year period, is based on many of the technologies and operational procedures developed by PASSCAL. A USArray Array Operations Facility (AOF) at the PIC (funded through a separate subaward to New Mexico Tech) supports the operation of both the Flexible Array and the Transportable Array. The AOF shares personnel and logistic support with the core PASSCAL program, leading to significant leverage and efficiencies for both programs. The AOF also acquires, tests, and assembles primary field Transportable Array components. A Transportable Array Coordinating Office (TACO), located at the PASSCAL Instrument Center, but staffed and operated as an independent USArray unit, is responsible for many of the specialized logistic and siting activities required in the operation of the Transportable Array. With EarthScope support, a remote backup for the IRIS DMC archive has been established at the PIC; office space is provided for a USArray data analyst and two UNAVCO employees who provide quality control for EarthScope PBO strain data.

TIMELINE

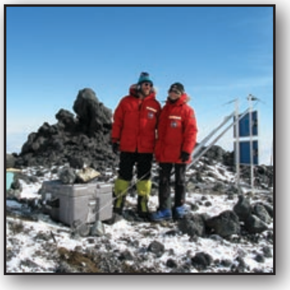
1984	IRIS incorporated
1985	Start instrument development
1986	Ouachita Experiment (1st IRIS sponsored experiment)
1986	Basin & Range Active Experiment
1986	Issue RFP for new instrument
1987	Issue contract to develop a new instrument
1988	REF TEK delivers first 10 prototype instruments
1988	Basin & Range Passive Experiment (1st experiment with prototype instruments)
1989	Delivery of first 35 production instruments
1989	Open first instrument center at Lamont
1989	Greenland Experiment (1st experiment with production instruments, 1st onshore/offshore experiment)
1989	Loma Prieta (1st aftershock experiment)
1990	Brooks Range (1st large active source experiment).
1990	Receive first broadband sensors
1990	SAMSON (1st experiment with broadband sensors)
1990	Development of three-channel instrument
1990	SERIS (1st deployment to Antarctica)
1991	Received first three-channel instruments
1991	Instrument center at Stanford established
1991	Tibet (1st large broadband experiment to produce SEED data)
1993	Cascadia (1st broadband experiment with high station density)
1993	DOE funds Geometrics instruments for high-resolution imaging
1993	REF TEKs upgraded with 24-bit digitizers
1995	Acquisition of first GPS clocks for REF TEKs
1997	Issued community-wide RFP for instrument center
1998	Test of broadband array in Colorado
1998	Established PASSCAL Instrument Center at New Mexico Tech, closed LDEO and Stanford instrument centers
1998	Issued RFP for new type of data acquisition system
1999	First TEXAN instruments delivered to UTEP, funded by State of Texas
1999	CDROM refraction: First large experiment to use TEXANs
1999	Kaapvaal experiment: First experiment with over 50 broadband stations
1999	Broadband array deployed to Kaapvaal
1999	LARSE II first deployment of > 1000 instruments in metropolitan area
2000	First TEXAN instruments delivered to PASSCAL
2000	TAMSEIS (1st large broadband experiment in Antarctica)
2002	First DOE money received to purchase new data acquisition system
2002	Hi Climb (1st experiment with 75 broadband stations)
2003	USArray starts, construction of additional space at NMT
2005	Phase out of old data acquisitions system begins
2007	High Lava Plains Experiment fields first 100-instrument broadband experiment


Tibet. Transporting equipment in the field.


Alaska. STEEP experiment.


Venezuela. Transporting gear.


Utah, Hill AFB. High resolution imaging using TEXANs.


Mt. Erebus, Antarctica.

INSTRUMENTATION

The 1984 IRIS proposal to NSF (the “Rainbow Proposal”) estimated that about 1000 instruments with 6000 recording channels would be needed to support modern field programs in seismology. The size and composition of the PASSCAL inventory has evolved through a continuing reassessment of the balance between technical and scientific pressures. A current instrument inventory is provided in Table 1.

Although standardization of equipment, data formats, and operational procedures is an essential ingredient in the success of all IRIS programs, PASSCAL has had to handle special challenges and trade-offs as experiment designs have evolved as a result of changing scientific interests. The wide variety of experimental configurations supported by PASSCAL, and the need for performance optimization under extreme field conditions, have led PASSCAL to develop a number of “standardized” field systems (Figure 19). For recording earthquakes, PASSCAL offers self-contained, short-period and broadband instruments, and telemetered broadband arrays. For active-source seismology, PASSCAL offers single-channel TEXAN reflection/refraction instruments, three-component short-period instruments, and multichannel cabled instruments for high-resolution, usually shallow, seismology.

REF TEK developed the first PASSCAL data acquisition system under contract to IRIS. This RFP approach to development allowed IRIS to purchase equipment built to specifications that was optimized for PASSCAL use. After initial instrument development, PASSCAL continues to work with the manufacturers to improve the equipment and add capabilities that are driven by community needs. A close working relationship with manufacturers entails collaborative testing of prototypes and sometimes paying for delivery of prototype instruments. This collaboration with manufacturers results in equipment that is nearer to our desired specifications and is cheaper to develop for PASSCAL because the manufacturer underwrites part of the development with an eye to the broader market. Almost all of the second-generation acquisition systems and sensors in use today have resulted from this sort collaboration.

LONG-TERM PASSIVE DEPLOYMENTS

Short-Period and Broadband Instruments

Much of PASSCAL’s efforts center around fielding long-term deployments of up to 100 broadband stations for recording teleseismic, regional, and local earthquakes. These experiments are designed by individuals or small groups of investigators, usually funded by NSF or DOE, who target Earth structures from the crust to the inner core (see Box 1). Frequent motivations include structural seismology investigations and study of earthquake aftershocks, fault-zone-properties, and active volcanoes.

PASSCAL instruments now used for passive experiments are either three-channel REF TEK RT130s or Quanterra Q330s, typically coupled with broadband or intermediate-period sensors with long-period response extending to 120 or 30 s, respectively. Most stations are installed in a stand-alone mode away from commercial power or communications, and rely on solar power systems and local disks to record data.

Although each portable PASSCAL network deployment is motivated by a specific research experiment, the combined effect of multiple experiments around the world is to effectively provide temporary, high-spatial-density augmentation

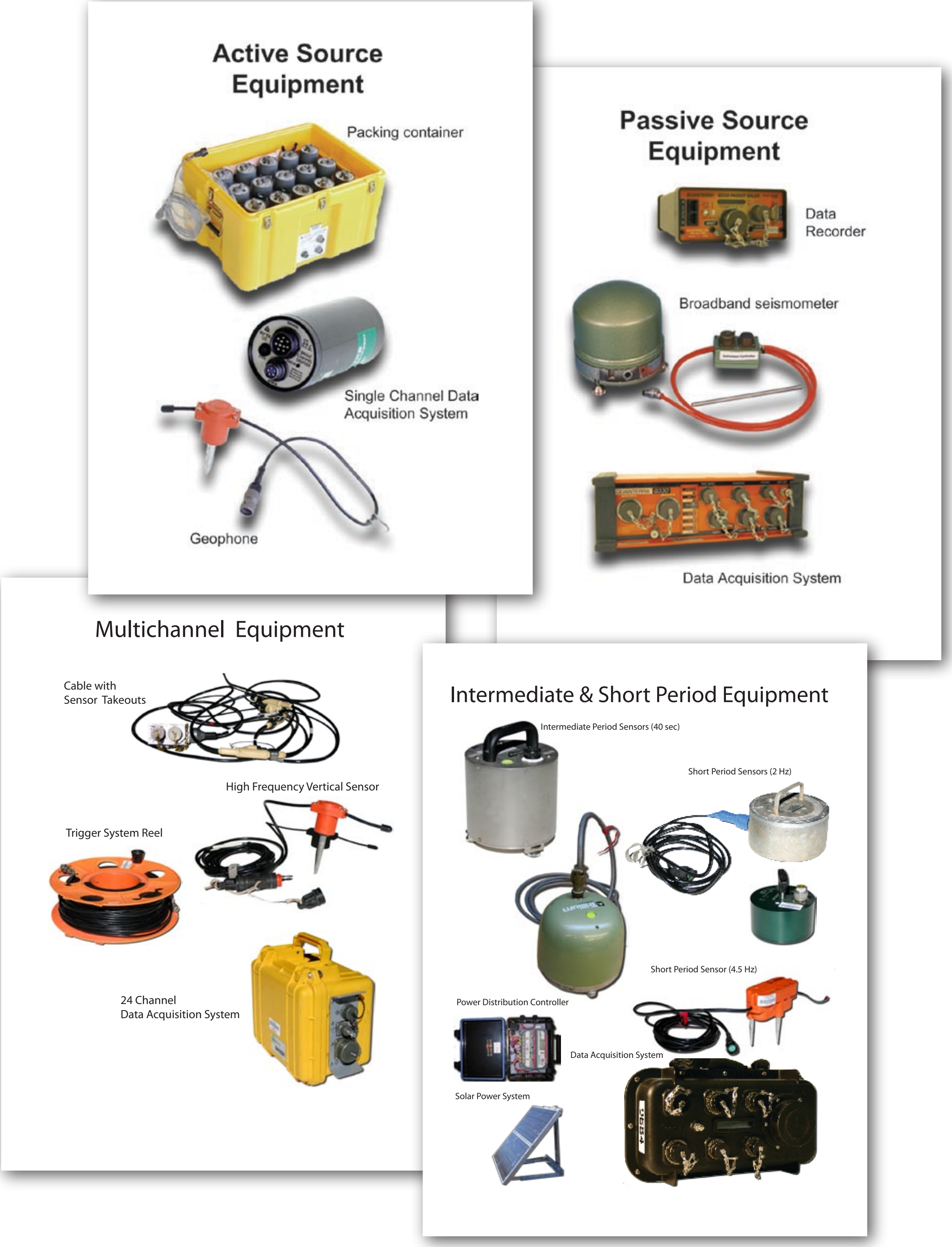


Figure 19. PASSCAL major equipment. Instrumentation provided and supported by the PASSCAL facility can be divided into four categories: active source, passive source broadband, intermediate and short period, and multichannel.

Table 1: PASSCAL Instrument Inventory (2/20/2007)

DATA ACQUISITION SYSTEMS

HIGH RESOLUTION	
PASSCAL	
Quanterra Q330, 3 Channel	381
REF TEK RT130, 3 Channel	445
REF TEK RT130, 6 Channel (RAMP)	10
USArray Flexible Array	
REF TEK RT130, 3 Channel	407
Quanterra Q330, 3 Channel	39
USArray Transportable Array	
Quanterra Q330, 3 Channel	450
Polar	
Quanterra Q330, 3 Channel	24
TOTAL HIGH RESOLUTION	1756

TEXANS	
PASSCAL	
REF TEK RT125, 32 MB	89
REF TEK RT125, 64 MB	204
REF TEK RT125A, 256 MB	249
USArray Flexible Array	
REF TEK RT125A, 256 MB	1700
UTEP	
REF TEK RT125A, 256 MB	440
TOTAL TEXANS	2682

CABLE RECORDING CHANNELS	
Geometrics Multichannel, 60 Channel	4 x 60 = 240
Geometrics Geode, 24 Channel	8 x 24 = 192
Polar	
Ice Streamer, 60 Channel	1 x 60 = 60
TOTAL CABLE RECORDING CHANNELS	492

SENSORS

BROADBAND	
PASSCAL	
Streckheisen STS2 (120 sec)	219
Guralp CMG 3T (120 sec)	216
Trillium 240 (240 sec)	3
USArray Flexible Array	
Guralp CMG 3T (120 sec)	326
USArray Transportable Array	
Streckheisen ST2 (120 sec)	251
Guralp CMG 3T (120 sec)	170
Trillium 240 (240 sec)	50
Polar	
Trillium 240 (240 sec)	20
Guralp CMG3T (120 sec)	17
TOTAL BROADBAND	1272

INTERMEDIATE TO SHORT PERIOD	
PASSCAL	
Guralp CMG3 ESP (30 sec)	56
Guralp CMG 40T (40 sec)	92
Trillium 40 (40 sec)	6
Trillium 40 (40 sec) RAMP	10
USArray Flexible Array	
Guralp CMG 40T (1 sec)	100
TOTAL INTERMEDIATE TO SHORT PERIOD	264

HIGH FREQUENCY	
Mark Products L22 (2 Hz), 3 comp	168
Mark Products L28 (4.5 Hz), 3 comp	406
Geospace HS1 (2 Hz), 3 comp	21
Teledyne S13, 1 comp	35
TOTAL HIGH FREQUENCY	630

STRONG MOTION	
Kinemetrics Episensor Accelerometer, 3 comp	10
Terra Tech Accelerometer, 3 comp	11
TOTAL STRONG MOTION	21

BOX 1. ANATOMY OF A PASSCAL EXPERIMENT

Typical interactions between most PIs and the PASSCAL facility during experiment planning and implementation involve 10 key steps.

Step 1: Planning

Individually or collaboratively, PIs motivated by a scientific question plan an experiment requiring instruments provided by the PASSCAL facility. At this stage, the facility often provides a deployment strategy that will be part of the proposal to a funding agency. It also supplies information for budgets (e.g., shipping costs). An estimate of the equipment schedule can also be provided at this time.

Step 2: Requesting Instruments

The PI places a request for the instruments through the online request form (http://www.passcal.nmt.edu/forms/request.html). Typically, instruments are requested as the proposals are submitted to the funding agency. This step ensures an early spot in the queue once the project is funded.

Step 3: Funding Notification

When the PIs learn that their project will be supported, PASSCAL is notified and the experiment is officially scheduled. In case of schedule conflicts, a priority system exists where NSF and DOE projects share the same high-priority level. Most active-source experiments can be scheduled within a year of funding, whereas broadband deployments have a waiting period of up to 2.5 years.

Step 4: Training and Logistics Meeting at the Facility

Users are required to visit the PASSCAL facility for a briefing on logistics, and training on equipment use. A complete list of all needed equipment and a shipping plan are generated.

Step 5: Shipment Preparation

Equipment IDs are scanned, the equipment packed into rugged cases and, for larger experiments, placed on pallets. The facility helps the PI to generate shipping documents and arrange for shipment. In the case of international experiments, assistance in providing the needed contacts and letters for customs is provided to the investigator.

Step 6: In-Field Training and Huddle Testing

On site, PASSCAL provides additional instrument training for experiment participants. PASSCAL personnel perform a function test "huddle" and attempt to repair any equipment that was damaged during transport.

Step 7: Assisting with Deployment

For active-source experiments, PASSCAL engineers stay with the equipment for the duration of the experiment. They are responsible for all instrument programming and data offloading, with substantial help from experiment participants. For broadband and short-period type experiments, PASSCAL support usually is limited to the huddle test, initial station deployment, and perhaps the first data service run. The goal is to have equipment in good working order and to have fully trained investigators operating the equipment.

Step 8: Service and Maintenance

A typical service cycle for broadband and short-period stations is an interval of about three months. While in the field, if any equipment fails or needs repair, the PASSCAL facility works with the experimenter to supply replacement parts or to perform the repairs as soon as possible.

Step 9: Data-Processing Support

Although it is the PI's responsibility to process the raw data into SEED format, PASSCAL offers extensive support. First, PASSCAL personnel train PIs on the use of programs used for data-quality support and data reduction. Data processed by the PIs are sent to the PASSCAL facility first for verification, are reviewed for completeness of waveforms and metadata, and are forwarded to the DMC for archiving.

Step 10: End of the Experiment

Coordination with PASSCAL at the end of an experiment is essential for a smooth transition to the next experiment. Final shipping documents are generated and PASSCAL personnel track the incoming equipment. Once the equipment is received from the field, it is scanned back into the inventory and routine testing and maintenance is conducted. PASSCAL personnel dedicated to data processing work with the experimenters to ensure that the final data are processed and archived. Any outstanding problems with the data are resolved at the PIC before being archived at the DMC.

Figure 20. Installation of a broadband sensor vault in southeastern Tibet with local assistance.

to the permanent coverage provided by the GSN and other networks. Many global tomographers make increasing and extensive use of data from past PASSCAL deployments to enhance their data sets. At the request of this community, one station in each PASSCAL and EarthScope Flexible Array experiment is now designated as "open" with the typical two-year data embargo waived.

Maintaining and operating the broadband instrument pool consumes a significant portion of PASSCAL efforts. The broadband sensors were not designed for portable operations in the manner in which they are now employed; they are sensitive to shock and vibration during shipping. When being deployed in the field, care must be taken to ensure that the vaults do not flood or retain moisture.

A large fraction of broadband experiments is conducted overseas in cooperation with foreign institutions. Foreign operations usually require significant effort in making arrangements for customs and shipping. While the PI is responsible for the costs associated with getting the instruments to the field, they usually rely on experienced PIC personnel to make these arrangements.

