2 | PROGRAM FOR ARRAY SEISMIC STUDIES OF THE CONTINENTAL LITHOSPHERE

HISTORICAL CONTEXT OF CURRENT OPERATIONS

The Program for Array Seismic Studies of the Continental Lithosphere (PASSCAL) provides and supports a range of portable seismographic instrumentation and expertise to diverse scientific and educational communities. Two basic IRIS 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 U.S. research institutions. By integrating planning, logistical, instrumentation, and engineering services, and supporting these efforts with full-time professional staff, IRIS 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 U.S. seismologists, and on many occasions enabled IRIS to spur or augment international collaborations by providing significant instrumentation and engineering. Many of the standards and facilities pioneered by IRIS for instrumentation and data collection, archival, and open exchange have been adopted by permanent networks and other groups in the United States and by seismological networks and organizations worldwide. Other seismological and nonseismological data collection groups in the United States have embraced open data, and obligatory data archival requirements and standards have increasingly been stipulated by federal agencies. Internationally, many portable seismograph facilities have adopted similar models for their operations.

THE INSTRUMENT POOL

When IRIS was established in 1984, the goals for PASSCAL were to develop, acquire, and maintain a new generation of portable instruments for seismic studies of the crust and lithosphere, with an initial target of 6000 data-acquisition channels. During the first IRIS/NSF Cooperative Agreement, the primary emphasis was on the careful specification of the design goals, and instrument development and testing. Three technological developments between 1985 and 1995 were critical to the success of portable array seismology: the

Figure A2.1. Photo of the PASSCAL Instrumentation Center at New Mexico Tech in Socorro, NM.

Table A2.1. Inventory of equipment.

	PASSCAL	Polar	USArray FA	USArray TA	RAMP
Datalogger 3-channel	875	44	472	438	
Datalogger 6-channel					10
Datalogger 1-Channel	980		1699		
Broadband Sensor	525	44	346	459	
Intermediate-Period Sensor	142	6			10
Short-period sensor	10		111		
High-frequency geophone	772				
Accelerometer	10		20		10
Multi-channel	14				

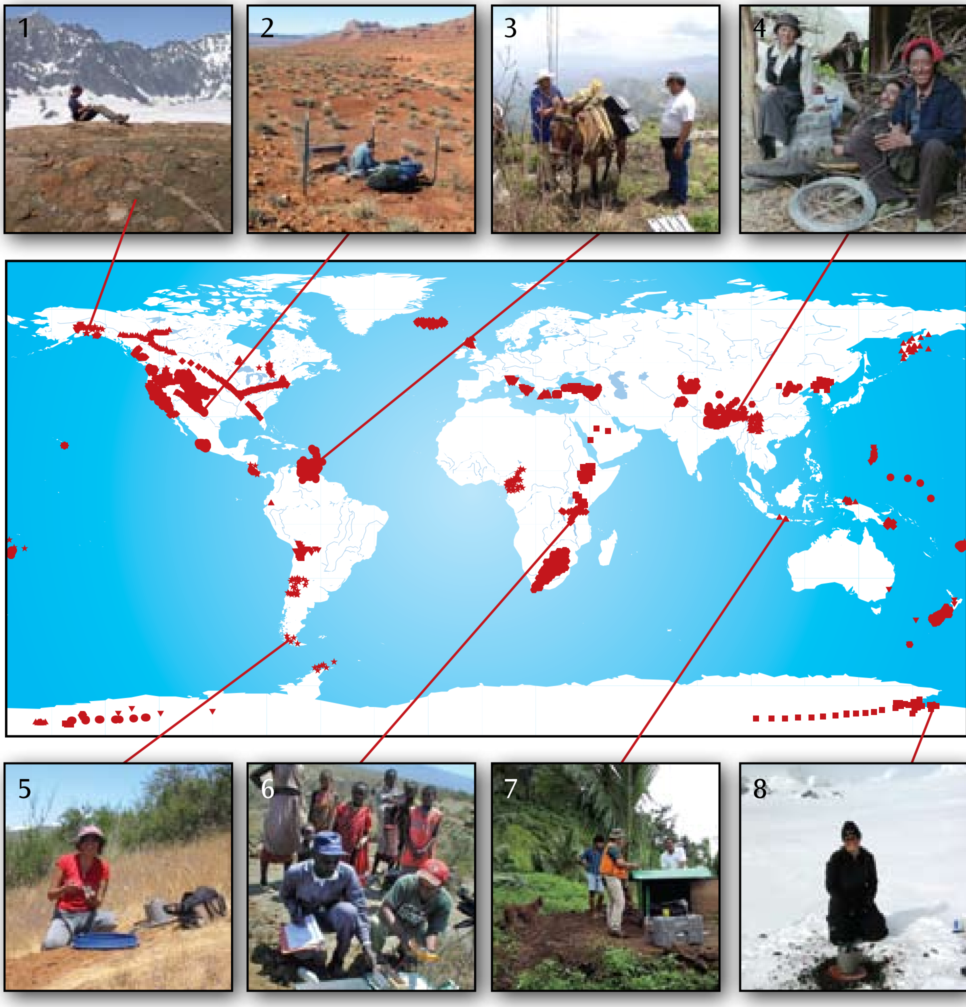


Figure A2.2. Global extent of station coverage for the history of the PASSCAL program, now totaling more than 3800 stations. PHOTOS. (1) Alaska. STEEP experiment. (2) La RISTRA, New Mexico. (3) Venezuela. Transporting gear the old fashioned way. (4) Tibet. Locals help with installation of a station. (5) Chile. Installing an intermediate period sensor. (6) Kenya. A short period station being serviced while local Masai look on. (7) Tiwi. Specialized enclosure for a rainy environment. (8) Mt. Erebus. An intermediate period sensor is installed directly onto the bedrock flanking the volcano.

