New instrumentation drives discovery of the earth's deep interior

THOMAS J. OWENS, University of South Carolina, Columbia, U.S.
JAMES FOWLER, Incorporated Research Institutions for Seismology, Socorro, New Mexico, U.S.

Since the observations of the first instrumentally recorded earthquake in the late 1800s, the discovery and documentation of the mysteries of the earth's deep interior and earthquake rupture processes have proceeded hand-in-hand with improvements in instrumentation and data exchange. The pioneering discoverers in the first half-century of instrumental seismology were those scientists fortunate enough to have a seismograph at their institute. The excitement of observing a distant earthquake as its energy was recorded was a powerful catalyst for curiosity-driven studies of the deep earth. The results were dramatic. Within about a decade of recording the first seismogram, the gross internal structure of the earth (crust, mantle, core) was established and geoscientists began to ponder the evolution of the earth from the perspective of these new discoveries. Forty years ago, the Cold War and the need to discriminate underground nuclear explosions from the background of natural earthquakes spawned the second revolution in whole earth seismology with the installation of the World Wide Standardized Seismograph Network and a more centralized archiving approach that facilitated effective data exchange. The WWSSN immediately contributed to another revolution in geoscientific thought: plate tectonics. Its 20-plus year archive of seismograms continues to contribute to new discoveries about the earth, such as the differential rotation of the inner core.

One hundred years after the first wiggly line hit paper, we are in the midst of discovery spawned by a third revolution in seismic instrumentation. It began in the mid-1980s when IRIS (The Incorporated Research Institutions for Seismology; *www.iris.edu*) was established by the United States' university community and the U.S. National Science Foundation to modernize seismic instrumentation to address outstanding problems on a wide spectrum of scales. In addition to installation and operation of new instrumentation, a key component of the present revolution is in data delivery capabilities as current and emerging technologies allow us to deliver seismological data to an individual's desktop from almost anywhere on the planet in near-real time. Core IRIS facilities for instrumentation and data delivery include The Global Seismic Network (GSN), The Program for Array Seismic Studies of the Continental Lithosphere (PASSCAL), and the Data Management System (DMS).

DMS operates the Data Management Center (DMC) at the University of Washington in Seattle. This is the central archive for both GSN and PASSCAL data and for data from many other sources around the world. DMC provides a variety of mechanisms to request and receive seismic data from its archive, from real-time data feeds to email requests for data to be mailed on tape. DMC has a 50 terabyte robotic mass storage device and a number of smaller disk farms to accommodate the several terabyte per year influx of worldwide data. DMC data can be requested by anyone in the world; it is not subject to any distribution restrictions.

The IRIS GSN maintains and operates a network of ~128 permanent seismological observatories around the globe (Figure 1). These stations and similar installations operated by the international community (loosely organized as the Federation of Digital Broadband Seismograph Networks or FDSN) are high fidelity digital instruments with broadband

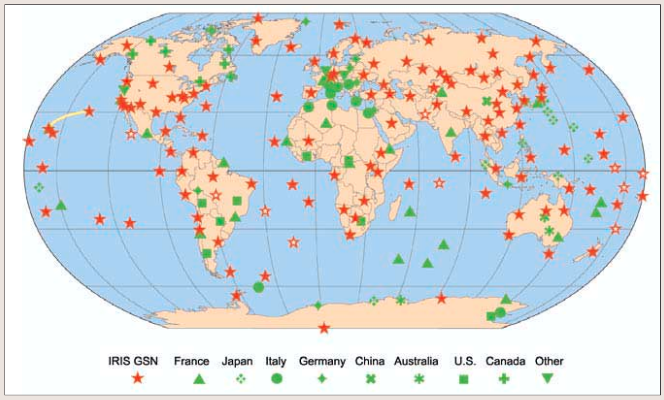

Figure 1. Permanent broadband seismograph stations operated by IRIS and a variety of international organizations around the globe. Open stars are planned new IRIS stations.

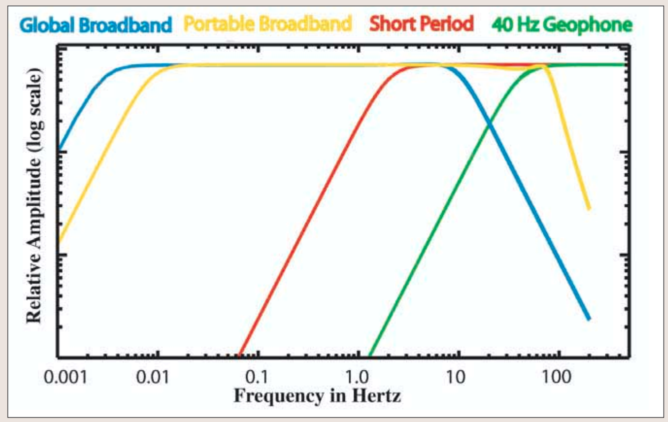

Figure 2. The relative frequency response of sensors of the IRIS facility.