Over PASSCAL's lifetime, the average number of stations per deployment has steadily increased and is now 30, with many experiments exceeding 50, and several using more than 75. One ongoing NSF Continental Dynamics program experiment is fielding ~100 stations, 75 of which are from PASSCAL and 25 are university-owned.

Telemetered Arrays

Using the same data-acquisition systems and sensors as in stand-alone deployments, telemetered arrays can be supported using specialized communications, software, and computing equipment. In addition to on-site recording to disk, data are telemetered to a central site and merged in real time (the on-site disks provide a backup for telemetry outages). The broadband telemetered array was developed in the early 1990s in collaboration with the University of California, San Diego, under the IRIS Joint Seismic Program (JSP) for deployment in the former Soviet Union for nuclear test-ban verification calibration tests. When the JSP program was completed, the equipment and expertise necessary to operate the array were transferred to PASSCAL. The original PASSCAL broadband array consisted of 32 broadband sensors and digitizers that telemetered the data via spread-spectrum radios to a concentrator site located up to 80 km away. This array was used for a number of experiments in locations as diverse as the South African craton, and the Wyoming province in the western United States. PASSCAL currently is supporting a 22-station telemetered array in southern Alaska. Telemetry expertise and new technologies developed and implemented in EarthScope are being incorporated into these systems.

Figure 21. Radio telemetered broadband station on the Olympic Peninsula, above the Cascadia subduction zone.

CONTROLLED-SOURCE INSTRUMENTS

Figure 22. Single-channel TEXANs deployed in a dense array at Hill Air Force Base to image a toxic waste site.

TEXANs

Controlled-source experiments are designed to observe signals from man-made energy sources, such as explosions, airguns, and Vibroseis™ vibrators. The primary data requirements are for high-frequency recording (up to 500 Hz) at high sample rates (100–1000 Hz) with precise timing. The REF TEK 125 "TEXAN," designed and developed by a consortium of Texas universities and REF TEK, comprises the largest number of PASSCAL seismic channels used for controlled-source instruments. The single-channel TEXAN is small, lightweight (1 kg), runs on D-cell batteries, and especially easy to use. The typical experimental mode is to record specific timed segments, synchronized with the timing of artificial sources, although these instruments are also capable of recording for several days continuously. The instruments are often moved to occupy many sites—ease of deployment and recovery are principal design features.

PASSCAL currently maintains ~ 550 TEXAN instruments and supports another ~ 440 through a cooperative agreement with the University of Texas, El Paso (UTEP). The UTEP-owned systems are routinely used for PASSCAL experiments, effectively creating a combined pool for the user community. To maintain access to the UTEP instruments, PASSCAL provides support to UTEP at the level of approximately one FTE. EarthScope's Flexible Array will also have 1700 TEXAN instruments upon completion of purchases.

Active-source instruments can acquire large amounts of data in a short time period. To easily handle the data and make them easier to archive, PASSCAL is collaborating with the DMC to develop a new paradigm for archiving active-source data, based on the data format HDF-5. This new approach decouples the metadata (geographic and instrument data) from the seismic waveforms (similar to SEED), permitting more efficient archiving for PIs and PASSCAL.

Multichannel Instruments

PASSCAL maintains ten multichannel recording systems. These systems are commercial products developed for high-resolution seismic reflection and refraction experiments, including geotechnical applications and shallow petroleum exploration. The PASSCAL equipment consists of four Geometrics Stratavisor instruments that each record 60 channels, and six Geometrics Geodes each of which record 24 channels.

Figure 23. Multichannel system recording mining blasts at the Tyrone Mine, New Mexico.

PASSCAL owns two sets of cables for this system: one set is used for high-resolution shallow studies, and the second set, with longer stations spacing and lower-frequency geophones, is used in basin and crustal studies. PASSCAL also has Galperin mounts for high-resolution, three-component data acquisition.

The multichannel equipment has been used very effectively for crustal imaging and a number of shallow studies of fault zones, aquifers, and hazardous waste sites, as well as extensively for training and education in undergraduate classrooms and field labs. One of the major uses for the multichannel equipment is in introductory geophysics courses such as the SAGE program (see http://www.sage.lanl.gov). The recorders along with associated processing software provide these courses with the ability to acquire, edit, and process reflection and refraction profiles.

The number of experiments supported by this pool of instruments is now ~ 20 per year, with many experiments using multiple systems.

RAMP: RAPID ARRAY MOBILIZATION PROGRAM

PASSCAL reserves ten instruments for the RAMP instrument pool to enable very rapid response for aftershock recording following significant earthquakes. PASSCAL instruments were first used in an aftershock study at Loma Prieta, less than one month after the first instruments were delivered in 1989. The pool continues to be used both for aftershock studies and for special short-term projects that otherwise might not fit into the schedule. In the event of a significant earthquake requiring an aftershock response, RAMP instruments are available for shipping within 24 hours.

The current RAMP pool now consists of 10 REF TEK RT130 six-channel acquisition systems with 10 Trillium 40 (intermediate-period) sensors and 10 Kinematics ES-1 accelerometers. See Appendix G for RAMP deployment policy.

Figure 24. Aftershock deployment after Landers earthquake in Southern California.

SUPPORT

The number of instruments available for use in experiments is frequently used to measure PASSCAL's progress. However, the scope of the facility extends well beyond the hardware resource alone. The support the PIC provides to users is also essential to the overall success of a given experiment. PASSCAL support has evolved through time in response to experiment methodologies and technological advances, with a continuing emphasis on improving data return and finding more efficient methods of operation. Generally, the support provided can be divided into three categories (Figure 25): (1) pre-experiment, (2) experiment, and (3) post-experiment. Within these three categories efforts can be further usefully grouped into equipment support, shipping support, user training, experiment support, software support, and data processing support.

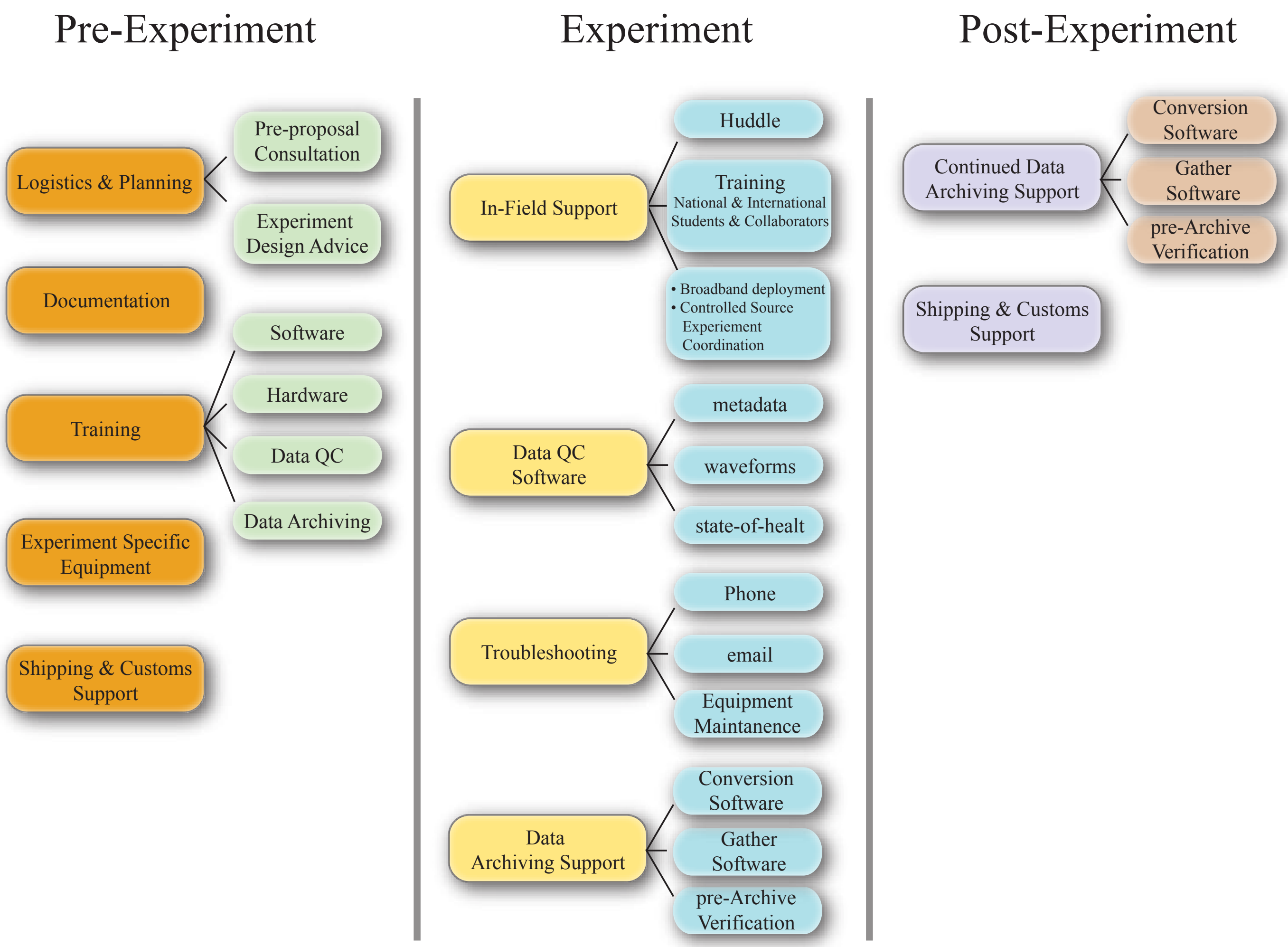


Figure 25. PASSCAL Instrument Center Support Functions. There are three main phases of support from the PIC to the typical experiment: before, during and after the field deployment.

EQUIPMENT SUPPORT

With the exception of communications equipment, PASSCAL has traditionally developed instrument packages that use commercially supplied components from a variety of relatively small vendors. To maintain this fleet of highly specialized equipment, the PIC operates an extensive suite of instrument testing and repair procedures, particularly for the RT125s (TEXANs), RT130s, and Q330s, and broadband sensors and has developed an in-house inventory system that facilitates shipping and receiving equipment from the field, as well as tracks maintenance records (Figures 26 and 27).

The PIC accepts instrument delivery from the manufacturer, performs acceptance tests, and maintains the equipment after receipt. In addition to initial equipment testing, the PIC provides general maintenance on all equipment. Personnel are trained to make board-level repairs as well as those that are identified by experience as “frequent.” Most major repairs are done by the manufacturers. In addition to repairing hardware, the PIC works with manufacturers to debug and test firmware bugs that are detected in the lab or field.

The PIC coordinates shipping of instruments to and from locations all over the world in collaboration with the user community. Equipment is packed and shipped in special reusable shipping cases that are customized for various instrumentation components. All major items have barcode identification that is indexed to the inventory system and shipping records.

Maintenance and Service

Equipment supplied by PASSCAL commonly deployed under harsh field environments for periods sometimes exceeding two years. The PIC comprehensively tests and maintains instruments returned from the field to prepare them for further deployments. For a broadband station returning from the field, sensors are cleaned, function tested, then tested on a pier for several days. PASSCAL staff are responsible for reviewing and archiving sensor performance to ensure that they meet specifications. Generally, about 15% of sensors

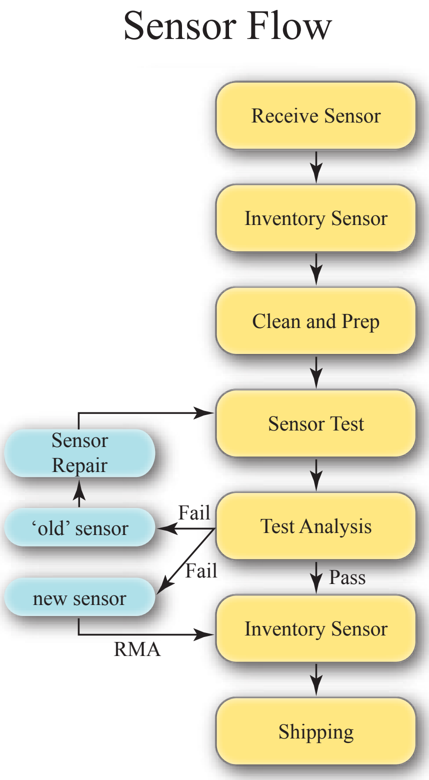


Figure 26.

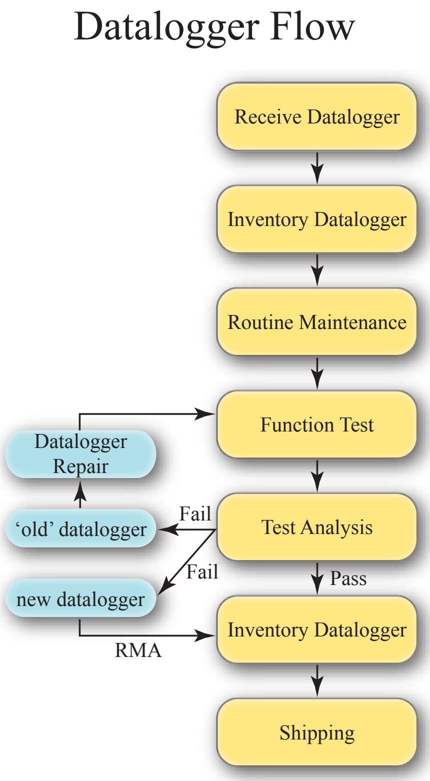


Figure 27.

need additional attention during this turn-around evaluation. Sensors encountering problems are usually repaired in house by factory-trained staff (Figure 26 and 27).

Three- or six-channel data acquisition systems, along with power systems and associated cables, are rigorously tested using routine procedures developed over the years. Specialized lab equipment and control software have been developed in house to streamline this testing process.

Active-source and multichannel systems receive similar check-in and maintenance procedures after each use. The TEXAN active-source recorders additionally require routine adjustment of internal oscillators along with replacement and updates of batteries and firmware.

All major repairs, testing, and maintenance procedures are logged into the equipment inventory database. Repair and other histories are readily accessible through this system, indexed by serial number.

SHIPPING SUPPORT

PASSCAL experiments are currently roughly split between domestic and international experiments. The PIC has two staff devoted to providing users with shipping support. These staff establish communications with carriers and provides users with quotes for various shipping options. They they typically arrange all carriers and provide shipping documentation necessary for both domestic and international shipments. Once equipment leaves the PIC, PASSCAL tracks a shipments progress through customs clearance (in international cases) to delivery. At the end of an experiment PASSCAL provides assistance to PIs in arranging equipment return.

USER TRAINING

Instrument training for PIs, their students, postdocs, and staff is an essential component of PIC service. All PIs are required to visit the PIC for experiment-planning sessions and instrument training, as software and hardware upgrades often change best field practices for any particular instrument configuration.

To reduce damage while the seismic equipment is deployed, PASSCAL personnel train users on instrument best use and care in the field. Training sessions include experiment planning meetings to ensure that the PASSCAL personnel understand experiment goals and can optimize how the equipment will be used during the experiment to meet these goals. Training materials, and hardware and software documentation, are provided during these sessions.

PASSCAL also provides some liaison activities with international partners for joint experiments that use PASSCAL and other portable seismic instruments.

Figure 28. The suite of PASSCAL one-pager documents used for general outreach.

EXPERIMENT SUPPORT

For any type of experiment, PASSCAL personnel assist PIs throughout the project to solve technical problems, including repairing instruments on site, troubleshooting problems remotely via telephone, and arranging shipments of replacement equipment (see Appendix F).

In passive-source experiments, PASSCAL personnel arrive shortly after the equipment arrives in the field. They are responsible for testing and repairing any equipment that may have been damaged during shipping, and providing in situ training for field personnel. PASSCAL staff usually participate in some initial station deployments to provide additional PI training. Once this initial support is finished, the PIC will continue to support the PI during the experiment, either on site or remotely, as necessary.

PASSCAL staff normally accompany active-source groups for their entire duration to ensure time-critical instrument deployments, to make repairs on instruments in the field, and to assist in the download of data and organization of metadata.

SOFTWARE SUPPORT

The PASSCAL software suite comprises programs written over the last two decades by PASSCAL staff and the wider community. The primary function of PASSCAL software is to assist with collecting, performing quality control, and transforming data into optimal formats for analysis and archiving with the IRIS DMC. The software is primarily designed to support dataloggers provided by the PIC but has been used by many international institutions not associated with IRIS or PASSCAL. There are over 150 fully open-source programs ranging from simple command line programs, to graphical user interface scripts, to fully graphical data viewing programs. The suite also contains many user-contributed programs for performing tasks such as reading and writing miniSEED files and converting raw data to SEGY format.