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 systems grew by 1995 to a pool of more than 100 broadband instruments that were used primarily in passive-source experiments.

Design of instruments to support controlled-source experiments and rapid deployment for earthquake aftershock studies began in 1991, and by 1995 almost 300 of these instruments were available. The instruments used in controlled-source experiments also included 200 seismic group recorders (SGRs) donated by AMOCO and reconditioned for crustal studies. A new generation of active-source instruments, "Texans," were developed by a corporate-university partnership in Texas with funds the Texas state government. Procurement of Texans began in 1999, and the SGRs were retired over three years.

Starting in 2002, the Department of Energy provided funds to replace the original data acquisition systems, which were becoming aged and failure prone, with modern systems. The new systems incorporate the latest technologies from the computer industry. Consequently, they require much less power, have higher recording capacities 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 TCP/IP nodes. All of the older recorders have now been retired from use in temporary deployments.

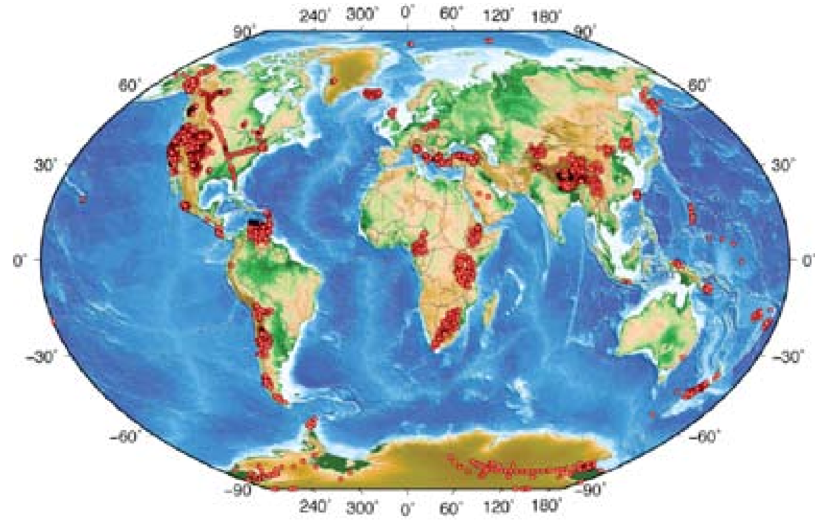
The next few years promise to be equally exciting. By the end of this Cooperative Agreement, we anticipate that there will be designs and prototypes for a whole new generation of data recorders and sensors that will be smaller, lower power, and capable of operating in extreme environments for extended time periods. Communication technology is changing so fast that the ability to connect to the Internet from any location may truly exist.

THE INSTRUMENT CENTER

The initial portable IRIS instruments were maintained at the first PASSCAL Instrument Center (PIC) at Lamont-Doherty Earth Observatory, which focused on the broadband sensors used primarily in passive-source experiments. 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. In 1998, the instrument centers merged and moved to the current location at the New Mexico Institute of Mining and Technology in Socorro, NM. The consolidation achieved greater technological synergy and coordination within the facility, cost savings from operating a single instrument center, and greater operational space thanks to construction of a new, custom-designed facility, with 7500 sq. ft. of office and lab space and 20,000 sq. ft. of warehouse space. The building was designed by the PASSCAL technical staff and New Mexico Tech to optimize PIC operations, but 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.

A major enhancement to U.S. seismological resources and increased activities began in 2003 with the start of EarthScope, including the seismological component, USArray, which is operated by IRIS. Although funded separately, the USArray Array Operations Facility (AOF) and the Transportable Array Coordinating Office (TACO) are both located at the PIC in Socorro. The AOF, which supports the operation of both the Flexible Array and the Transportable Array, shares personnel and logistic support with PASSCAL, leading to significant leveraging and efficiencies for both programs. TACO is staffed and operated as an independent USArray unit that is responsible for the specialized logistic and siting activities required for TA. Again, at State of New Mexico expense, the PIC complex was expanded to accommodate USArray operations, adding 11,000 sq. ft. of office and lab space.

The staff and facility at the PIC provide the equipment, technical support, and training necessary for the seismic research community to conduct field experiments to gather the data necessary to do their research. Approximately 60 new experiments are supported every year, each of which may include training for investigators and students, shipping and other logistical support, field engineers and other technical support during the deployment, and data download and archiving services.



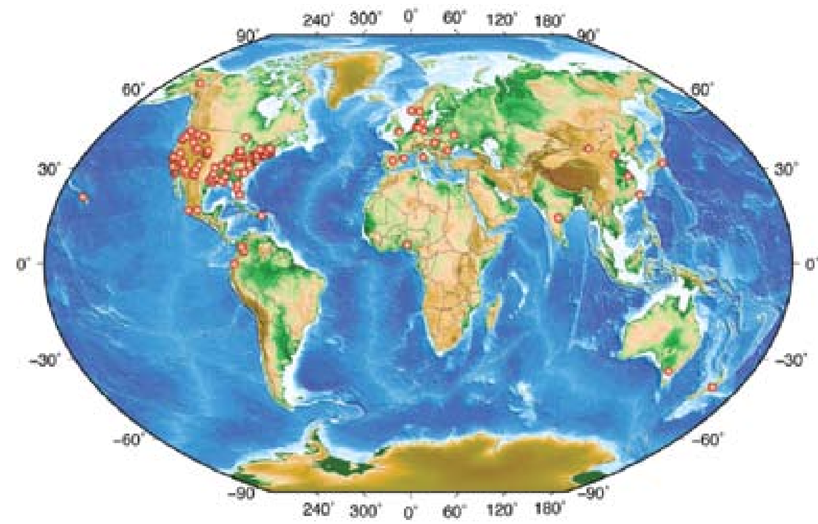


Figure A2.3. (top) Maps of all PASSCAL stations. (bottom) Map of institutions supported by PASSCAL.