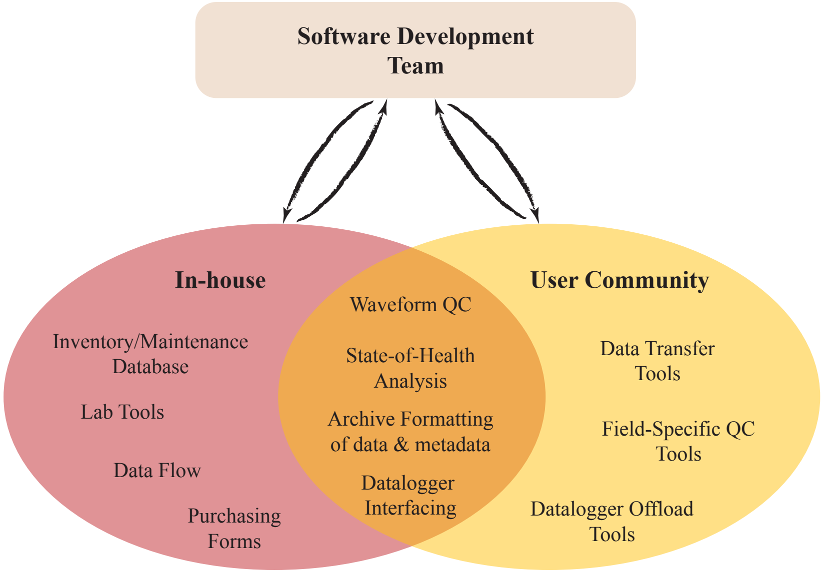


Figure 29: PASSCAL software development serves both PASSCAL staff and the user community. Development both in-house and user-community software is a dynamic process reliant on user feedback.

Functionality of the PASSCAL software suite can be roughly broken into two partially overlapping categories (Figure 29): in-house and user-community software. In-house software includes bench-testing utilities that allow PASSCAL staff to quickly and efficiently test multiple dataloggers and to update associated inventory and maintenance database. User-community software includes quality control code geared toward field and archiving applications. Examples of widely used software with overlapping in-house and user-community uses include waveform viewing tools, state-of-health analysis tools, and format conversion routines. PASSCAL provides pre-configured field computers containing the PASSCAL software suite as well as commercial programs that may be needed for a particular experiment.

DATA PROCESSING SUPPORT

Prior to, during , and following an experiment, PASSCAL personnel work with the PI and staff responsible for archiving the data on the use of essential quality-control and processing tools (Figure 30). During passive experiments, PASSCAL personnel receive and verify preliminary SEED data, working closely with both the PI and DMC personnel to assure data and metadata completeness, accuracy, and quality. Verified SEED data sets from passive experiments are forwarded to the DMC for archiving as soon as possible, usually during the experiment.

Active-source data are normally collated and verified following the experiment. A new archival data format, HDF-5, has recently been adopted so that active-source metadata can be corrected without having to re-archive the whole data set at the DMC. Software for archiving and retrieval is currently being tested. This software will provide the active-source experimentalists with a data-retrieval model similar to that for the passive experimentalists—the DMC acquires the data at an early stage, and maintains the waveform and metadata independently (see Appendix C).

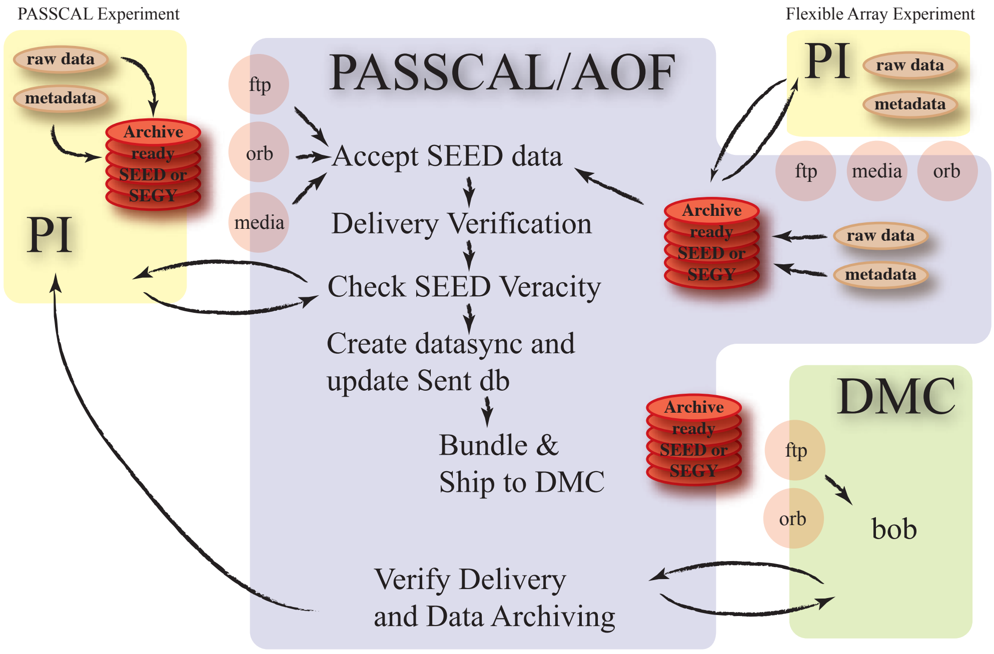


Figure 30. Flow of data from the PI to the IRIS Data Management Center.

Interactions Between the IRIS Data Management System and PASSCAL Programs

Twenty years ago, few people anticipated the present scope of PASSCAL's data-generation capabilities. Instead of being dominated by active-source data sets in SEGY format, the PASSCAL facility has evolved into one largely dominated by broadband data collected during dozens of multiyear experiments led by numerous PIs. Proper archival of data and metadata for the long-term benefit of the community is obligatory for essentially all science-driven uses of PASSCAL instrumentation, and requires substantial interaction between PASSCAL and the IRIS Data Management System.

Data Availability

Permanent archival of broadband data from PASSCAL experiments is now routine and relies heavily upon close coordination between the PIC and the IRIS DMC in Seattle. SEGY data sets from active-source experiments also continue to routinely flow to the DMC (Figure 31). PIC personnel performs all front-line quality control on PASSCAL data and metadata.

At the end of 2007, the IRIS DMC had 2.22 terabytes of assembled PASSCAL data archived and 14.97 terabytes of broadband data available in SEED format.Total PASSCAL DMC holdings are now approximately 25% of the DMS archive—roughly 30% more data than the IRIS GSN archive, and include data from 3,862 PASSCAL stations in its archives.

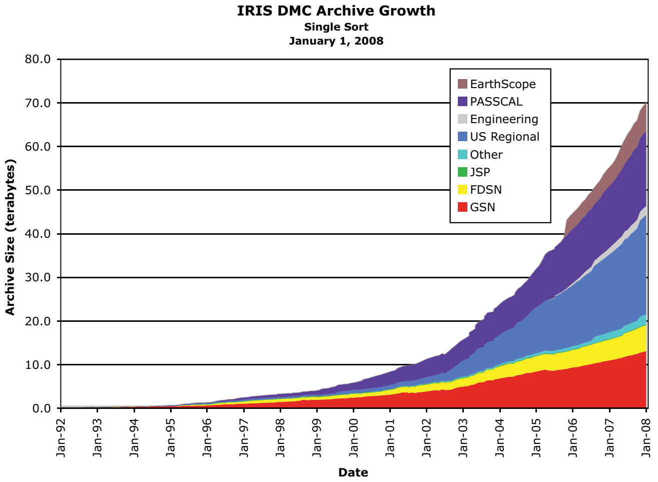


Figure 31. PASSCAL data form one of the largest data volumes at the IRIS DMC, second only to US regional networks.

A key feature at the DMC is that its various request tools can generate requests for SEED-formatted data volumes for users regardless of whether those data were collected by the GSN, FDSN partners, US regional networks, USArray, or PASSCAL. For instance, a simple query procedure using the jWEED program allows a user to draw a region on a world map and request all broadband data collected within that box. This was not originally anticipated as a capability when IRIS was originally formed, but now allows for the seamless use of the worldwide broadband data resource by the broad community.

PASSCAL Data Distribution

GSN data are the most frequently requested single data source at the DMC, but the amount of distributed PASSCAL data is also very large (Figure 32). The annual request rate is also accelerating for both data sets with a doubling time of approximately two years. Data volume requested from PASSCAL sources is currently more than one-half of that requested from GSN sources (e.g., 9.9 terabytes total as compared with 18.4 terabytes for the GSN). Although the Transportable Array is in many respects the most exciting new data source in seismology, total shipments from PASSCAL experiments currently still exceed data shipments for the Transportable Array (9.9 terabytes as compared to 7.4 terabytes) and only last year did more data ship on an annual basis from the Transportable Array than from PASSCAL (3.8 terabytes from the Transportable Array as compared with 3.4 terabytes for PASSCAL).

Support for Assembled Data from Controlled Source Seismic Experiments

The PASSCAL Instrument Center continues to improve support for SEGY format data. Over the past two years, PASSCAL and the DMS have developed a system based

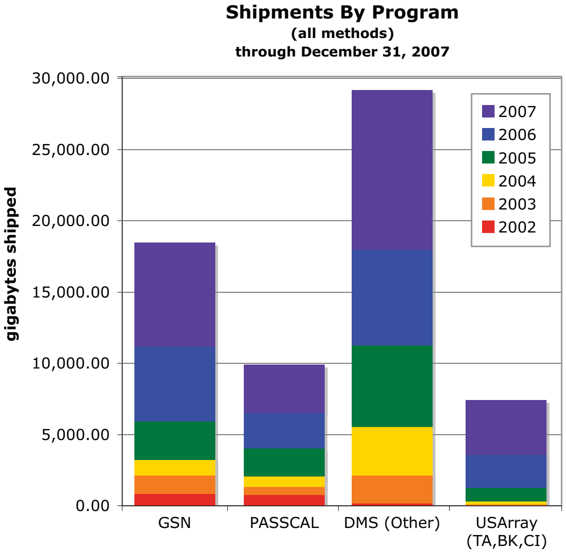


Figure 32. Data volume distributed by the DMC for GSN, PASSCAL, other DMC sources, and for the major components of the EarthScope Transportable Array. These statistics have been compiled since 2002 and are updated monthly by the DMC.

upon the HDF-5 format that allows better management of and access to SEGY data, the standard archive format for controlled-source data. PASSCAL electronically transfers HDF-5 files to a specific directory on a DMC machine. Scripts at the DMC produce Web forms that allow users to view details about shot points and sensor locations from which they can determine what data can be requested.

The motivation to develop this PASSCAL-DMS Web form was to simplify data curation, specifically in the area of separating metadata from waveform data. This structure reduces the data-processing burden on PIs as they uncover errors in the metadata; they no longer have to rewrite an entire data set, but instead simply correct the metadata. This development has also produced a new request tool where the IRIS DMC is better able to service the community's requests for this type of data.

The new system to support SEGY data was developed by PASSCAL staff and allowed DMC staff to focus on the development of the Web components of the system. Although this new system has not yet been officially released, it is well developed and will improve distribution and support for SEGY data sets to the broad community.

Box 2: A Guide to the PASSCAL Instrumentation Center Web Site

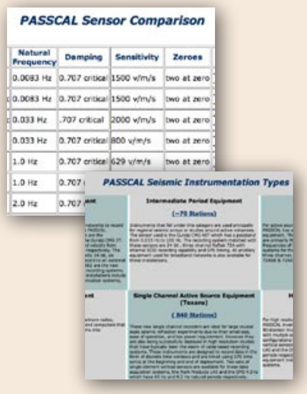
www.passcal.nmt.edu

Information provided on the PASSCAL Web site is targeted at the user community. Although every project has unique features, basic policy and contact information needed by the user community to initiate support is present there. PIs can use the Web site to interact with PIC staff for instrument and scheduling requests, and during experiment and logistics planning, training, data collection, and data archival. During proposal writing or experiment planning, the PIC Web site provides general technical information about supported instrumentation and online access to PASSCAL support schedules, which can be especially important when contemplating large, broadband experiments. While an experiment is active, users frequently access the Web site for detailed procedures or technical specifications, to access PASSCAL software, and for data archiving information. The Web site also services requests for software or instrumentation specifications for researchers or students using archived data from the IRIS DMC. The PIC Web site was designed and developed prior to the advent of content management systems (CMS), which are now standard for maintaining and creating large Web sites. Thus, PASSCAL initiated a site redesign in January 2008 with professional consultation. This redesign will implement CMS and organize the site based on common-use profiles. The new site is scheduled to be operational in late 2008. The current structure and content of the Web site is outlined below.

SUPPORT
- Equipment
    - Available Equipment (http://www.passcal.nmt.edu/user_support/equipment_inventory.html)
    - Inventory (http://www.passcal.nmt.edu/user_support/inventory_chart.html)
- Software (http://www.passcal.nmt.edu/software/software.html)
- Shipping
    - Estimate shipping (http://www.passcal.nmt.edu/user_support/shipping.html)
    - List of shippers (http://www.passcal.nmt.edu/user_support/shippers.html)
- Training
    - Scheduling and planning (http://www.passcal.nmt.edu/user_support/Training/preparing.html)
    - Agenda (http://www.passcal.nmt.edu/user_support/Training/planning.html)
    - Feedback form (http://www.passcal.nmt.edu/user_support/Training/feedback.html)

- Visiting PASSCAL
    - Directions and maps (http://www.passcal.nmt.edu/user_support/map2PASSCAL.html)
    - Lodging (http://www.passcal.nmt.edu/user_support/lodging.html)
    - Virtual tour (http://www.passcal.nmt.edu/user_support/tour_1.html)
- Contact Information
    - General contact (http://www.passcal.nmt.edu/user_support/contact.html)
    - Staff directory (http://www.passcal.nmt.edu/user_support/staff.html)
- How Tos
    - RACS (Redundant Array Copy System) (http://www.passcal.nmt.edu/user_support/Training/racs.html)
    - REF TEK timing correction file (http://www.passcal.nmt.edu/user_support/Training/PCF_tutorial.doc.pdf)
    - Calibrating and Autosensorting (http://www.passcal.nmt.edu/user_support/Training/Calibration.html)
    - Emergency laptop install of RH 7.0 (http://www.passcal.nmt.edu/user_support/Training/RHInstall.html)
- FAQs (http://www.passcal.nmt.edu/user_support/faqs.html)

SCHEDULES
- Broadband
    - 2007–2008 (http://www.passcal.nmt.edu/schedules/BB07-08.html)
    - 2008–2009 (http://www.passcal.nmt.edu/schedules/BB08-09.html)
    - 2009–2010 (http://www.passcal.nmt.edu/schedules/BB09-10.html)
- Intermediate period 2007–2008 (http://www.passcal.nmt.edu/schedules/IP07-08.html)
- Short period 2007–2008 (http://www.passcal.nmt.edu/schedules/SP07-08.html)
- TEXAN 2007–2008 (http://www.passcal.nmt.edu/schedules/TXN07-08.html)



PASSCAL Sensor Comparison

Natural Frequency	Damping	Sensitivity	Zeroes
0.0083 Hz	0.707 critical	1500 v/m/s	two at zero
0.0083 Hz	0.707 critical	1500 v/m/s	two at zero
0.033 Hz	.707 critical	2000 v/m/s	two at zero
0.033 Hz	0.707 critical	800 v/m/s	two at zero
1.0 Hz	0.707 critical	629 v/m/s	two at zero
1.0 Hz	0.707		
2.0 Hz	0.707		

PASSCAL Seismic Instrumentation Types

Intermediate Period Equipment

(~75 Stations)

Single Channel Active Source Equipment (Texans)

(840 Stations)

FORMS

- Instrument request forms PASSCAL and USArray (http://www.passcal.nmt.edu/forms/request.html)
- PASSCAL rebill (http://www.passcal.nmt.edu/forms/PASSCAL_Rebill_Form.html)
- Request FDSN network code (http://www.iris.edu/scripts/getcode.html)
- Mobilization form (http://www.iris.edu/stations/mob.htm)
- Demobilization form (http://www.iris.edu/stations/demob.htm)
- Evaluation forms (http://www.passcal.nmt.edu/forms/EvalForms.html)

INSTRUMENTATION

- Sensors
  - Comparison chart (http://www.passcal.nmt.edu/instrumentation/Sensor/sensor_comp_chart.html)
  - Specification sheets (http://www.passcal.nmt.edu/instrumentation/Sensor/sensor_info.html)
- Data Acquisition Systems
  - Geode (http://www.geometrics.com/seismographs/Geode/geode.html)
  - Geometrics RX60 (http://www.geometrics.com/nxdesc.html)
  - Quanterra Q330 (http://www.q330.com/)
  - REF TEK R125 (http://www.reftek.com/products/125-01.html)
  - REF TEK RT130 (http://www.reftek.com/products/130-01.html)

IRIS PASSCAL Polar Support

IRIS PASSCAL Pola
Support

INFORMATION AND POLICY

- Instrument use policy (http://www.passcal.nmt.edu/information/Policies/InstUse_Policy.htm)
- Instrument use agreement (http://www.passcal.nmt.edu/information/Policies/InstUse_Agreement.htm)
- Field staffing policy (http://www.passcal.nmt.edu/information/Policies/PASSCAL_Field_Policy.htm)
- Data delivery policy (http://www.passcal.nmt.edu/information/Policies/data.delivery.html)
- RAMP policy (http://www.passcal.nmt.edu/information/Policies/RAMP_policy.html)
- Standing committee (http://www.iris.washington.edu/about/committees.htm#passcal)
- Instrumentation report (http://www.passcal.nmt.edu/information/inst_rpt_2001.html)

USArray

- Flexible Array information for the PI (http://www.passcal.nmt.edu/information/Flexible_Array.html)
- Instrument request form (http://www.passcal.nmt.edu/forms/requestUS.fillout.html)
- Flexible Array data policy (http://www.passcal.nmt.edu/information/Policies/FA_DataPolicy.html)
- Data archiving responsibilities (http://www.passcal.nmt.edu/information/Policies/FA_archiving.pdf)
- Schedules (http://www.passcal.nmt.edu/schedules_FA/Index.html)
- EarthScope home page (http://www.earthscope.org/)
- EarthScope data management plan (http://www.iris.iris.edu/USArray/files/USDataPlan_FinalV7.pdf)
- USArray design workshop (http://www.passcal.nmt.edu/information/arraydesign.html)

EXPERIMENT PROFILES

- 1986–1995 (http://www.passcal.nmt.edu/schedules/experiment_profiles/exp8695.html)
- 1996–1999 (http://www.passcal.nmt.edu/schedules/experiment_profiles/exp9699.html)
- 2000 (http://www.passcal.nmt.edu/schedules/experiment_profiles/exp2000.html)
- 2001 (http://www.passcal.nmt.edu/schedules/experiment_profiles/exp2001.html)
- 2002 (http://www.passcal.nmt.edu/schedules/experiment_profiles/exp2002.html)
- 2003 (http://www.passcal.nmt.edu/schedules/experiment_profiles/exp2003.html)
- 2004 (http://www.passcal.nmt.edu/schedules/experiment_profiles/exp2004.html)
- 2005 (http://www.passcal.nmt.edu/schedules/experiment_profiles/exp2005.html)
- 2006 (http://www.passcal.nmt.edu/schedules/experiment_profiles/exp2006.html)

POLAR SUPPORT (http://www.passcal.nmt.edu/Polar/index.html)

COOPERATION WITH OTHER FACILITIES AND AGENCIES

NSF funds IRIS to support facilities for a broad range of seismological studies. All IRIS data are openly available to all interested researchers and to the public, and requests for use of PASSCAL instrumentation will be accepted from any qualified research organization. NSF- or DOE-funded projects receive first priority. Other requests are filled based on a priority ranking, as defined in the PASSCAL Instrument Use Policy (Appendix B), and on an as-available basis to other US federal projects and foreign institutions.

UNAVCO

Collaborative efforts with the geodetic consortium, UNAVCO, have been strengthened recently through EarthScope and NSF Office of Polar Programs (OPP) activities. The USArray Array Operations Facility hosts computers used by the GAMIT-based Analysis Center of the EarthScope Plate Boundary Observatory (PBO) in association with PI Mark Murray (NMT). The PIC also hosts a PBO Strainmeter Analysis Center for two full-time UNAVCO staff and provides a server room to accommodate a backup data management facility for PBO.

Figure 33. UNAVCO collaboration.

PASSCAL and GSN collaborations with UNAVCO driven by new opportunities in polar science have fostered successful pursuit of a joint Antarctic facility project under NSF Major Research Instrumentation (MRI) grant for instrument development ("A Power and Communication System for Remote Autonomous GPS"). This effort was first funded in 2006 and has recently resulted in the deployment of second-year field prototypes of geodetic and seismological instrumentation in the deep Antarctic interior for two NSF-funded OPP efforts: POLENET and AGAP. This Antarctic MRI effort is advised by a Polar Networks Science Committee, currently chaired by Terry Wilson (Ohio State University).

NETWORK FOR EARTHQUAKE ENGINEERING SIMULATION (NEES)

NEES is a national earthquake engineering resource funded by the NSF Engineering Directorate that includes geographically distributed, shared-use experimental research equipment sites built and operated to advance research in earthquake engineering. One of the NEES equipment sites with particular relevance to PASSCAL is located at the University of Texas at Austin. This facility is home to three truck-mounted vibrators purchased to study near-surface soil properties and investigate soil-structure interactions. These vibrators also have been used in collaborative geophysical investigations as sources for studies of deep basin structure. Over the last few years, several experiments have been conducted combining the NEES vibrators and sensors from the PASSCAL pool. In these experiments the PIs make the initial arrangements for the experiment while PASSCAL and NEES staff coordinate scheduling and technical arrangements.

Figure 34. NEES vibrator deployed with PASSCAL multichannel systems in Garner Valley, California (Photo c/o Jamie Steidl, UCSB)

OCEAN BOTTOM SEISMOGRAPH INSTRUMENT POOL (OBSIP)

OBSIP is analogous to PASSCAL in that it is a multi-user pool of seismological instruments made available to the research community. In the case of OBSIP, instruments are funded through the NSF Division of Ocean Sciences and are designed to operate autonomously on the ocean floor. Some OBSIP experiments are carried out in remote ocean basins and rely solely on ocean bottom instruments. Experiments involving interactions with PASSCAL, include active-source, onshore-offshore experiments (often coupled with air guns and hydrophone streamers), and long-term deployments for earthquake and structure studies at continental margins and oceanic islands.

Because of complex logistics and the high cost of ship time, the PASSCAL and OBSIP groups work closely together to schedule joint experiments. One of the OBSIP PIs (John Collins) was recently a member of the PASSCAL Standing Committee. Although no longer a voting member, Dr. Collins continues to attend meetings and otherwise advise PASSCAL. The PASSCAL Program Manager is a member of the OBSIP Oversight Committee and regularly communicates with OBSIP operations. The PASSCAL Instrument Request Form flags experiments proposing use of equipment from both the PASSCAL and OBSIP facility. This additional alert ensures that schedulers become aware of the need to coordinate at the earliest opportunity. In addition to interactions with IRIS related to PASSCAL instrumentation, OBSIP facilities also arrange for all OBSIP data to be archived at the IRIS DMC.

UNIVERSITY-NATIONAL OCEANOGRAPHIC LABORATORY SYSTEM (UNOLS)

UNOLS is responsible for coordinating activities of the academic research fleet used in most NSF experiments in ocean sciences. UNOLS also sets schedules for vessels used in marine geophysical studies, including those involving PASSCAL instruments. Staff from OBSIP and PASSCAL staff attend scheduling meetings for the UNOLS ships and work to identify and resolve potential problems associated with coordinating instrument and ship schedules.

US GEOLOGICAL SURVEY

There is close collaboration between IRIS and the USGS throughout all IRIS programs. PASSCAL instruments are used in USGS-sponsored experiments (frequently with participation of university PIs) and USGS investigators frequently are collaborators on NSF-funded experiments. USGS participation is especially common in earthquake hazard studies as part of the USGS National Earthquake Hazards Reduction Program (NEHRP), and in active-source studies in which the USGS brings valuable capabilities in explosive handling and permitting that university partners commonly lack.

DEPARTMENTS OF ENERGY AND DEFENSE

US programs in seismic verification of nuclear test ban treaties and nuclear nonproliferation are primarily supported by DOE and DOD. These programs also support the US mission to monitor nuclear explosions in real time, support research efforts in the identification and characterization of explosion sources, and the characterization of regional seismic wave propagation. Efforts conducted by academic, private, and government investigators, make use of openly available, archived data from IRIS—including PASSCAL and GSN. In many cases, PASSCAL data, often collected for other scientific reasons, provide unique regional data that are key to characterizing natural and anthropogenic seismicity and wave propagation. Field experiments directly supported by DOE's National Nuclear Security Administration and the Air Force Research Laboratory have used instrumentation from the PASSCAL facility. In 2001–2004, DOE provided funding, through interagency transfer to NSF, to support the upgrading of a significant portion of the PASSCAL broadband instrument pool. In recognition of this support, the PASSCAL Instruments Use Policy (Appendix B) was modified to provide DOE-funded experiments equal priority in scheduling with NSF experiments.

FOREIGN INSTITUTIONS AND INTERNATIONAL PARTNERSHIPS

A number of international groups have acquired portable instruments that are similar (and in many cases identical), to those of PASSCAL. Centrally managed facilities operating and maintaining seismic sensors exist in Canada and many European and Asian countries, and large-scale projects modeled after US initiatives, such as EuroArray, have started to develop.

International, multi-institutional experiments have been organized to take advantage of merged instrument pools, permitting experiments to draw on a larger instrument base than is typically realizable with instruments from only one facility. These collaborative opportunities include both use of PASSCAL equipment overseas and use of foreign equipment in the United States. This is especially true in the case of large-scale, active-source crustal investigations incorporating TEXAN-style instruments. Although PASSCAL does not officially exchange instruments with other facilities, the PASSCAL staff work with PIs and their foreign collaborators to coordinate instrument schedules so that, if at all possible, PASSCAL instruments can be in the field at the same time as instruments from international pools. During the last five years, joint international experiments of this type have been conducted in Poland, Denmark, Jordan, Israel, Tibet, Venezuela, Costa Rica, New Zealand, Ethiopia, and Italy. For longer-term broadband deployments, US investigators sometimes develop collaborative, but separately funded, experiments with foreign teams to achieve expanded coverage in complementary studies. This future mode of collaboration has significant potential, for example, in Europe and China, where a moderately large national, PASSCAL-like facilities, are being developed, and in Antarctica, with its many international research participants and bases.

In addition to working with the international community to coordinate instrument deployments, IRIS also works with the international Federation of Digital Seismographic Networks (FDSN) to make data from foreign-coordinated experiments with portable instruments openly available after a short waiting period in a manner that is analogous to the PASSCAL data policy. The "open" data policy and culture encouraged by IRIS has already had significant impact on the routine sharing data from permanent global networks and US-lead portable experiments. The extension of this culture to include data from all portable deployments worldwide would be a significant advance international earth science.

PASSCAL's primary function has been to support NSF-funded experiments. However, opportunities exist at little cost to expand the purview of this resource to benefit seismology more broadly through the world. Through numerous field programs, PASSCAL investigators have developed a web of international scientific contacts throughout most of the scientifically interesting regions of the planet. In many cases, PASSCAL field personnel have provided technical advice and assistance to scientists in developing countries on an ad hoc basis, appropriate to the particular experiment being supported. In a small number of carefully selected cases, this relationship has been extended on a more formal basis through long-term loans of depreciated equipment and by serving as a pool of expertise to frequent foreign scientists who are also operators of in-country seismic equipment. In 2006, IRIS instituted a long-term loan program with foreign partners to utilize the retired PASSCAL REF TEK 72a series recorders. This program is coordinated through a proposal and selection process overseen by a panel that includes representation from IRIS Planning, PASSCAL, and DMS staff. A flagship pilot project for this effort has been working with AfricaArray, an NSF Partnerships for International Research and Education (PIRE) program that is seeding new long-term seismographic stations and student opportunities throughout the continent. Future initiatives could take the form of technical training sessions at PIC for groups of regional scientists, assistance with hardware or software development, or in minor repairs and upgrades of PASSCAL-compatible instrumentation.

Developing World

- PASSCAL is a principal global technical resource for seismology.
- Many of the established contacts in Africa, central Asia, and South America can be formalized to provide technical guidance on equipment purchase, installation, and maintenance.
- In some cases, PASSCAL can act as an equipment resource for long-term loan of depreciated instruments. This model has been successfully used to develop AfricaArray and is being pursued in the IRIS Long-term Loan Program.

Developed World

- IRIS and PASSCAL can establish collaborative agreements, including joint use of instrumentation, with other centers for portable seismology.
- PASSCAL can use its successes and user community to advocate that the open data model be adopted for all portable experiments and central data centers.

MANAGEMENT AND OVERSIGHT

The PASSCAL Instrument Center operates under annually revised subawards from IRIS to New Mexico Tech. The PIC presently has a total PASSCAL and USArray staff of 31 (with two pending), including a Director, software and hardware staff, office managers, and office personnel (Figure 35).

The PIC supports PASSCAL core operations as well as significant EarthScope Flexible and Transportable Array operations. EarthScope support is provided by the Array Operations Facility (AOF), which is responsible for most purchasing, delivery, checkout, and final integration and

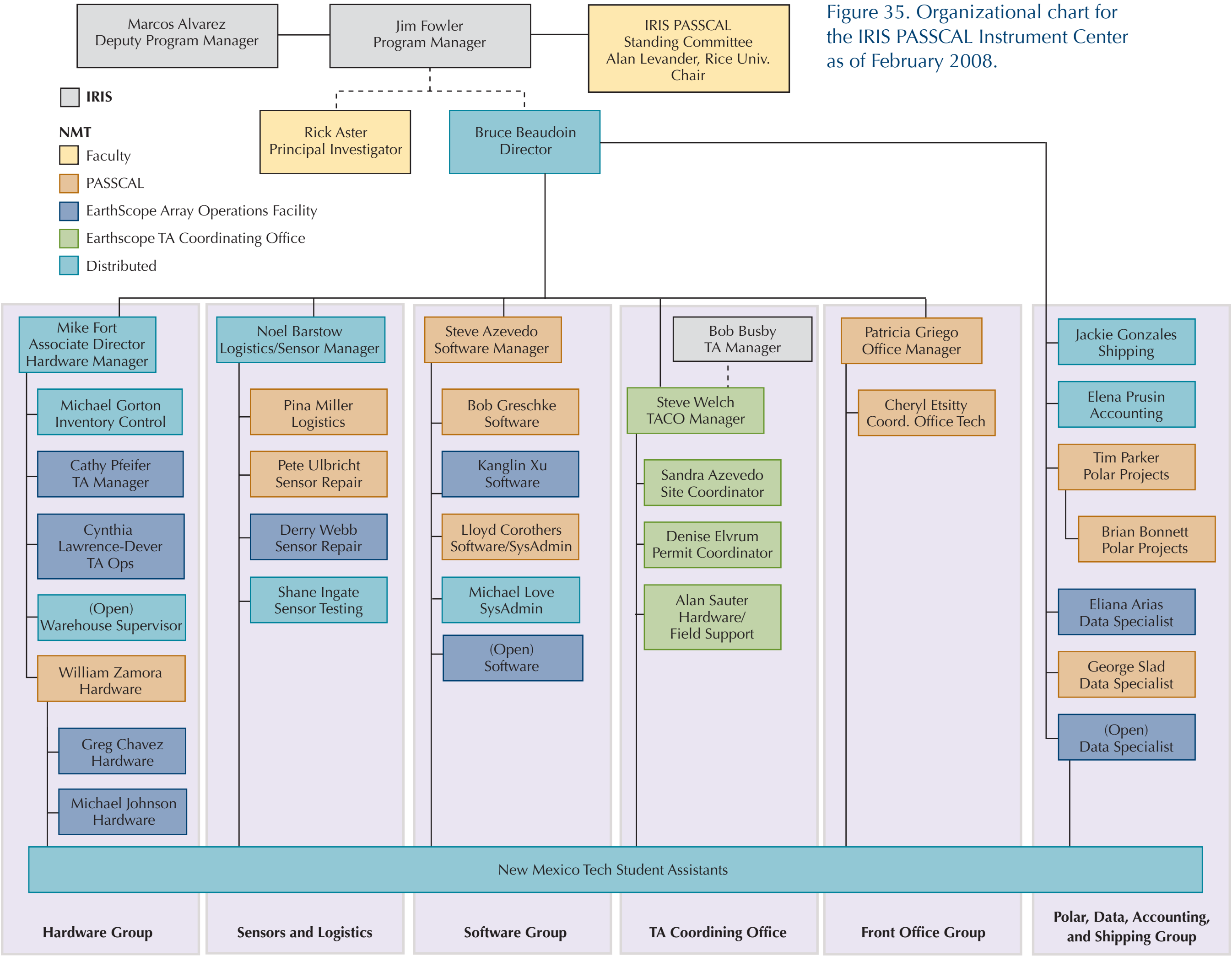


Figure 35. Organizational chart for the IRIS PASSCAL Instrument Center as of February 2008.


Derry Webb prepares a cart of broadband sensors for maintenance and repair in Socorro, NM.


Marcos Alvarez prepares to install a broadband sensor, eastern Tibet.

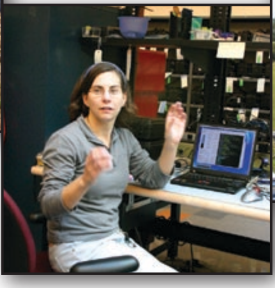

Crew work quickly to install a station on mount Erebus, Antarctica.


Bob Greschke and Greg Chavez work together to develop new testing procedures, Socorro, NM.