DEVELOPMENTS UNDER THE CURRENT COOPERATIVE AGREEMENT

Thus far during the current Cooperative Agreement, the PIC has supported 302 experiments, an average of 65 experiments each year. Broadband experiments account for one-third of this total, and there have been 75 short-period experiments using passive sources, 51 controlled-source Texan (single-channel) experiments, and 77 high-resolution studies using multichannel cable systems. Of the high-resolution experiments, 33 have been for classroom demonstrations and teaching. The typical number of stations per broadband deployment has steadily increased, with many experiments exceeding 50, and several using more than 75. Although each deployment is motivated by a specific research goal, the combined effect of multiple experiments around the world is to provide a temporary, spatially dense augmentation to the coverage provided by networks, allowing global and regional tomographers to enhance resolution. At the request of this community, one station in each experiment is now designated as "open," meaning that the typical two-year data embargo does not apply.

To ensure that investigators can continue executing a broad range of experiment types efficiently and at the cutting edge, under the current Cooperative Agreement, PASSCAL has continued development in experiment support services in four areas:

- Increased reliability of all equipment used in experiments
- Improved facilities for data archiving support
- Expanded experiment support services
- Specialized support for extreme environments, including polar regions

INCREASED EQUIPMENT RELIABILITY

Equipment for Passive Recording

Instruments now provided for passive experiments include modern data loggers, typically coupled with broadband, intermediate, or short-period sensors. In addition to lower power, these data loggers are proving more reliable, which translates into more uptime and hence more data. They also have better GPS timing, ensuring that the data collected are of better quality than the equipment used through 2004. Most stations are away from commercial power or communications, and rely on solar-power systems and local disks to record data. Advances in electronics and on-site storage have lowered station power requirements to less than 1 W for a passive sensor and less than 2 W for an active sensor installation.

Equipment for Controlled-Source Experiments

The single-channel rapid-deployment REF TEK 125 Texan are used to observe signals from man-made energy sources, such as explosions, airguns, and vibrators. The community draws on a combined pool of nearly 1000 Texans, including 550 maintained at the PIC and others maintained at the University of Texas at El Paso under a Cooperative Agreement with IRIS. There are 1700 additional Texans available in the USArray Flexible Array pool. The Flexible Array pool of Texans introduced a new generation of instruments with greater on-board storage and a modern (USB) communications interface. To unify the PASSCAL and Flexible Array Texan pools and to optimize the combining of the two pools for large, crustal imaging experiments, the PASSCAL Texans were upgraded under the current Cooperative Agreement.

Multichannel equipment has been used very effectively for crustal imaging and a number of shallow studies, including fault zones, aquifers, glaciers, and hazardous waste sites, as well as extensively for training and education in undergraduate classrooms and field labs. These commercial systems are designed for high-resolution seismic reflection and refraction experiments, including geotechnical applications and shallow petroleum exploration. The PASSCAL equipment consists of four 60-channel Geometrics Stratavisor instruments, and ten 24-channel Geometrics Geodes acquired during this Cooperative Agreement. PASSCAL owns three sets of sensor cables for this system: one is used for high-resolution shallow studies; a second, with longer station spacing and lower-frequency geophones, is used in basin and crustal studies; and a third is a snow streamer used on glaciers, ice shelves, ice caps, and sea ice.

Telemetry

Recent advances in cell modem technologies simplified telemetry for seismic stations compared to spread-spectrum radios to

Figure A2.4. (left) Completed PIC external sensor vault building. (right) Crane lowering granite slab into place on one of the two piers during construction. *Photos provided by Bruce Beaudoin.*

transmit data to a central data concentrator used in broadband seismic experiments in the past. Leveraging USArray experience, these modem systems have been integrated throughout the instrument pool. For high-latitude and/or remote regions where cellular modems are not an option, PASSCAL has developed a low-power, Iridium modem system for state-of-health (SOH) and command and control. Newer Iridium modems are now being developed that will permit flexible data transmission, up to 10 sps continuously.

Figure A2.5. 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.

Station Power

Stand-alone power systems, which are critical in most portable stations and are a frequent point of failure, typically consist of sealed lead acid (SLA) batteries, solar panels, and the associated electronics. Recently, air cells have been successfully deployed where insulation is marginal. For extreme conditions such as low temperatures, where SLAs and air cells lose capacity, use of lithium thionyl chloride batteries have made year-round station operation possible. Charge controllers have been engineered specifically for extreme conditions and are in use in the Antarctic. This new technology is also being used in a new generation power system for the PASSCAL pool of instruments.

Power failures continue to be one of the most common reasons for station failure. Leveraging development from PASSCAL's Polar effort, the PIC designed and is fabricating a new generation of power boxes under the current Cooperative Agreement. These new power boxes, along with the PIC's continuous refinement of field methods, ensure that stations operate continuously throughout deployments and that the data collected are of the highest quality possible.

Equipment Maintenance and Service

PASSCAL initiated development of a new maintenance database during the current Cooperative Agreement. About 15% of the sensors need attention beyond testing between deployments in harsh field conditions. Usually, these repairs are done in house by specialized factory-trained staff. Data loggers returning from the field are also tested, and routine maintenance performed. Board-level repairs are made at the PIC, if required. The new maintenance database is critical for maintaining highly specialized equipment, and provides historical metrics on hardware performance and maintenance efficacy.

Staff Training

The PIC has developed an in-house capability to completely strip and rebuild sensors, which is unique to the community and is based on multiple visits to manufacturers for intensive training. These repairs are paramount to meeting the strong demand from the community to optimize the scheduling of broadband sensors. Turnaround time for repairs from manufacturers can range from months to years, further emphasizing the need for the PIC to provide this service.