Bruce Beaudoin in Tibet, 2003.


Mike Fort sets up a test on the Q330 work bench, Socorro, NM.


Noel and Mingmar Sherpa at station in Namche Bazaar, Nepal for experiment HICLIMB. Photo by Anne Sheehan.


Pnina Miller conducts a training session the use of the Reftek data loggers, Socorro, NM.


Greg Chavez programs a broadband station, Paso Robles, CA.


Jim Fowler installs an early TA station in California.

assembly of Transportable Array and Flexible Array equipment. PASSCAL and AOF efforts are physically integrated to take advantage of numerous commonalities, and nine personnel at the PIC are presently supported by a combination of PASSCAL and EarthScope funding sources. The Transportable Array Coordinating Office (TACO) is an AOF group that responsible for logistical and siting support for Transportable Array field efforts.

The PIC Director, Bruce Beaudoin, manages and reviews the activities of all NMT PIC staff, organized into six groups. The Director allocates fiscal and personnel resources on a daily basis, and coordinates longer-term budgeting and planning in association with the New Mexico Tech PI (Rick Aster) and IRIS staff. General PIC activities are coordinated by IRIS and implemented through the PIC PI, Rick Aster and Director, Bruce Beaudoin. The PI also acts as the principal point of contact with and representative of New Mexico Tech to collaborate with the director in budget, human resources, construction, student, education and outreach, employee evaluation, and general administration.

General PIC activities are coordinated by the PASSCAL Program Manager with assistance from the Deputy Program Manager and implemented through the PIC PI and Director. The IRIS PASSCAL Program Manager, Jim Fowler, and Deputy PASSCAL Program Manager, Marcos Alvarez, are IRIS employees stationed in Socorro. The Program Manager is responsible for the PASSCAL Program as well as the overall IRIS/NMT operation. Marcos Alvarez oversees the Flexible Array component of the USArray and works with the Program Manager to optimize the overall instrument pool.

The development of budgets, managing contracts, placing major equipment purchases and the tracking of expenditures are performed by the Program Manager and Deputy Program Manager. Additionally, initial communications with the PIs for instrument scheduling are conducted by the IRIS staff on site in Socorro. Transportable Array Manager Robert Busby, based in Massachusetts, coordinates with the overall AOF operations and remotely directs day-to-day TACO operations in association with TACO Manager, Steven Welch.

Resource prioritization, aspects of instrument development and acquisition schedules, and annual budget recommendations for the PASSCAL Program and the PIC are provided by the IRIS PASSCAL Standing Committee (Appendix A), which meets semiannually and reports directly to the IRIS Board of Directors.

PIC OPERATIONS

PASSCAL management and staff are generally organized into supervisory and specialization groups. Five of these groups have supervisors reporting to the director: Hardware, Sensors and Logistics, Software, the Transportable Array Coordinating Office, and a Front Office. The Director directly supervises a sixth group that includes Polar, Data, and Accounting and Shipping activities. Because personnel are frequently working directly with PIs in the field, there is considerable overlapping expertise and a sharing of tasks across these groups. Many of the staff have distributed support reflecting overlapping responsibilities between PASSCAL and EarthScope Array Operations Facility operations.

Hardware

The Hardware Group overseen by Associate Director Mike Fort is responsible for quality assurance and maintenance of dataloggers and ancillary electronic equipment and power systems.

Sensors

Between the PASSCAL core program and EarthScope, PASSCAL supports over 1200 broadband and a nearly equal number of intermediate- to short-period seismometers. Sensor staff are responsible for both testing and repair, with three staff using the PIC's two seismic piers essentially full time. Broadband sensor evaluation for new and returning seismometers is typically done in simultaneous batches of ten sensors per pier. Each pier test typically takes from three to five days, after which staff reviews the time series, both individually and in comparison with a reference sensor. A sensor that fails a pier test will evaluated by a repair staff of two, who have received special training from both of our principal broadband sensor vendors, Guralp and Streckeisen.

Logistics and Shipping

PASSCAL currently supports roughly 60 unique experiments per year worldwide. Logistics and shipping, overseen by Noel Barstow, typically handles all shipping arrangements from the PIC to the remote field in close association with the Hardware Group. Logistics and shipping staff work closely with PIs at all project stages to ensure that projects run smoothly and that science objectives are achieved. Services include shipping and customs documentation, carrier information, and general liaison activities with brokers and carriers. Shipping activities are also assisted by Jackie Gonzales under the direct supervision of the Director.

Software

The Software Group, supervised by Steve Azevedo, includes software developers and systems administrators. The group supports software development and implementation essential for processing PASSCAL data from raw field format to formats suitable for quality assurance, archival and scientific analysis. The staff also develops software for in-house hardware testing, programming, and quality-control tools, as well as supporting and distributing a PASSCAL software suite of data format-conversion, inventory control, metadata, data visualization, and quality-control tools that have overlapping uses both in-house and for the user community.

Polar

Approximately five to ten projects per year, predominantly funded by the NSF Office of Polar Programs, have recently been supported in polar regions. These projects typically require a level of support that is several times that of deployments in nonpolar environments. To ensure that these challenging projects achieve the highest level of success, PASSCAL has established a polar projects effort and has secured NSF MRI funds to support the unique instrumentation needs of a growing group of novel deployments, especially for OPP-funded research in Antarctica. At present, the PIC has two staff members dedicated to these efforts. This group is pursuing unique approaches to maintaining continuous operation throughout the polar winter, and to generally maximize data return in consideration of very-high-cost polar logistics. Specific efforts include extreme environmental enclosures, IRIDIUM satellite telemetry, low-temperature broadband sensors, and advanced power and battery systems.

Transportable Array Coordinating Office

A staff of four under the overall guidance of Transportable Array Manager Bob Busby provides core site selection, scheduling, permitting, and general field coordination services for the 400-station EarthScope Transportable Array in close coordination with AOF staff at the PIC.

Front Office

A front office staff of two assists IRIS and NMT staff in the overall coordination of visitors, special events, visitor and employee travel, student employees, Web content updates, and purchasing.

Data

The Data Group provides direct user support for data archival and acts as the principal intermediary between the PI and the IRIS DMC during the archiving process to ensure proper archival of experiment data and metadata. PASSCAL data staff are expert in addressing special issues relevant to PASSCAL data sets and are thus critical to ensuring timely and accurate archival of data at the DMC.

Accounting

IRIS staff, the Director, and the PI use an accounting specialist, Elena Prusin, to facilitate budget monitoring, preparation, and reporting for PASSCAL and EarthScope funds and projects.

TRENDS AND RECENT DEVELOPMENTS

Throughout its history, PASSCAL has evolved and program emphases have changed in response to the demands of science and the scientific community. In this section, we explore some of this evolution, its impact on operational procedures and budget structure, and anticipate future directions.

As initially conceived in 1984, PASSCAL was a basic community instrument resource facility, and acquiring and maintaining hardware were the primary activities. As the program has evolved, there has been increasing emphasis on training, field services, and software support. All of these activities place high demand on human resources, which has in turn increased pressure on balancing budgets to include both growth of the instrument pool and attendant expanded services.

As IRIS completed the fourth five-year cooperative agreement with NSF (2001–2006), the PASSCAL facility approached the initial targets set in 1984 in terms of numbers of instruments and channels. In recent years, the budget profile for PASSCAL has shifted from growth of the pool through acquisition of new instruments to sustaining the pool through replacement of aging and damaged equipment.

Unlike the USArray project where the focus of study lies within the North American continent, the PASSCAL program provides instruments for worldwide investigations. Most PI' using the facility are funded by national organizations such as NSF and DOE to conduct studies driven by global tectonics. In particular, the majority of broadband and active-source (TEXAN) experiments have been conducted outside the US (Figure 36). This has been a consistent trend since the beginning of the program. In 2007, for example, out of a total of 18 broadband deployments, 11 were conducted overseas. In contrast, experiments using short period equipment have remained predominantly within the United States (Figure 36). Short period equipment is mainly used for regional or local seismicity studies often augmenting existing networks. All PASSCAL equipment types combined, the distribution of experiment are evenly split between foreign and domestic locations.

USAGE TRENDS

Demand for instruments from the user community has exceeded the available resources. The PASSCAL pool has grown over the years to a complement of over 1000 digital recording systems (Table 1). What has changed is the character of the typical experiment. Through time, experiments have evolved to deploy larger numbers of instruments, reflecting the scientific need for higher-resolution studies, and longer durations, reflecting the higher data return through capturing more earthquakes (Figure 36). Experiments using multiple instrumentation types have also increased.

The average number of stations deployed in a typical broadband experiment now exceeds 30 (Figure 37a), and several deployments have been fielded in recent years that have exceeded 75. Instruments used for controlled-source studies (primarily the single-channel TEXANs) have also grown with the available pool now in excess of 2600 stations (including USArray equipment, Table 1). Interestingly, the number of broadband experiment starts has remained relatively level at around 10 experiments per year (Figure 37b). Another important trend observed in passive-source recording is the duration of an average experiment, which has increased gradually to around 2.5 years from approximately 1 year in the

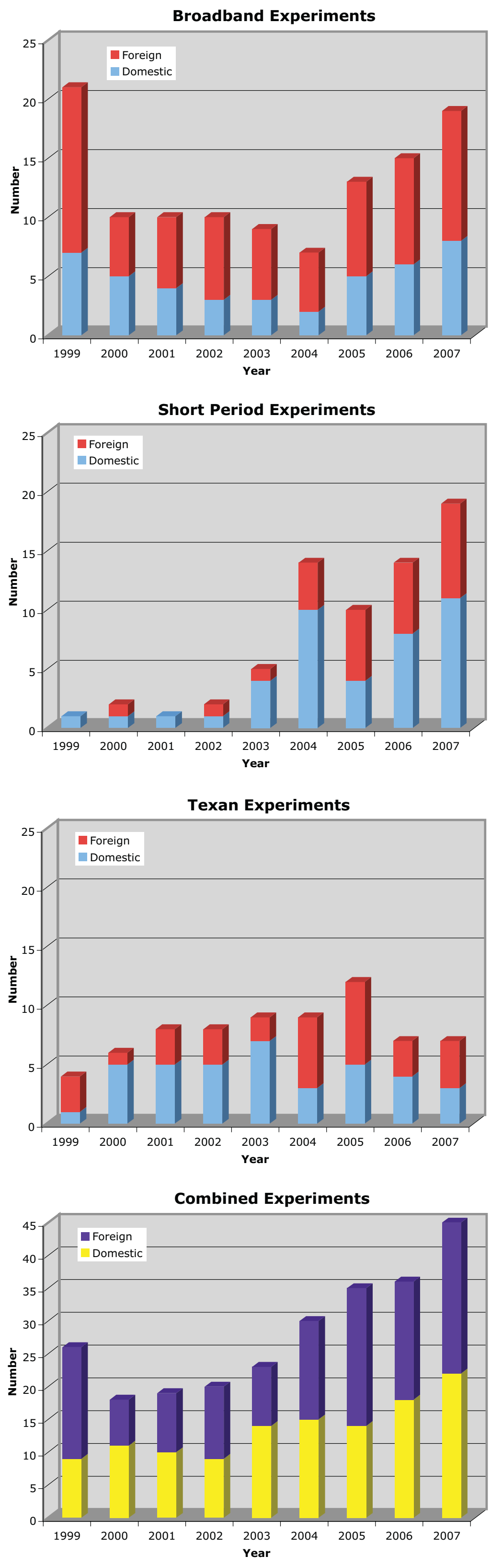


Figure 36. Distribution of experiment location as a function of equipment type (multichannel experiments not shown). The majority of broadband and TEXAN instruments are used in overseas deployments. This trend has been constant through time with increasing total number of experiments supported. The majority of short period experiments are conducted domestically. The graphs show concurrently conducted experiments.

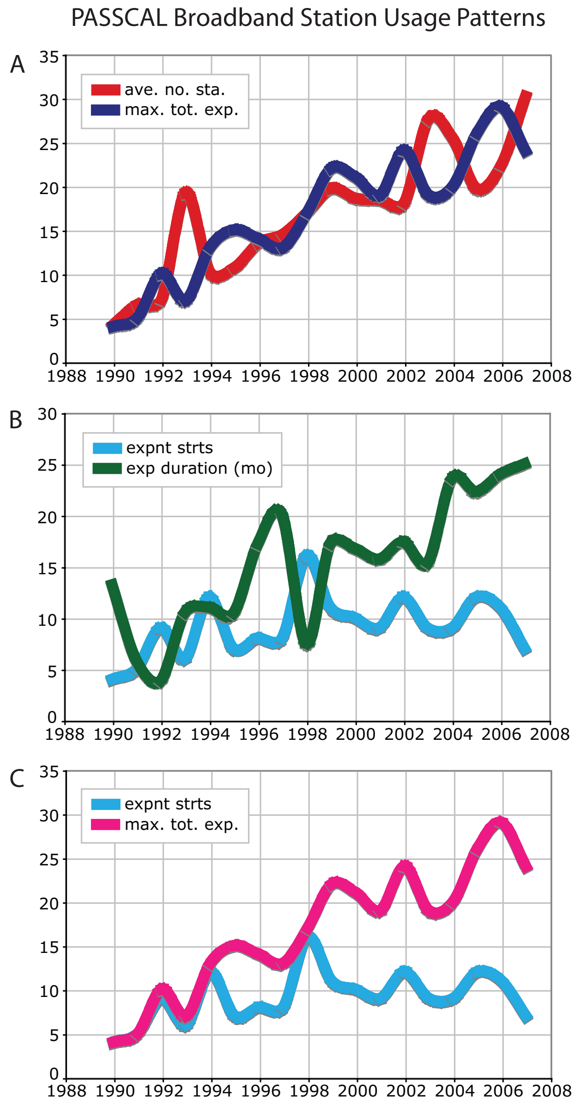


Figure 37. PASSCAL Broadband Sensor Usage Patterns. (A) Average number of stations per experiment (yellow) vs. total experiments deployed in a given year (purple). The average size of broadband experiments has steadily increased to approximately 30 stations. Due to the limited pool size, the number of new experiments fielded in a given year has declined with increasing experiment size. (B) Number of new experiment starts (blue) has stayed relatively constant through time while the maximum number of experiments deployed has gradually risen as a result of increased instrument pool. (C) Number of new experiment starts (blue) vs. average experiment duration. Deployment length (red) has gradually increased to an average of approximately 18 months.

early 1990s (Figure 37c). This reflects community advances in higher-resolution studies incorporating large numbers of events. The time between experiments where the equipment is reconditioned and maintained at the PIC has always been a critical interval for optimal utilization of the PASSCAL pool. Larger experiments mean that large pulses of equipment need to be processed in a short amount of time, straining the multitasking personnel and other resources.

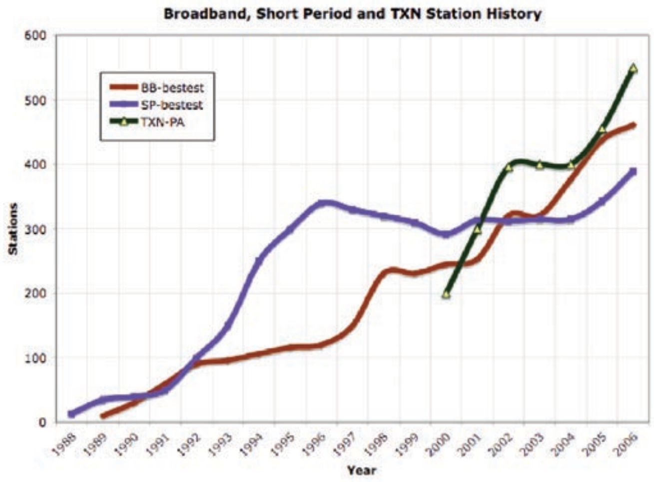


Figure 38. History of the short-period instrument pool. The reduction in short-period stations between 1995 and 2000 reflects retirement of three-channel, controlled-source experiments that were replaced by the TEXAN instruments in 2000.

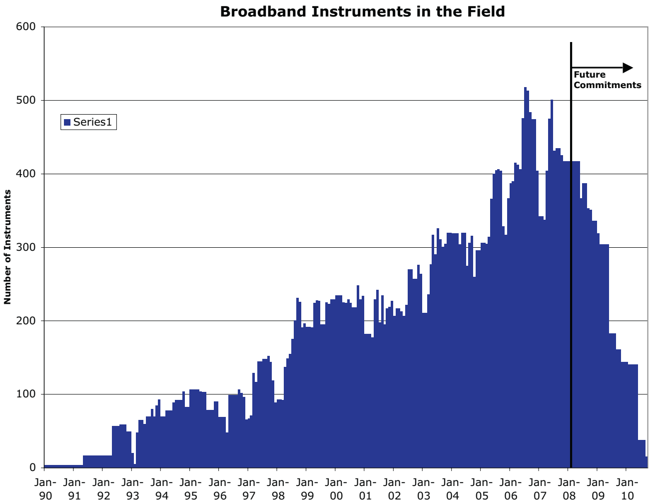


Figure 39. PASSCAL broadband experiment history. Histogram of all experiments through time plotted as a total of stations. Current broadband inventory is approximately 460 sensors. Average wait time for equipment has remained constant at approximately 2.5 years. Actual experiments are plotted before the current time, equipment requests after 2007.

Overall, new projects each year have remained constant while the size and duration (and number of PIs) for a typical experiment continues to grow. In the past, PASSCAL has been able to manage these trends with an increasing yearly inventory (Figure 38). If the total equipment inventory reaches a stable level, the net effect will manifest itself predictably into longer wait times for instruments. This trend can be seen in Figures 39 and 40, where the cumulative number of experiments and future equipment requests are plotted versus the total inventory of equipment.

The "wait time" for instruments—the time between NSF's or some other agency's decision to fund a proposal and when the full complement of instruments are available for deployment—has been a constant source of concern for the user community. As noted above, in spite of increasing numbers of instruments, the general growth in experiment size has meant that the broadband pool remains in continual use—and there has not been a decrease in wait time. For most of the lifetime of PASSCAL, the wait time has remained at 2–2.5 years. The length of the wait time depends on a complex interaction among the number of instruments available, the desired size of arrays, the number of proposals funded, and the level of resources available to fund field programs. Indirectly, the pressure of wait times may also influence the number of proposals submitted. A reasonable delay between the funding decision and the start of field programs can sometimes be an advantage in planning and logistical preparation, but significant delays are problematic, especially for young faculty, students, and postdocs.

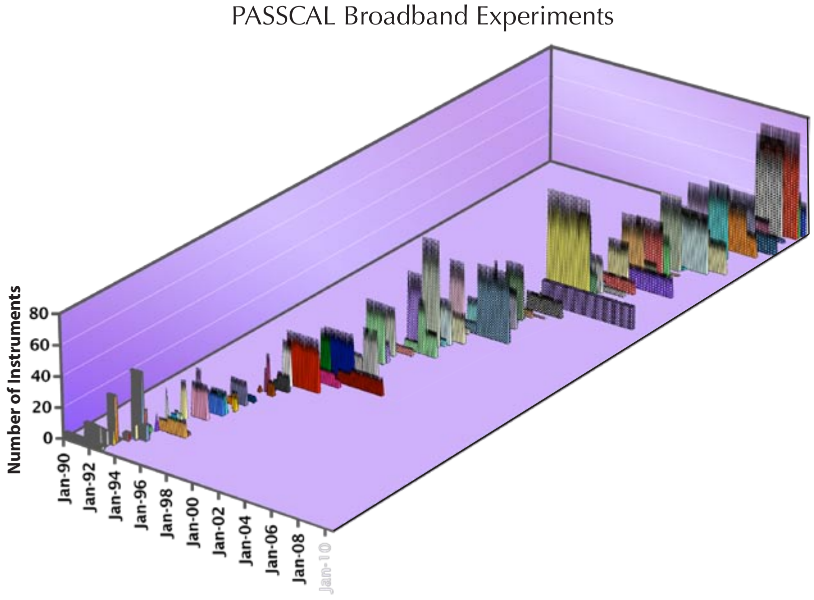


Figure 40. Time history of PASSCAL broadband experiments. Each experiment is one line. The earliest experiments are in the front; recent and proposed experiments are in the back. The size of each box shows experiment duration (length on the time axis) and number of instruments (vertical axis). The trend toward longer experiments (wider boxes) with more instruments (higher boxes) is clearly seen.

BOX 3. PASSCAL EDUCATION AND OUTREACH

PASSCAL-supported projects often incorporate graduate students (and sometimes undergraduates) in preparation, deployment, data collection, and science analysis, publication, and thesis efforts. For example, during 2007, new or ongoing student-associated projects included efforts in Antarctica, many sites in the western United States, Montserrat, Argentina, Venezuela, and Vietnam. Additionally, PASSCAL annually supports numerous equipment requests for purely educational efforts. The majority of these requests are for short-term use of the cabled multichannel systems for university classes and educational field programs (e.g., the Summer of Applied Geophysical Experience [SAGE] program) supported by the US Department of Energy and NSF.

Since 2006, in association with IRIS E&O, the PIC and NMT host an annual orientation week for the IRIS Intern Program (an NSF-funded Research Experience for Undergraduates [REU] initiative). During the orientation, IRIS interns (typically 10) from a broad range of backgrounds participate in field trips and lectures lead by IRIS E&O staff, and by NMT and other IRIS community faculty. The agenda includes seismology “state-of-the-science” talks, elements of instrumentation and data analysis, geological and geophysical field trips, PASSCAL instrumentation data acquisition exercises, and a career discussion panel of professionals from government, academia, and industry. The orientation is designed to provide a common introduction to the field prior to the students’ departure for their summer intern research at widely scattered IRIS institutions and field sites. Since 1999, PASSCAL has also supported a Summer Graduate Intern at the Instrument Center. PASSCAL Graduate Interns acquire a detailed knowledge of many aspects of seismographic instrumentation and data collection by working with PIC staff for up to 12 weeks in a wide variety of efforts, both at the PIC and in the field. To participate in outreach at the local level, IRIS supports an annual science award to a deserving student at Socorro High School.

PIC staff and NMT faculty frequently gives tours and overview talks for diverse groups, including NMT graduate and undergraduate classes, groups on earth science field trips to the region, visiting administrators, lawmakers, and foreign colleagues (e.g., a 2007 delegation of Chinese colleagues on a planning trip for establishing a PASSCAL-like facility in China). The PIC is also used several times per year for IRIS and partner science groups for science, review, and facility meetings.

PERSONNEL TRENDS

Faced with the trend of larger experiments and bigger inventories, PASSCAL has been able to maintain a high level of service, with only minor increases in staff, by becoming more efficient in all aspects of the operation, most fundamentally by consolidating PASSCAL operations to a single Instrument Center in 1998. Advances in warehousing techniques, testing procedures, automated processing tools, and improved facilities have all contributed to our ability to keep up with the increased workload. Nevertheless, there have been inevitable stresses on the staff, as the personnel levels have only slightly increased as the number of instruments has steadily risen. For example, in the early 1990s, the personnel-to-instrument ratio was approximately 35 instruments per person, with a staff of approximately 13. In 2008, there are approximately 31 staff positions with a ratio of roughly 130 instruments per person (Figure 41). These ratios include USArray equipment and personnel, but do not differ substantially if only PASSCAL personnel and equipment are considered. One present effect of this increased workload is a reduction in our ability to advance user support in such important areas as documentation, training resources, and new instrumentation development.

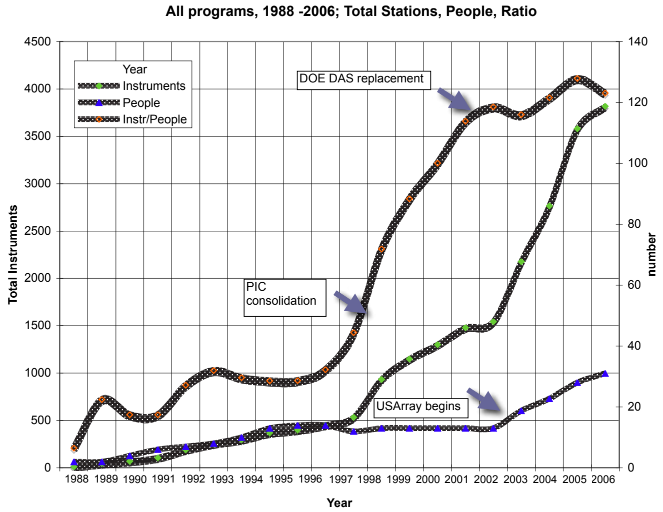


Figure 41. PIC personnel. Instruments and ratio for all programs, 1988–2006. The PASSCAL equipment inventory has dramatically increased since 1998 while total personnel levels have risen only slightly. Currently, the instrument-to-person ratio is near 130, up from 35 in 1998. This plot shows all PASSCAL and USArray personnel and equipment but does not include TACO or contracted personnel.

BROADBAND SENSORS—PROTECTING PAST INVESTMENTS

A powerful trend during the 20-year lifetime of IRIS and PASSCAL has been the increased use of broadband instruments. Modern computers make it possible to record and analyze large quantities of long-duration, high-sample-rate data, resulting in increased interest in full waveforms and long seismograms, and new seismological methodologies have opened up that exploit the full bandwidth of these data. Small, relatively low-power feedback designs provide stable sensors that can be easily transported and installed in relatively simple vaults. The feedback sensors used in these experiments, however, are inherently more complex, fragile, and higher power than the passive short- or long-period sensors. Note that the PASSCAL broadband sensors, the Streckheisen STS2 and the Guralp CMG3T, were not inherently designed to be portable in the frequent redeployment sense that they are now used by PASSCAL, but were instead designed primarily as observatory instruments for infrequent transport and long-term installation. However, the majority of the broadband sensors purchased throughout the buildup of the PASSCAL inventory are still in use today. In a large part, that so many of these sensors are still in use is the result of careful maintenance and repair by PIC staff, and commitment of resources to sensor testing and repair. The median age of a PASSCAL broadband sensor is now 10 years (Figure 42). Some of these older sensors are now beginning to fail and are no longer reparable. Additional resources per sensor are furthermore commonly required to replace and repair these older instruments.

PASSCAL and other national and international groups have worked closely with a small number of commercial companies to develop sensors with higher reliability and lower power that will be more appropriate for rugged field programs and long-term deployments. Both new manufacturing techniques and fundamental new designs have been explored. In spite of some refinements in design and improvements in the manufacturing process (resulting in modest improvements in ruggedness and reliability), the approximately 30-year-old fundamental mass-spring-feedback design has not been changed. There may be new design options on the horizon for rugged, short-period (few seconds) sensors, but it appears unlikely that there will be significant breakthroughs in the intermediate and long-period range (tens to hundreds of seconds). In this environment, PASSCAL will continue to explore the best means to maintain and repair the current designs and work with PIs to develop procedures for proper care of sensors during shipping and in the field.

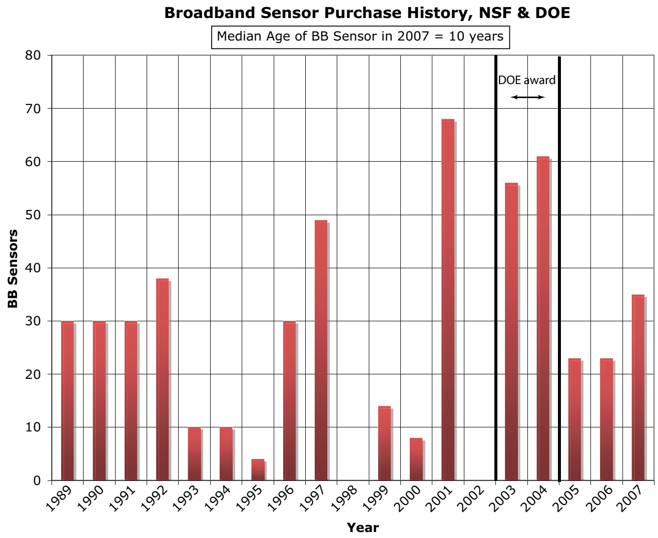


Figure 42. Broadband sensor purchase history from NSF and DOE funds. The median age of the PASSCAL broadband sensor in 2007 was 10 years. Most broadband sensors purchased are still in service today.

FUTURE TRENDS

The composition of the PASSCAL instrument pool and its modes of field and software support evolve as new scientific opportunities arise and as advanced technologies develop. Sustaining state-of-the art instrumentation thus entails adopting new technologies, notably in communications, power sources, and sensors, as they become available and pursuing the development of increasingly lower-power and lower-cost instrumentation.

Recent experience with the USArray has demonstrated that real-time data recovery increases data quality and data return while optimizing field resources. However, the cost for operating a real-time network is associated with significant service fees and data center infrastructure that still precludes its use in the typical PASSCAL experiment. The technology is continuing to progress, and we expect real-time communications will be increasingly feasible for more experiments in the near future. The funding of recurring communications fees is an issue that will need to be worked out with PIs and NSF.

The new generation data loggers that comprise the PASSCAL pool (REF TEK RT130s and Quanterra Q330s) are all equipped with modern communications protocols. These systems have been configured to work well with modern radio, cell phone, IRIDIUM, and VSAT communications systems. Although setting up a real-time seismic network in a foreign country is still very challenging, worldwide communications are advancing and becoming standardized so rapidly that we expect that real-time communications for overseas projects will also be realistic in the near future. But, here again, the budgeting of communications costs will be an issue. We are also watching with interest several initiatives in the community for “mote” or other small-scale, self-organizing sensor networks that may eventually offer other robust telemetry options in smaller scale experiment situations such as volcano or glacier seismology.

A promising integration into the PASSCAL mode of operations is the development of power and telemetry systems suitable for Antarctic deployments. The use of a combined solar, wind, and lithium battery system matched with a very-low-power seismic system is currently being implemented in two deep-field projects. The knowledge and experience acquired in support of deployments in such extreme environments permeates into the rest of the program, and helps to improve support throughout.

BUDGET

The primary source for PASSCAL core funding has been through a series of five-year cooperative agreements between IRIS and the National Science Foundation. Figure 43 shows the overall IRIS core (without EarthScope) funding. Each of the three major programs—PASSCAL, DMS, and GSN—operate with a base budget of about $3.2M. This funding has remained level over the last several years. A significant enhancement of over $9M to the PASSCAL budget has come from special Congressional appropriations coordinated through the Department of Energy between 2001 and 2005. This money was targeted for the replacement of the original data acquisition systems. EarthScope and USArray funding come through a separate cooperative agreement, and includes separate budgets for Major Research Equipment and Operations and Maintenance.

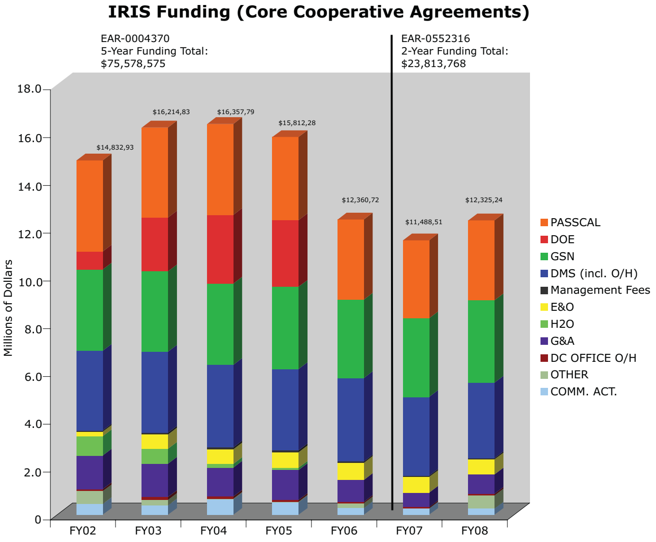


Figure 43.

Figure 44 shows a breakdown of core PASSCAL spending by category. With the exception of the money spent on hardware, the spending levels for the rest of the program are relatively constant. The major non-equipment items in the budget are subawards. Currently, there are two major subawards: one to the UTEP and one for the PIC at NMT.

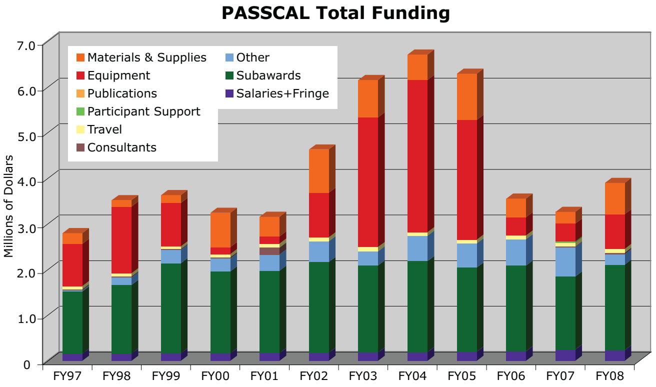


Figure 44.

The PIC award to NMT provides salary support for 13 full-time employees. Included within the overhead structure of this award is the provision and maintenance of office, laboratory, and warehouse facilities. Other basic services, such as administrative support and Internet bandwidth, are supported through this award. The yearly costs associated operating the core instrument center stabilized markedly after the consolidation of instrument centers from Lamont and Stanford to NMT in 1998 (Figure 45). For fiscal year 2007, the NMT PIC award was $1.637M.

The UTEP award provides support for approximately 1.2 full-time employees. UTEP has title to 440 single-channel TEXAN instruments purchased by the state of Texas. This subaward ensures PASSCAL user community access to these instruments and thus more than doubling the number of PASSCAL TEXAN instruments. For fiscal year 2007, the UTEP award was $199K.