Pier Facilities

To satisfy the need for additional pier space associated with USArray and to establish a quieter pier, USArray funding was used to construct an external DC-powered facility with two new piers. Each pier is topped by a 10" thick granodiorite slab installed on lead plugs for coherence across pier positions. In addition to doubling the capacity to test broadband sensors, the new vault has enhanced thermal and airflow stability.

IMPROVED DATA ARCHIVING

Data Archiving Support

A critical part of the archiving process is verification of data volumes prior to shipping to the DMC. PIC refined and expanded the in-house developed, automated system that provides this service. The in-house QC system is designed to catch the most common errors and present the data flow from the PI through the PIC to the DMC in a browseable interface. Prior to, during, and following an experiment, PIC staff members work with the PI to develop correct metadata and

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.

to use essential quality-control and processing tools. During passive experiments, staff members receive and verify preliminary SEED data, working closely with the PI to assure data and metadata completeness, accuracy, and quality. Verified SEED datasets from passive experiments are forwarded for archiving as soon as possible, usually soon after they are collected from the field. Active-source data are normally collated and verified following the experiment, and soon after they are archived in HDF5 format.

New Paradigm for Archiving Controlled-Source Data

SEG-Y—the format historically used to archive data from controlled-source experiments—is cumbersome and inefficient. Data in that format require a time-consuming complete rework of a data volume if corrections, additions, and recalibrations need to be made. It is costly to reprocess and re-archive those data. To reduce these inefficiencies, PASSCAL developed an archival processing package—PIC KITCHEN—that organizes data and metadata for an experiment into HDF5 format, decoupling the metadata from the seismic waveforms. Future or last-minute updates, corrections, or additions can thus be folded into small text files, sent, and incorporated with the original data. This process permits data to be archived promptly, ensuring more complete and efficient data archiving. A complementary process extracts raw data and metadata from the HDF5 file and converts them to the format requested by users.

EXPANDED EXPERIMENT SUPPORT SERVICES

The support that PIC provides is essential to the overall success of user experiments. PASSCAL support has evolved through time in response to changing experiment methodologies and technological advances, with a continuing emphasis on improving data return and finding more efficient methods of operation. Support is provided through all phases—before, during, and after an experiment—and is generally grouped into equipment support, logistics support, user training, experiment support, software support, and data archiving support.

Intern Training

Since 2007, PIC and New Mexico Tech have hosted the IRIS Undergraduate Summer Internship Program orientation. NSF REU-supported students from around the United States gain hands-on experience in seismological science, instrumentation, and professional development during this one-week program, then disperse to IRIS institutions for summer research. This program supplements the summer graduate internship that PIC has been hosting, where the intern works with the staff on new developments and assists users and staff in the field.

User Training

To ensure the highest rate of success and to reduce damage to seismic equipment in the field, users are trained on instrument best use and care. With the launch of the new PASSCAL web site, many of the training documents and "How-To's" are now available online. In addition to these electronic documents, PASSCAL produces several trifold field references for users. All PIs visit the PIC for experiment planning sessions and instrument training. Experiment planning sessions ensure that staff are cognizant of project goals and thus can help optimize equipment use.

PASSCAL staff recently organized several training sessions on data handling both at the PIC and aligned with the fall meeting of the American Geophysical Union. Sessions have been well received and attended.

Logistics Support

PIC has created a specialized position of International Logistics Coordinator to handle all import and export arrangements for foreign shipments. The professionalization of this service and availability of a comprehensive facility with specialized shipping documentation have led to a diversified and in-depth understanding of import/export procedures and international transport and insurance requirements. Since this service was established, 100% of foreign PASSCAL experiments have opted to rely on PIC shipping, which is also available for domestic experiments.

Experiment Support

For all experiments, PASSCAL personnel assist PIs to solve technical problems, including repairing instruments on site, troubleshooting problems remotely via telephone and email, and arranging shipments of replacement equipment. In passive-source experiments, PASSCAL personnel typically 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 members 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 members 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

In addition to developing a new method for archiving controlled-source data (see above) the PIC has developed new and improved existing inward- and outward-facing software during the current Cooperative Agreement. Improvements to field software tools have enhanced the user's ability to quickly and efficiently review station status, aiding the evaluation of station performance in the field. A web-based instrument-scheduling database greatly simplifies the complexities of efficiently scheduling 60+ new experiments each year and affords a dynamic schedule to keep the community apprised of instrument availability. These new tools are now part of the larger PASSCAL software suite that consists of programs written over the last two decades by PASSCAL staff and the wider community. The primary functions of PASSCAL software are to assist with collecting data, performing quality control on the data, and transforming data into optimal formats for analysis and archiving. The software is primarily designed to support data loggers provided by the PIC, but has been adopted by many international institutions. 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.

Data Archiving Support

A critical part of the archiving process is verification of data volumes prior to shipping to the DMC. PIC refined and expanded the in-house developed, automated system that provides this service. The in-house QC system is designed to catch the most common errors and present the data flow from the PI through the PIC to the DMC in a browseable interface. Prior to, during, and following experiment, PIC staff members work with the PI to develop correct metadata and to use essential quality-control and processing tools. During passive experiments, staff members receive and verify preliminary SEED data, working closely with the PI to assure data and metadata completeness, accuracy, and quality. Verified SEED datasets from passive experiments are forwarded for archiving as soon as possible, usually soon after they are collected from the field. Active-source data are normally collated and verified following the experiment, and soon after they are archived in HDF5 format.