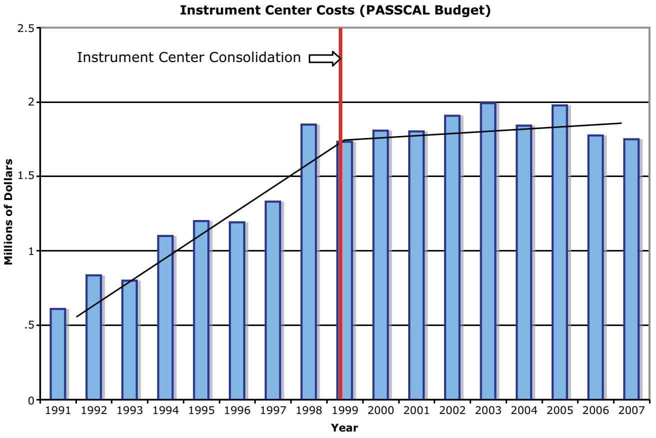


Figure 45.

APPENDIX A
PASSCAL STANDING COMMITTEE AND PAST CHAIRS

Current Members

Alan Levander (Chair)	Rice University
Richard Allen	University of California, Berkeley
Matthew Fouch	Arizona State University
Tom Pratt	University of Washington
Stéphane Rondenay	Massachusetts Institute of Technology
Arthur Rodgers	Lawrence Livermore National Laboratory
Ray Russo	University of Florida
George Zandt	University of Arizona

Past Chairs

Larry Braile	Purdue University (1987–1990)
Anne Trehu	Oregon State University (1991–1992)
Gary Pavlis	University of Indiana (1993–1995)
Anne Meltzer	Lehigh University (1996–1998)
Roy Johnson	University of Arizona (1999–2001)
David James	Carnegie Institution of Washington (2003–2005)
Alan Levander	Rice University (2006–2008)

APPENDIX B

POLICY FOR THE USE OF PASSCAL INSTRUMENTS

September 12, 2006

INTRODUCTION

Portable field recording equipment and field computers purchased by the PASSCAL Program are available to any research or educational institution to use for research purposes within the guidelines established in this document. The intent of these guidelines is to establish the procedures to enable investigators to request the instruments, to let them know what requirements and responsibilities are incurred in borrowing the equipment and to know when and how the decisions on instrument allocation will be made.

The efficient use of the instruments will require close cooperation among all of the parties involved. The Principal Investigator is encouraged to contact the PASSCAL Program Manager about any planned experiment during the proposal development stage in order to determine if there are any problems in operating the equipment in the environment called for in the experiment. It is also important for everyone to know of possible schedule conflicts as early as possible. Open communications will allow the development of alternative plans early in the scheduling process.

The PASSCAL instrumentation and associated services are provided, without charge, as part of the facility support developed by IRIS through funding from the Instrumentation and Facilities Program, Earth Sciences Division, National Science Foundation, with additional equipment provided through the Air Force Office of Scientific Research, the Office of Nonproliferation Research & Engineering of the Department of Energy and the Office of Basic Energy Sciences of the Department of Energy. As a community resource, IRIS and NSF rely on the individual PIs to conform to a limited number of rules and conditions related to the use of PASSCAL instruments, to treat the instruments with care and respect, and to acknowledge the support which is provided. Only through your continued support and feedback will IRIS be able to develop and expand the services it provides for seismological research.

PASSCAL publishes an inventory of all of its equipment through the IRIS World Wide Web site (http://www.iris.edu). This inventory includes all data loggers, sensors, field computers and major ancillary equipment. A description of the capabilities of the various pieces of equipment are available with the inventory as well as a copy of the current instrument schedule.

PROCEDURE FOR BORROWING INSTRUMENTS

Any research or educational institution may request the use of the equipment for experiments of scientific merit. The initial request will be submitted to the IRIS via the Worldwide Web using:

- http://www.iris.edu

The initial request should be sent to IRIS at the time the proposal is sent to the funding agency.

Each request will as a minimum contain the following information:

1. A short description of the experiment to be conducted; including any unusual field conditions which may be encountered;
2. The location of the experiment (latitude - longitude as well as an estimate of the aerial extent);
3. Starting and ending dates of the experiment along with information on any extenuating circumstances which may make it impossible to slide the date forward or backward;

4. The types and number of pieces of equipment requested for the experiment;
5. An estimate of the amount of data to be gathered and archived;
6. A notification of any special support which may be required;
7. The name of the funding agency and status of the funding support; and
8. A mailing address, email address, phone and fax numbers for the designated contact person for this experiment.

SCHEDULING

The schedule is determined in the fall of each year for the next year. If conflicts exist, a committee of impartial members from the PASSCAL Standing Committee along with any interested representatives from the National Science Foundation will meet to make the final determinations. Only experiments with established funding will be entered into the schedule. Priorities will be set in the following order:

1. Programs funded by the Earth Sciences Division of NSF or by the Office of Nonproliferation Research & Engineering of the Department of Energy;
2. Programs funded by other divisions of NSF;
3. Programs funded by other US government agencies; and
4. Other programs.

All other conditions being equal, the highest priority will go to experiments with the earliest funding dates, then the earliest request dates. The goal of the scheduling is to optimize the use of the instruments, and accommodate as many experiments as possible. Therefore, it is sometimes necessary to negotiate with the PI the exact type and number of instruments or to move the scheduled time of the experiment.

IRIS will publish the schedule for the coming year as soon as the committee recommendations are completed and approved by the President of IRIS. Once the experiment has been scheduled, the PI will be contacted to work out the details about the exact type of equipment, the ancillary equipment and the field support personnel who will be assigned to the experiment. At this point the PI will also have to start working with PASSCAL to provide information to the Data Management System about the experiment and the data delivery.

Experiments which receive funding after January 1 will be entered into the schedule so as not to interfere with previously approved experiments. Requests can be made for instruments at any time during the year, and they will be made available to users as the schedule permits. If an experiment can not go in its allocated slot for some reason it goes to the back of the line unless:

1. The PI's in affected experiments voluntarily agree to delay or modify the experiment schedule, or
2. The applicable NSF and/or DOE Program Manager(s) decides that the delayed experiment takes priority over one of their subsequent experiments.

PRINCIPAL INVESTIGATOR COMMITMENTS

Investigators borrowing instruments will be required to meet the following conditions:

1. Copies of all data sets acquired with the instruments will be made available to the IRIS Data Management Center in accordance with the PASSCAL Data Delivery Policy. The delivery of the data is considered the equivalent of delivery of a final report.

2. The PI and key experiment personnel are required to attend an Experiment Planning Session at the PASSCAL Instrument Center. At this session they will work with the PASSCAL personnel to finalize the operational plans for the experiment and receive training on the recording instruments and the field computers. This is necessary even for a repeat users, as equipment and software are being upgraded continuously.

3. Experiments should budget to pay travel expenses for personnel from the PASSCAL Instrument Center to accompany the equipment to the field to insure that the equipment is functioning properly and to provide additional in-field training to the experiment personnel. This personnel support, which can be requested by the PI or at the discretion of PASSCAL, is intended to be short-term support to insure that the experiment can start collecting useful data in a timely manner. Experiments with very large numbers of instrument (> 100) or other special

requirements should be prepared to pay for more than one person to come to the field. The final arrangements for support will be negotiated after the experiment is on the schedule.

4. The experiment will be responsible for all shipping costs and duties which may be incurred in getting the equipment to and from the field site. The PASSCAL Instrument Centers provide advice, documentation and other support in this effort. For international experiments the PI is responsible for making all shipping and customs arrangements and paying any fees involved.

5. The PI is responsible to see that the equipment is returned to the appropriate instrument center on the date specified. In the case of foreign experiments, the PI will have at least one person in country overseeing the customs and shipping efforts until the equipment has cleared customs and is in transit back to the US.

6. The investigators will be responsible for loss or damage that occurs as a result of negligence or improper handling of the equipment. IRIS will carry an insurance policy on all of the equipment but this is intended to cover major losses due to theft or accident.

7. Immediately after the field work has been completed, the PI will submit a short report summarizing the field portion of the experiment. This report will contain the following:
   - A short description of the completed field experiment;
   - A list of station locations;
   - A summary of the data collected as well as any unusual events which may be included;
   - A description of problems encountered with either the hardware or the software furnished by the PASSCAL program; and
   - Recommendations for further improvement in the facility.

8. Acknowledgment - In any publications or reports resulting from the use of these instruments, please include the following statement in the acknowledgment section. You are also encouraged to acknowledge NSF and IRIS in any contacts with the news media or in general articles.

   "The instruments used in the field program were provided by the PASSCAL facility of the Incorporated Research Institutions for Seismology (IRIS) through the PASSCAL Instrument Center at New Mexico Tech. Data collected during this experiment will be available through the IRIS Data Management Center. The facilities of the IRIS Consortium are supported by the National Science Foundation under Cooperative Agreement EAR-0004370 and by the Department of Energy National Nuclear Security Administration."

9. The Principal Investigator must sign and return a PI Acknowledgement Form such as the one attached below.

Please provide IRIS with copies of any publications related to your experiment.

IRIS COMMITMENT

IRIS/PASSCAL will provide the following services to the experiment:

1. The equipment will be ready to ship from the instrument center on the date specified.
2. Appropriate technical support as negotiated with the PI during planning. IRIS will contract for the salaries for the support personnel, but it is up to the experiment to pay any travel costs for these personnel.
3. Maintenance on units which malfunction in the field. IRIS will attempt to repair or replace the equipment as quickly as possible.
4. Computer support in the form of a full capability field computer which will be located at the PASSCAL Instrument Center. This system, which may be in addition to the field computer provided for use during the field experiment, is to help investigators who do not have access to a field computer to get the data into formats acceptable to the Data Management Center.
5. IRIS will provide system support to help investigators install IRIS-developed non-proprietary field computer software on the PI's own compatible systems.

This policy is effective as of May 12, 2003 and is subject to change and revision as needs dictate.

APPENDIX C

PASSCAL DATA DELIVERY POLICY

November 18, 2004

The equipment in the PASSCAL facility represents a significant community resource. The quality of the data collected by this resource is such that it will be of interest to investigators for many years. In order to encourage the use of the data by others and thereby make the facility of more value to the community, IRIS policy states that all data collected by instruments from the PASSCAL Facility should be submitted to the Data Management Center so that they can be accessed by other interested investigators after the proprietary period.

This policy outlines the guidelines for data submission. IRIS's policy is that delivery of data to the DMC is an obligation of the PI. It is important to IRIS that the PI acknowledges this obligation and meets it within the required time frame. Failure to complete this requirement not only deprives the community of a valuable data resource, but also may jeopardize future requests to borrow IRIS equipment.

IRIS expects data delivery while the experiment is in the field (for long term deployments), or immediately at the conclusion of the field deployment. The data and Data Report will remain confidential for a period of 2 years after the end of the fieldwork.

DATA REPORT

The Data Report is not intended as a formal technical paper but it should contain enough information to allow someone to work with the data. If possible the report should be in a widely accepted electronic format such as RTF or PDF. Any figures can be included as Postscript files. The following types of information should be included:

- A short description of the experiment;
- A list of stations occupied along with coordinates and a short description of the sites;
- A description of the type of calibration information acquired; and
- For non-SEED data a description of the data archive volume.

The Data Report and completed Demobilization Form are due immediately after the completion of the experiment.

DATA

The actual format of the data and the amount of data depend upon the type of experiment. Most PASSCAL experiments fall into one of the following categories: Broadband, short period or reflection /refraction. The first two are passive source experiments while the third utilizes active sources.

Broadband (Continuous Data)

The data from broadband experiments (that is experiments collecting continuous data from broadband sensors at sample rates less than or equal to 40 sps) can be used in a variety of different investigations. Therefore, it is in the best interest of the community to archive these data for easy access by the seismology community. Each PI conducting a broadband experiment will utilize the PASSCAL database or equivalent software to provide all of the data collected to the DMC for archive in SEED format. It is expected that the PI will ship the data to the DMC on a continuing basis during the experiment as soon as timing and other corrections are made and that the final data will arrive shortly after the experiment is over. The DMC will make the data available only to the PI or his designated representative for a period of two years after the completion of the experiment. After that, the data will be made available to the public.

Short Period (Triggered)

Short period experiments are generally different from broadband experiments in both the amount and the bandwidth of the data they produce. Short period sensors are generally run at higher sample rates than broadband sensors, and the ability to record low frequency signals is very limited. As the short period data are typically recorded in a triggered mode, their principal archive will be as event data. The time windows should be long enough to include a reasonable amount of pre-event noise signal as well as all of the significant seismic phases for the event. As above, the data should be delivered to the DMC for distribution in SEED format. The PASSCAL field computers have the necessary software for this delivery.

Reflection/Refraction

Reflection/Refraction experiments differ from the above experiments in that they nearly always involve active sources. The receivers are typically arranged in regular one or two-dimensional arrays. The accepted data format for these active source experiments is conventional SEG-Y format. The data should include all of the necessary information on the geometry of the experiment (metadata) and they should be corrected for all known timing problems.

Non-Standard

There will always be some experiments that do not fit directly into one of the above categories. In those cases the exact form of the data delivery will be negotiated between the PI, the IRIS Data Management System and PASSCAL.

PROPRIETARY DATA

Data of all types should be delivered to the DMC, in the appropriate format, as soon as possible and normally well before the general release of the data. The DMC will only allow access to the waveforms to the PI and others designated by the PI. Access will be by password that will be provided by the DMC to the PI. The PI can share the password with anyone he/she wishes. The PI will be notified when anyone registers for access to a proprietary dataset.

Information about the experiment such as station locations and characteristics will be made publicly available during the experiment, only waveform data will be limited in distribution during the proprietary period.

All passive experiments with five or more stations will designate at least one station as and "open station". The data from the "open station/s" will be made available to the public immediately upon being archived.

SUPPORT AVAILABLE FROM IRIS

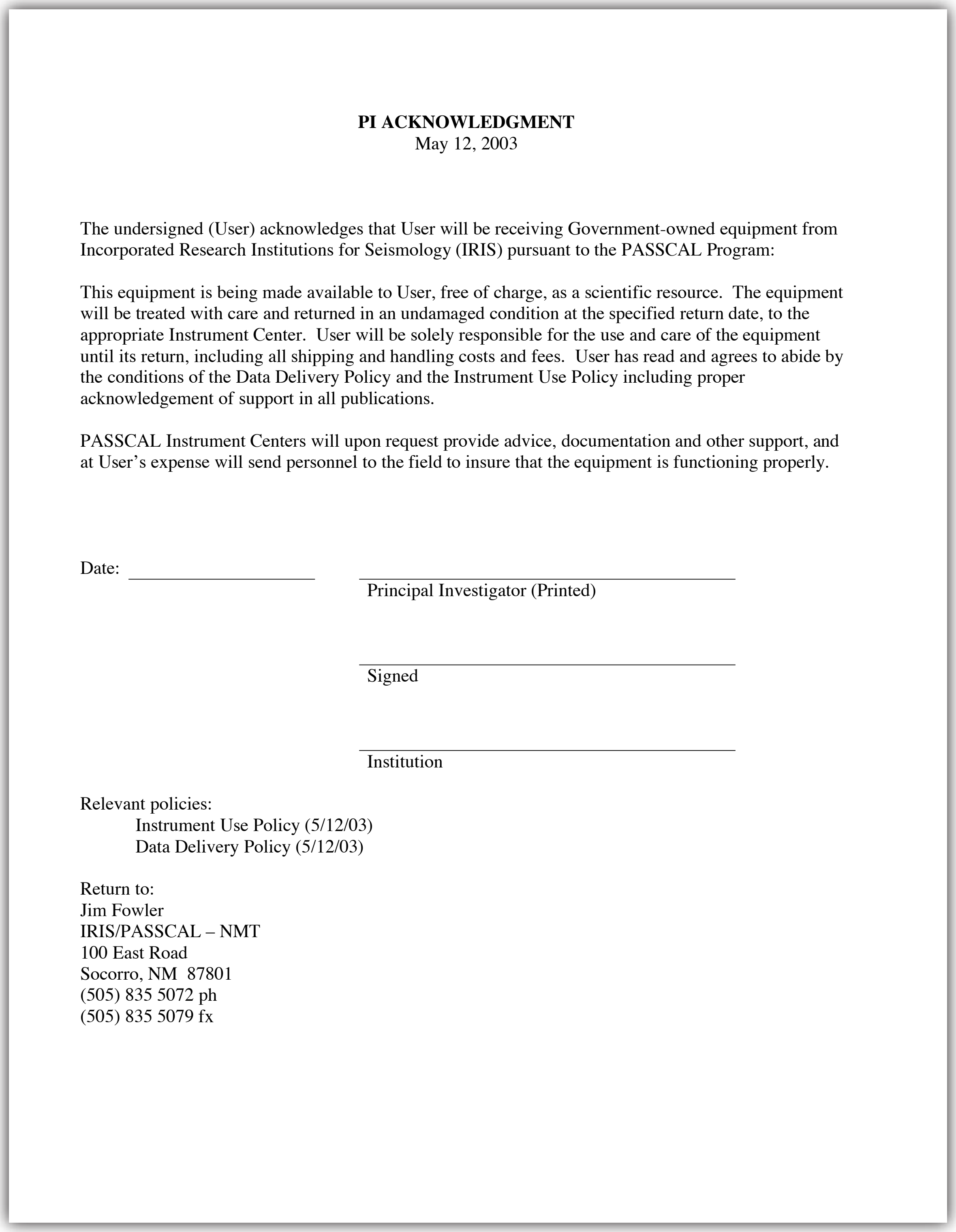
Every field computer has the software necessary to accomplish the data delivery task, and the PASSCAL Instrument Center has personnel who can provide assistance to the PI during and after the experiment. The Instrument Center also has software, computers, and large disk systems available for use by the PI. The Data Management System has additional facilities and support available to the PI. The PI is encouraged to utilize these resources at all stages of the work. In all cases, however, the ultimate responsibility for delivery of the data rests with the Principal Investigator. The PI must ensure that adequate resources are budgeted to accomplish this task.