SPECIALIZED SUPPORT FOR EXTREME ENVIRONMENTS, INCLUDING POLAR REGIONS

In 2006, IRIS and UNAVCO received NSF Major Research Instrumentation (MRI) program funds from the Office of Polar Programs (OPP) to develop power and communications systems that would enable portable seismic and GPS stations to operate in the Antarctic through the austral winter. Based on the results of this work, additional MRI funds were received to construct about 40 broadband seismic stations that could operate for two years without being serviced. These stations are deployed as part of the POLENET (Polar Earth Observing Network) and AGAP (Antarctica's Gamburtsev Province) experiments. Despite being deployed in areas where the ambient temperature reached -80°C, a data return in excess of 90% was achieved.

With these development and acquisition MRI awards, IRIS leveraged PIC expertise to design and develop smaller, lighter, and more robust observatory platforms that have greatly improved science opportunities and data return from the most remote and extreme parts of the Arctic and Antarctic. The activities of IRIS's Polar Services group are described

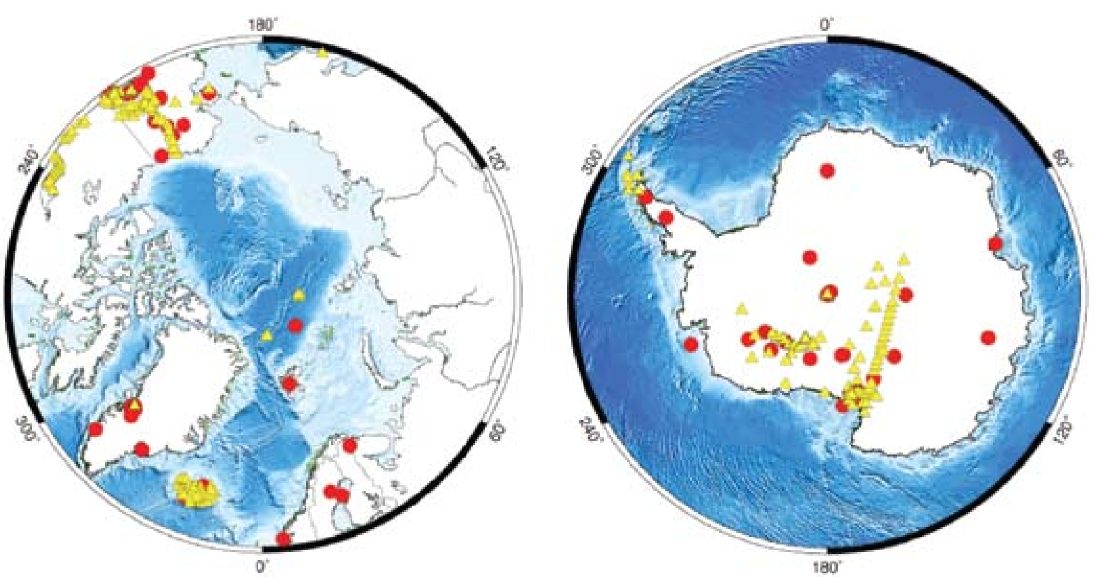


Figure A2.6. Locations of PASSCAL polar experiments.

separately in this proposal, but it is worth noting here that the experience and expertise of PIC staff were essential to the initial effort and, with funding from OPP and additional facilities constructed by New Mexico Tech, the Polar Services group can continue to provide additional needed to support these challenging deployments without taking resources from other projects, without inefficiencies that would arise from a operating an independent facility, and simultaneously introducing new capabilities for operating in extreme environments that can benefit PASSCAL and USArray deployments worldwide.

NEW OPPORTUNITIES AND DIRECTIONS

NEXT GENERATION OF EQUIPMENT FOR EXISTING AND NEW PASSCAL USERS

PASSCAL has benefitted tremendously from advances in technology during its first 25 years. Especially notable examples include advances in storage, GPS timing, and portable broadband seismometers. At present, most PASSCAL systems (some active-source configurations excepted) are highly evolved versions of the original prescient IRIS concept of a stand-alone (occasionally telemetered) data logger attached to a stand-alone sensor. Such systems have anchored outstanding science in deployments of tens to several hundred instruments, and have recently been adapted for polar and other especially challenging environments.

However, scientific results highlighting the remarkable heterogeneity of the deep Earth, and fundamental resolution limits of teleseismic imaging (incorporating wavelengths of several kilometers and longer; 1 s and longer periods), indicate that tighter spacing of recorders and deployments in greater numbers will drive further advances in imaging and understanding processes at the lithosphere and mantle scale. For example, such an experiment in a tectonic region of special interest might consist of a two-dimensional 100 x 100 array of seismographs deployed at a spacing of 5 km. When recording in an aftershock, volcano, glacial, or other microseismicity zone, similar large-array motivations apply to approach unaliased spatial sampling of the seismic wavefield over desirable areas, although the frequencies and station spacing density would be commensurately higher.

Deployment of 10,000 stations using present technology is far beyond current reasonable cost and manpower resource limits. To approach such an experiments requires new deployment strategies and a new generation of miniaturized equipment that can be installed and recovered very quickly, yet that can usefully approach the response, recording, reliability, and other state-of-the-art characteristics of present PASSCAL instrumentation. A key component of such efforts would be a rapidly deployable micro-electro-mechanical systems (MEMS) accelerometer/seismometer-based system that would usefully extend into the body wave band (e.g., to 15 s period) with self-noise approaching the Peterson low-noise curve (e.g., on the order of 1 nano-g/Hz or better out to 10 s). This noise level is approximately 100 times quieter than many currently available microsensors (see Merchant, 2009, available at http://www.iris.edu/hq/instrumentation_meeting/files/pdfs/MEMS_Seismology.pdf), but appears to be approachable with further engineering (e.g., incorporating larger masses than are currently used in such devices and/or averaging over many sensors with statistically independent noise). The handling of data from such large arrays of seismographs will require additional levels of metadata surety and other archive-ready data handling features. Advances in digitizer and GPS hardware should facilitate much smaller digitizer and timing modules, and advances in lithium ion batteries should greatly reduce the size and weight of the power system. Ultimately, a next-generation station should strive to be integrated into a single miniaturized and environmentally secure package that is rapidly deployed in recording mode, and establishes its geographic and instrument metadata upon installation. Such stations, even if not as broadband as current broadband stations, might be very usefully deployed in hybrid arrays, where the vast majority of the stations are intermediate and/or short period, but are embedded in a relatively sparse (e.g., USArray Transportable Array-scale) broadband network that incorporates direct burial, lithium battery, and other efficiency improvements over current installations. Such a hybrid array would thus allow multiscale imaging and otherwise utilize the full range of useful seismic bandwidth. Real-time telemetry for such large networks using current protocols would probably require much lower costs per station than current (e.g., cellular modem) rates. At small scales, self-configuring Wi-Fi network capabilities might make telemetry of even large networks that generate archive-ready data in near-real time technically and financially feasible. Such a telemetered system might also be inexpensive enough to spur novel deployments in especially hazardous environments (e.g., volcano and glacier settings) where 100% recovery of instruments is not possible.

These sensor and electronic technologies and standards are very rapidly evolving and now appear to be at or beyond the requirements necessary for some PASSCAL science (e.g., Flexi-Ramp). Under the newly established Instrumentation Services, IRIS, along with industry, government (e.g., national laboratory), and university partners, plan to proactively pursue the development of miniaturized, low-power systems. This pan-IRIS undertaking hopefully will drive the development of the next generation of seismological equipment for a range of environments. We propose to consolidate this effort with a dedicated engineer to test available equipment, develop complete integrated systems, and interact and motivate PASSCAL-appropriate development within the public and private sectors.

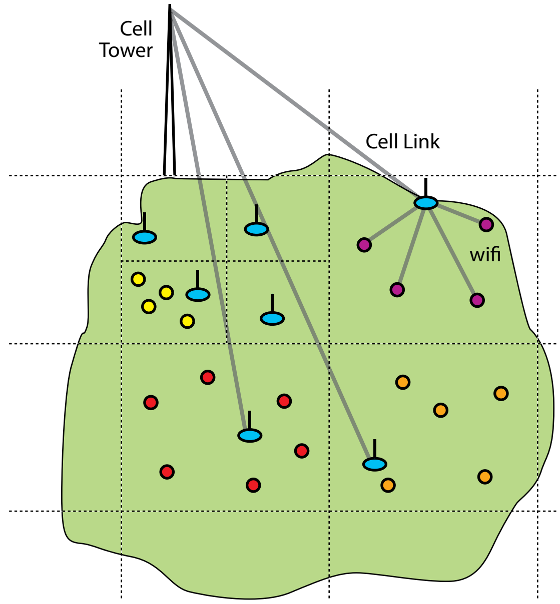


Figure A2.7.

A FLEXIBLE ARRAY FOR RAPID ARRAY MOBILIZATION PROGRAM (FLEXI-RAMP)

Objectives

As the recent earthquakes in Baja, Haiti, and Chile demonstrate, a large earthquake is followed by strong aftershocks, with the largest being one or two magnitude units less than the main shock. If a large network of seismic stations can be installed rapidly in the main shock region, we could capture large events at much greater resolution than has been previously possible with permanent networks. Seismic waves lose spatial coherence after a station separation greater than a wavelength. To capture correlated high-frequency radiation from the largest aftershocks requires much smaller spacing than previously achieved (e.g., <1 km for >3 Hz). FlexiRAMP is intended to provide such a pool for aftershock deployment while also making use of the equipment between big earthquakes.

FlexiRAMP's goal is to install an order-of-magnitude more stations (500–1000) in an aftershock zone for high-resolution measurements. The stations are required to be of sufficiently simple design that they can be installed rapidly and capture the largest aftershocks, the probability of which decays rapidly after the event. Rather than leaving all of the equipment in a warehouse between major earthquake-aftershock sequences, a fraction (perhaps 75%) of the equipment will be used in flexible array mode (i.e., in temporary deployments in earthquake regions). Users could investigate local targets such as magma chambers, structural geology, trapping, scattering and focusing of seismic waves, and harmonic tremor. However, loan of the equipment would be contingent on an agreement to demobilize at the time of a large event and contribute to the RAMP pool. The advantage of this approach is that: (1) expensive equipment is being used for scientific discovery, (2) a pool of qualified operators maintains proficiency with the equipment for rapid deployments after a large event, and (3) more sensors will likely capture a main event while installed elsewhere.

The specifications for FlexiRAMP have been developed at two workshops, one at the IRIS workshop in 2008, and a second sponsored by IRIS at the Seismological Society of America meeting in 2009. We propose a hierarchical array with stations that complement, but do not duplicate, the present broadband pool. Some of the broadband pool should also be installed, as was recently accomplished in Chile. But, for rapid installation, simpler intermediate-period systems are needed with telemetry for rapid event association. It will be necessary to measure both weak and strong motions, requiring sensors with a dynamic range of 10^{-10} g to 2 g, or combinations of strong and weak motion sensors, or emerging technologies. The FlexiRAMP unit should be able to survive on batteries for one week, and on small solar panels indefinitely. It should have wireless and/or cellular communication, technologies that are rapidly advancing.

Table A2.2. Summary of specifications for FlexiRAMP units

Seismometers	Nano g to g at intermediate periods.
DAS	6 channels 24 bit A/D, < 0.5 W, Wireless/GPRS capability, GPS, 200 sps up to 1000 sps, On board data storage for full experiment (GB)
Battery	Lead acid or lithium 10 Amp Hr
Software	Event detect, duty cycle RF, meshed networking, array event detect, real-time warning capability
Design	Single unit with MEMS/wireless/GPS on board and seismometer, solar panel, antenna attached. Plug-and-play components for easy maintenance. Simplicity in installation and networking essential (e.g., throw out of the back of a truck). Lightweight-small form-factor (e.g., Texan size).