A PASSCAL data submission is not considered complete until both the PASSCAL and DMS Program Managers certify that the information contained in the report is sufficient to allow other members of the community to utilize the data. IRIS will not certify that it has received data from any PI until the data submission is deemed usable.

This policy is effective as of November 18, 2004 and is subject to change and revision as needs dictate. For updated versions of the policy and additional information on data delivery see the PASSCAL and DMS pages on the IRIS web site (http://www.iris.edu).

APPENDIX D

PI ACKNOWLEDGEMENT



PI ACKNOWLEDGMENT
May 12, 2003

The undersigned (User) acknowledges that User will be receiving Government-owned equipment from Incorporated Research Institutions for Seismology (IRIS) pursuant to the PASSCAL Program:

This equipment is being made available to User, free of charge, as a scientific resource. The equipment will be treated with care and returned in an undamaged condition at the specified return date, to the appropriate Instrument Center. User will be solely responsible for the use and care of the equipment until its return, including all shipping and handling costs and fees. User has read and agrees to abide by the conditions of the Data Delivery Policy and the Instrument Use Policy including proper acknowledgement of support in all publications.

PASSCAL Instrument Centers will upon request provide advice, documentation and other support, and at User's expense will send personnel to the field to insure that the equipment is functioning properly.

Date: ____________________

____
Principal Investigator (Printed)

____
Signed

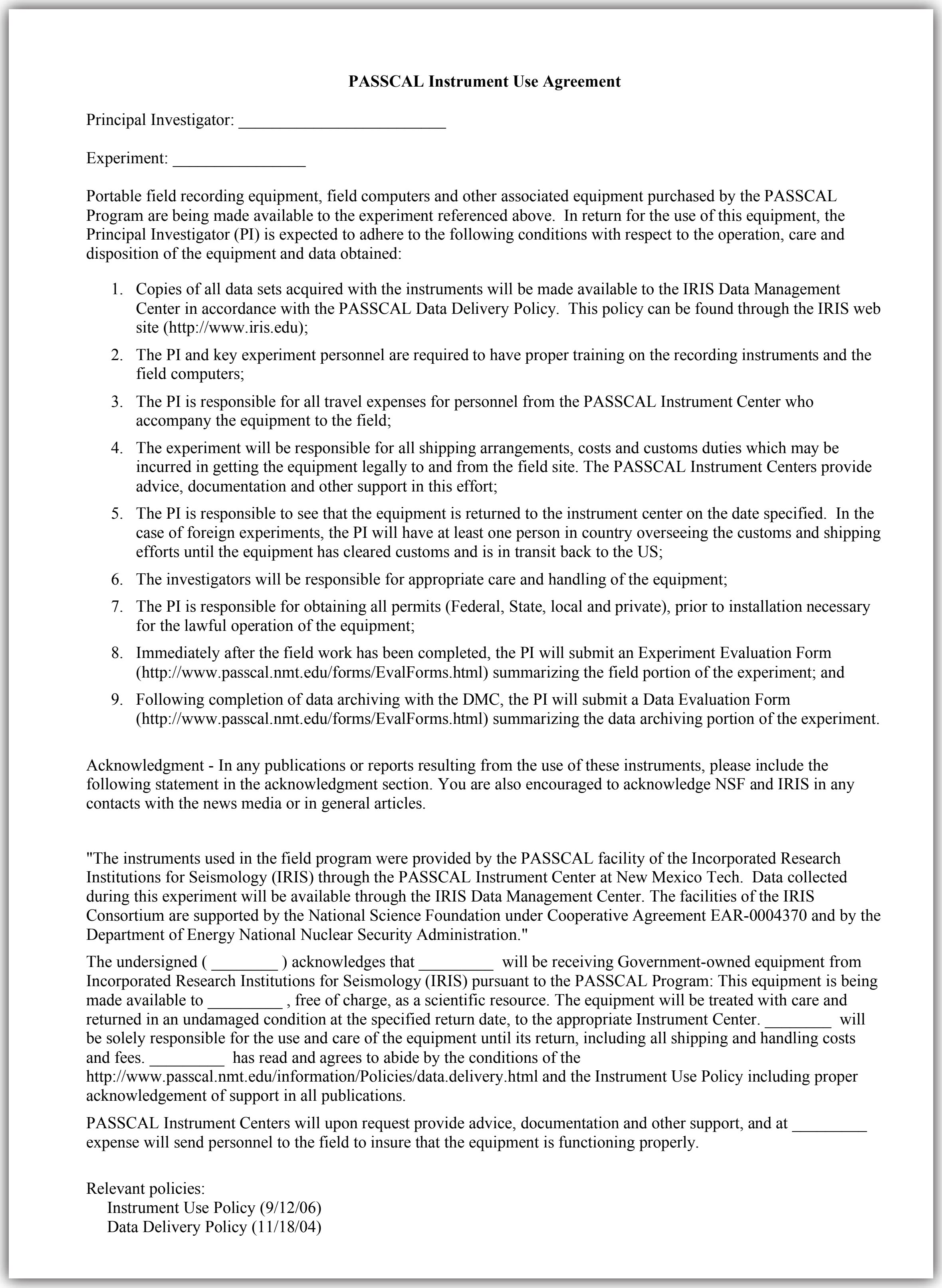
____
Institution

Relevant policies:
    Instrument Use Policy (5/12/03)
    Data Delivery Policy (5/12/03)

Return to:
Jim Fowler
IRIS/PASSCAL – NMT
100 East Road
Socorro, NM 87801
(505) 835 5072 ph
(505) 835 5079 fx

APPENDIX E

PASSCAL INSTRUMENT USE AGREEMENT



PASSCAL Instrument Use Agreement

Principal Investigator: ________________________

Experiment: _______________

Portable field recording equipment, field computers and other associated equipment purchased by the PASSCAL Program are being made available to the experiment referenced above. In return for the use of this equipment, the Principal Investigator (PI) is expected to adhere to the following conditions with respect to the operation, care and disposition of the equipment and data obtained:

1. Copies of all data sets acquired with the instruments will be made available to the IRIS Data Management Center in accordance with the PASSCAL Data Delivery Policy. This policy can be found through the IRIS web site (http://www.iris.edu);
2. The PI and key experiment personnel are required to have proper training on the recording instruments and the field computers;
3. The PI is responsible for all travel expenses for personnel from the PASSCAL Instrument Center who accompany the equipment to the field;
4. The experiment will be responsible for all shipping arrangements, costs and customs duties which may be incurred in getting the equipment legally to and from the field site. The PASSCAL Instrument Centers provide advice, documentation and other support in this effort;
5. The PI is responsible to see that the equipment is returned to the instrument center on the date specified. In the case of foreign experiments, the PI will have at least one person in country overseeing the customs and shipping efforts until the equipment has cleared customs and is in transit back to the US;
6. The investigators will be responsible for appropriate care and handling of the equipment;
7. The PI is responsible for obtaining all permits (Federal, State, local and private), prior to installation necessary for the lawful operation of the equipment;
8. Immediately after the field work has been completed, the PI will submit an Experiment Evaluation Form (http://www.passcal.nmt.edu/forms/EvalForms.html) summarizing the field portion of the experiment; and
9. Following completion of data archiving with the DMC, the PI will submit a Data Evaluation Form (http://www.passcal.nmt.edu/forms/EvalForms.html) summarizing the data archiving portion of the experiment.

Acknowledgment - In any publications or reports resulting from the use of these instruments, please include the following statement in the acknowledgment section. You are also encouraged to acknowledge NSF and IRIS in any contacts with the news media or in general articles.

"The instruments used in the field program were provided by the PASSCAL facility of the Incorporated Research Institutions for Seismology (IRIS) through the PASSCAL Instrument Center at New Mexico Tech. Data collected during this experiment will be available through the IRIS Data Management Center. The facilities of the IRIS Consortium are supported by the National Science Foundation under Cooperative Agreement EAR-0004370 and by the Department of Energy National Nuclear Security Administration."

The undersigned (________) acknowledges that _________ will be receiving Government-owned equipment from Incorporated Research Institutions for Seismology (IRIS) pursuant to the PASSCAL Program: This equipment is being made available to _________ , free of charge, as a scientific resource. The equipment will be treated with care and returned in an undamaged condition at the specified return date, to the appropriate Instrument Center. ________ will be solely responsible for the use and care of the equipment until its return, including all shipping and handling costs and fees. _________ has read and agrees to abide by the conditions of the http://www.passcal.nmt.edu/information/Policies/data.delivery.html and the Instrument Use Policy including proper acknowledgement of support in all publications.

PASSCAL Instrument Centers will upon request provide advice, documentation and other support, and at _________ expense will send personnel to the field to insure that the equipment is functioning properly.

Relevant policies:
Instrument Use Policy (9/12/06)
Data Delivery Policy (11/18/04)

APPENDIX F

PASSCAL FIELD STAFFING POLICY

August 23, 2006

PIC STAFFING SUPPORT FOR FIELD OPERATIONS

PIs may request PASSCAL Instrument Center (PIC) staff to support field operations. The PIC will do its best to provide the requested support given the available resources at the time of the field campaign. The PIC also reserves the right not to provide field support if the field area is deemed to dangerous; in such a case the PIC will do all that is possible to ensure the success of the experiment. The PIC strongly recommends that all PIs take advantage of this resource recognizing the expertise that the PIC staff offers field operations. Any individual PIC staff will not be required to spend more than four (4) weeks supporting a field campaign unless special circumstances exist and all parties, PI, PIC management and PIC field personnel, have agreed. For field campaigns that last longer than four (4) weeks PIs can opt to have rotating shifts of PIC staff support. Arrangements should be made such that PIC staff arrive in-country after the equipment has cleared customs. PIC personnel travel arrangements are the responsibility of PASSCAL staff and will be coordinated with the PI for both schedule and budget considerations.

PIC STAFF AND PI RELATIONS

PIC staff is 'in the field' at the request and invitation of the PI. As such, PIC staff is there to provide technical support and advice to the PI and will defer to the PI regarding decisions that impact the experiment. PIC staff will also abide by guidelines established by the PI for doing fieldwork and respect cultural, religious, and social mores of the host country.

PIC STAFF RESPONSIBILITIES IN THE FIELD

General (applies to all types of experiments)

On arriving in country, PIC staff is responsible for checking the shipment inventory, setting up the field lab, and providing all in-country software and hardware training. PIC staff is responsible for determining that all PASSCAL equipment is functioning prior to deployment. Any equipment damaged in shipping will be repaired to the best of PIC staff ability. The equipment will be tested during a huddle test at which time complete stations will be assembled in a lab environment and the PI approved recording parameters will be tested. If time permits and the above responsibilities have been satisfied, PIC staff can participate in the deployment of seismic stations or any other tasks identified by the PI that will aid in the success of the experiment. Under no circumstances will PIC staff take personal time during an experiment unless granted by the PI.

Active Source

For active source experiments PIC staff is responsible for ensuring that all of the instruments have been correctly programmed prior to deployment. After the recording, PIC staff is responsible for offloading all of the data, performing QC, creating backups of the raw data, and reprogramming the instruments if necessary. If time permits, PIC staff can produce record sections at the PI's request.

Passive Recording

For broadband passive experiments an overnight huddle test will be performed to allow for the sensors to stabilize. PIC staff should participate in at least the first several installations to provide expert advice and help finalize the station design.

APPENDIX G

POLICY FOR AN IRIS RAPID ARRAY MOBILIZATION PROGRAM (RAMP)

INTRODUCTION: WHAT IS RAMP?

RAMP is a component of the IRIS response to unanticipated seismic events such as earthquakes or volcanic eruptions. It permits deployment of instruments in the field on a timetable that is not possible within the conventional PASSCAL structure. It is justified on the basis of the potential scientific return from studies of aftershocks of a significant earthquake or of other seismic sources, and represents a natural and responsible effort by the seismological community to address a societal need.

IRIS POLICY AND RESOURCES

The initiative for a RAMP must come from the scientific community. The decision on whether IRIS will support a RAMP is ultimately the decision of the IRIS president and will generally be made within 24 hours of a request for RAMP instruments. The decision will be based on the guidelines outlined in Appendix A. IRIS will provide the following services to scientists undertaking a RAMP.

A. IRIS has dedicated 10 6-component REF TEKs to this program at the present. RAMP instruments are expected to be at the instrument center when not in the field for a RAMP deployment, and are not considered as part of the general PASSCAL instrument pool during the normal PASSCAL scheduling process.

B. The level of IRIS support for a RAMP response will fall within one of three possible categories, depending on the significance of the event and the scientific potential of the opportunity.

- Large scale effort (>$100K) for an exceptional event such as Loma Prieta.
- Modest support ($10-30K) to support small arrays deployed for relatively short times.
- Loan of instruments only.

These levels of support include, at most, funds for data acquisition and processing to generate a data base suitable for submission to the DMC in a timely manner. Funds for scientific analysis of the data or for instrument loan on a long-term basis must be arranged separately. Given expected rates of seismicity and funding limitations, level 2 efforts might be supported 2-4 times/year, whereas level 1 efforts might be supported once every 2-5 years. Of course, there may be exceptions to these estimates, given the unpredictability of Mother Nature.

C. IRIS will be responsible for coordinating RAMP activities with other agencies such as NSF, USGS, NCEER, EERI, UNAVCO, SCEC, FEMA, CDMG. Policies pertaining to detailed coordination will be developed in conjunction with these agencies.

D. IRIS maintains the right to recall instruments lent either through RAMP or through the normal PASSCAL program in the case of an instrument shortage due to an important event occurring on the heels of another. IRIS hopes that the instrument pool will be large enough for this to rarely be necessary.

E. Additional resources provided by IRIS:

1. Training interested scientists on use of instrumentation. IRIS expects that PI's proposing a RAMP will have already undergone training and does not intend to routinely provide technical field support for RAMPS activities.

2. Maintaining current lists of trained instrument users and compatible instrumentation that might be available within the IRIS community .
3. Facilitating organization of regional planning groups (see III.A.).
4. Acting as an scientific information center during a RAMP response.
5. Developing and distributing software at the DMC for rapid processing of data from a RAMP.

OBLIGATIONS OF RAMP PARTICIPANTS

A. Initiation of a RAMP will generally be in response to a request from the scientific community. IRIS expects that individual groups interested in conducting a RAMP for a given event will communicate among themselves and develop a deployment plan before contacting IRIS. To facilitate this process IRIS will conduct workshops to organize regional interest groups and plan responses.

B. Participants are responsible for obtaining training on PASSCAL instruments prior to deployment.

C. Participants are responsible for obtaining necessary permission and/or official permits for deploying instruments.

D. Data collected during a RAMP must be submitted to the DMC within 6 months of the deployment. This deadline is shorter than that for a normal PASSCAL program (ie. 1 year) because of the timely nature of the data collected.

APPENDIX A: GUIDELINES AND PROCEDURES

Criteria for Supporting a RAMP

Level 1: A very important event because of magnitude, location, and/or social impact. (examples: Loma Prieta, New Madrid [1811])

Level 2: An important event with broad-based scientific interest (examples: Joshua Tree, Mendocino Triple Junction, Borah Peak)

Level 3: Events of significant scientific interest when other instruments are not available (examples: large man-made shots of opportunity, moderate-size regional earthquakes of significant scientific interest)

(note: Requests for instruments to support RAMPs outside of the US must also demonstrate advance preparation to assure customs clearance for the equipment and adequate access to deployment sites.)

How to Activate a RAMP

Call or send email to:
Jim Fowler
(505) 835-5072
jim@iris.edu
or
David Simpson
(202) 682-2220
simpson@iris.edu

IRIS
PASSCAL

www.passcal.nmt.edu

February 2008

IRIS