EXPANDED GEOPHYSICAL INSTRUMENTATION

PASSCAL instrumentation has traditionally been limited to seismometers for recording the wave field, and has not included electromagnetic imaging and seismic sources. However, the purchase and support of small seismic sources and electromagnetic imaging systems would serve and expand the IRIS community in three ways: (1) encourage more shallow seismic work by removing the hurdle of obtaining a seismic source and integrating it with the PASSCAL recording systems, (2) increase the effectiveness of shallow imaging and characterization by providing complementary electromagnetic imaging equipment, and (3) foster ties with the hydrology community, which uses both shallow seismic and electromagnetic imaging systems.

Making seismic sources available to the IRIS community through PASSCAL will provide "one-stop" shopping in which an investigator can borrow a complete seismic system suitable for shallow imaging. This setup will remove one of the main barriers to widespread use of the multichannel seismic recording systems (Geodes), specifically the separate rental and subsequent interfacing of a seismic source with the PASSCAL recording systems. PASSCAL seismic sources would also be a large contribution to the educational use of the PASSCAL equipment, in that it would make it easy for a researcher to image to several hundred meters depth rather than to simply conduct a small-hammer seismic demonstration. The intent is to start with a small purchase—a small weight drop system and radio trigger system—and potentially expand as demand warrants. A weight drop system and radio triggers are being purchased during the final year of the current Cooperative Agreement.

For larger seismic sources, mini-vibrators and full-size vibrators are already available for rental from a variety of government and industry sources. PASSCAL at this point does not intend to commit to purchase or maintenance of these vibrators, but a staff member at the PIC will be charged with keeping abreast of availability and operations of these sources so that PASSCAL can advise the community. PASSCAL also plans to put in place cooperative agreements for mini-vibrators to ease their use within the IRIS community. For explosives sources, IRIS is supporting creation of an Explosives Sources Center as proposed to NSF by the University of Texas and New Mexico Tech.

Moving beyond the modest, initial purchases under the current Cooperative Agreement, a number of items that are beyond the scope of the normal PASSCAL budget and merit additional funding include:

1. Staff time (0.5 FTE) to assist researchers in selecting seismic sources (vibrators, weight drops) for a study, advise on permitting, and helping integrate the seismic sources with the PASSCAL acquisition system. This person would be familiar with available seismic source and with permitting issues (but will NOT carry out the permitting) and, if needed, would be available at the start of active-source seismic experiments that use vibrator sources to advise or be in the field. This person could also negotiate contracts with operators of vibrators to make them more readily available to the IRIS community, and would help maintain and service the additional electromagnetic equipment.
2. The demand for the PASSCAL Geode recording systems is already substantial, and is expected to increase with the availability of PASSCAL seismic sources and the long-term trend of increasing interest in shallow imaging. To maintain the capability of supporting shallow seismic imaging within the research community, the PASSCAL pool of Geode recording systems should be doubled from the current 240 channels to 480 channels. Accommodating these extra Geode channels at the PIC will require an additional 0.5 FTE to deal with maintenance and servicing of more shallow seismic experiments. Additional computers and other miscellaneous equipment will also be needed to support the extra recording channels.
3. To make full 3D imaging of shallow targets possible, PASSCAL soon should bring their total number of Geode recording channels to 1000. Again, these additional recording channels will require more staff time (0.5 FTE), and accessory equipment such as more radio triggers and recording computers.
4. The purchase of ground-penetrating radar (GPR), and conductivity and magnetics instruments, will be useful complements to shallow seismic imaging. In particular, GPR is a method that involves data acquisition and processing similar to shallow seismic imaging, and provides different information about shallow subsurface materials. Conductivity and magnetic mapping permit rapid extrapolation of shallow seismic or GPR surveys in three dimensions. This equipment is widely used in groundwater, glaciology, archeological, and hazard surveys, and will serve to bring scientists in those areas of research into the IRIS community.

The additional Geode channels proposed here reflect the increasing interest in shallow, 3D imaging of contaminant plumes, aquifers, ice sheets, and active faults. The additional capabilities these instruments provide have the potential to increase and improve research in topics important to society, specifically global climate change, water resources, and hazard studies.

INTEGRATED DATA SUPPORT

PIC-supported experiments record data from either passive sources (e.g., earthquakes, ambient noise, and icequakes) or controlled sources (e.g., weight drop, explosion, and vibrator). These data are archived with the IRIS DMC in SEED (passive source) or PH5 (active source) formats. Data from both PASSCAL and EarthScope's USArray Flexible Array experiments comprise over 5 TB of archived data per year. Roughly two-thirds of all data collected with PASSCAL and Flexible Array equipment is from non-EarthScope-funded experiments.

PIC currently provides two levels of data support, one for PASSCAL experiments and one for Earthscope-funded experiments (Figure A2.8). The main difference between these two support levels is that for core PASSCAL experiments, the creation of an archive-ready dataset is the PI's responsibility, whereas for a USArray Flexible Array experiment, PIC staff members create the archive-ready dataset. All archive-ready data are transferred to PIC for QA prior to shipment to the DMC.

The IRIS community has requested the same higher level of support for all experiments that EarthScope-funded experiments currently enjoy. The most compelling arguments for this change are freeing graduate students from the onus of archiving data so that they can focus on research, and improving overall data quality. To effectively integrate data services for both PASSCAL and Earthscope-funded experiments without significantly increasing PIC staff will require minimizing the necessary user support time and reducing manual data handling. In addition to the above advantages, moving data archiving to PASSCAL will provide consistent data services regardless of instrument pool, help remove the ambiguity of what service will be provided when borrowing across pools occurs, and will afford the opportunity to run uniform metrics on all PIC-supported experiment data.

We propose a development effort to streamline data-handling operations so that the same, higher level of support can be provided to all experiments by the time that PASSCAL and EarthScope operations are integrated. For both PASSCAL and EarthScope experiments, the majority of user support time is spent clarifying metadata and instructing users on data manipulation. To minimize this effort, tools need to be developed that will aid the user to consistently capture accurate metadata in the field and that will correctly format raw data recorded on the datalogger to archive-ready data on offload. Both of these efforts are software based and will incur moderate risk. The greatest risks are functional: Can we develop a system that will guide users through the offload process while minimizing user error? Will the increased CPU time required to create archive-ready data be insignificant? And finally, can software mitigate current user support levels?

Localizing all of the data handling from a distributed PI computing network (roughly 40 PASSCAL experiments archiving data each year) to the PIC will require new hardware for computing and data storage. At a minimum, PIC will require a dedicated server for data handling, and a large enough RAID array to store data until they are confirmed as archived at the DMC. We will also require a redundant RAID data storage unit to ensure that no data are lost once loaded on PASSCAL's system. PIC will not maintain a permanent archive of raw or processed data, but will require an on-site backup to ensure efficient recovery if a system fails.

Migrating all EarthScope and PASSCAL experiment data archiving to the PIC will require both new development and maintenance of current and existing systems. We anticipate both field and lab tools will need to be developed and maintained to ensure accurate metadata and to automate tasks that are now done manually by the PI. Maintenance of the current in-house data-delivery system and additions to PIC infrastructure will also require support. An integral part of a new field system will be a dataless generator. This task is nontrivial and will, in part, be contracted to a developer that has successfully integrated a dataless generator in other applications.

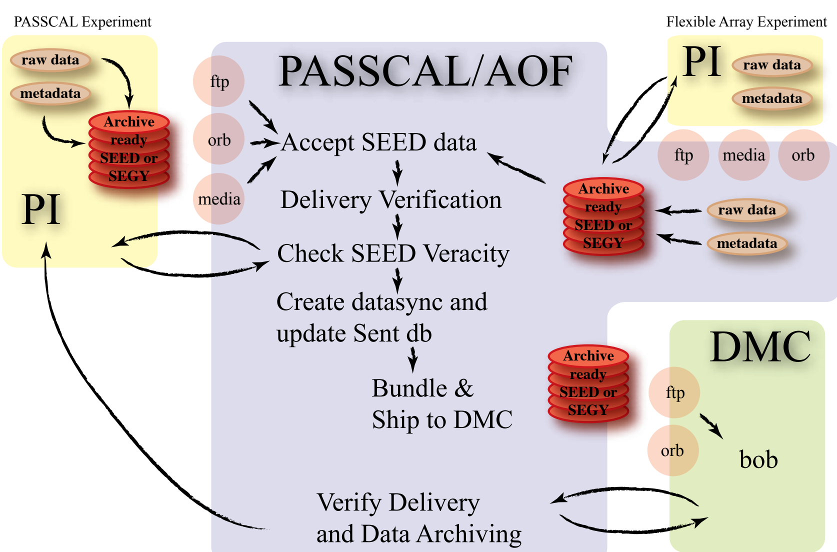


Figure A2.8. Figure showing the difference between PASSCAL and Flexible Array data archiving support. For PASSCAL experiments (left) the PI builds the data archive from the raw data and then ships the archive to the PIC for verification. For Flexible Array experiments (right) the PI is only responsible for providing the PIC with raw data and metadata; the PIC builds the archive.

POLAR AND CRYOSPHERE

Over the past decade, increasing PASSCAL involvement in support of polar research has led to the development of a specialized Polar Support Services group described elsewhere in this proposal. The initial PASSCAL polar efforts focused primarily on support of seismic studies of the crust and lithosphere in Antarctica, but there has been expanded use of PASSCAL resources to support seismic investigations of glaciers and other ice-related processes in both polar regions. Seismic deployments in the study of cryospheric change must cope with the dichotomy of glacial and polar environments: ice and snow are accumulated in high-altitude/latitude, extreme cold conditions, but ice discharge via melting and iceberg calving is focused in extremely wet, unstable marine environments. PASSCAL's approach to coping with these environmental challenges is to adopt a proactive, "get in front of the community" stance in the development of instrumentation, deployment techniques, logistical efficiencies, and data telemetry that address the problems of Earth's icy environments, from the cold, power-starved environments of Antarctica and Greenland, to the challenges of wet, surface-wasting ice-terrains found on mountain glaciers, collapsing ice shelves, and ablating ice sheets.

Specific goals embodied in PASSCAL's support of polar research over the coming period are: (1) assist in the establishment of permanent reference networks in Greenland and Antarctica (particularly focusing on the future legacy of GLISN, POLENET, and AGAP); (2) continue development and support of a "summit to calving margin" sensor deployment capability to support glaciological research in the wet (and corrosive, if atop active volcano) ablating environments of Greenland outlet glaciers and wasting alpine and tidewater glaciers; (3) assess new telemetry technologies for improving bandwidth and power costs in high-latitude and other challenging environments; (4) continue improvement of power systems designed to function reliably and cheaply in extreme cold, wet, or dark environments; and (5) continue support of active seismological experiments designed to establish geophysical parameters necessary for glaciological modeling (e.g., measurements of sub-ice-shelf ocean bathymetry and subglacial lake geometry).

The key outcome expected from the investment of intellectual and material resources in PASSCAL's support of polar, high-altitude/latitude and wet-ablation zone seismology will directly influence the understanding of changing polar environments and, ultimately, global sea level.