frequency sensitivity. Digitizers have 24 bits of resolution with sampling rates of at least 20 samples per second (sps) for continuous recording with 80-100 sps becoming more common. Timing is provided through GPS systems. A major design goal for GSN is to deploy instruments with a minimum station spacing of 2000 km. Perhaps the largest receiver spacing deployment ever discussed in *TLE*, the GSN design was considered the absolute minimum necessary to improve tomographic imaging of the whole earth using surface waves and long-period body waves. The longer-period sensors of GSN have responses similar to the blue line in Figure 2 and are those used for whole earth tomographic studies. Sites with higher sampling rates are often also equipped with a sensor of response similar to the yellow line. The higher frequency recording is motivated by the need to monitor the globe for clandestine underground nuclear tests, a role that GSN inherited from its analog predecessor, WWSSN. Many GSN and FDSN stations contribute data to the International Monitoring System under development in anticipation of a Comprehensive Nuclear Test Ban Treaty (*www.ctbto.org*).

The second element of the IRIS instrumentation facility is PASSCAL (Program for Array Seismic Studies of the Continental Lithosphere). As its name implies, PASSCAL's original focus was on detailed studies of the continental lithosphere. With the ultimate goal of collecting unaliased sampling of the seismic wavefield from both active (planned

Figure 3. Members of the PASSCAL family of sensors. Clockwise from the top: Silver sensor = three-component L-22 with a natural period of 2 Hz; green sensor = Strekheisen STS-2 broadband sensor with a frequency response shown by the yellow line in Figure 2; orange single component 40-Hz geophone; and three-component 4.5-Hz geophone similar to those used in the exploration industry. Responses are shown in Figure 2.

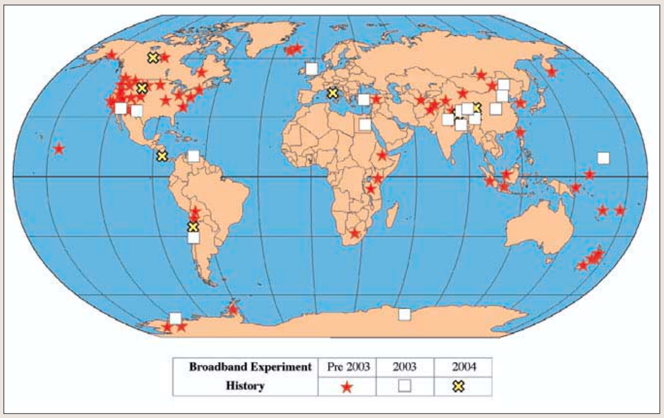

Figure 4. Past, present, and future PASSCAL broadband experiment deployments.

Figure 5. Instrument check-out during a refraction experiment in Antarctica.

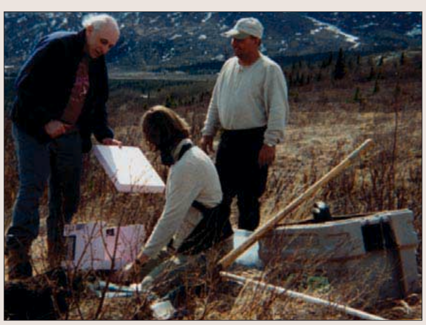

Figure 6. Broadband station deployment in Alaska.

explosions and vibrators) and passive (earthquakes and other unexpected seismic signals) sources, PASSCAL has developed a very versatile instrument pool (Figure 3). With sensors available with a frequency sensitivity range of over five orders of magnitude (Figure 2), university researchers have deployed PASSCAL instrumentation at receiver spacings ranging from a few meters to a couple of hundred kilometers to address an equally diverse range of scientific problems. In addition to more familiar temporary instrument deployments such as active source experiments using industry-style equipment available in the PASSCAL pool and

Figure 7. *An STS-2 sensor deployed in a 55-gallon drum, a common "vault" used by PASSCAL investigators. The hole for the vault is normally dug down to bedrock in a location with a meter or so of soil cover. This provides thermal stability of the sensor and some security. The sensor pad may be a paving stone or a concrete pad secured to the underlying bedrock. In this site, river stones are used to enhance drainage in the vault; many sites also use a French drain to keep water away from the equipment. The steel bar extending from the sensor in this photo is used to align it with geographic coordinates. Sensor alignment is both crucial and difficult. A Brunton compass, care, and patience are still the primary tools for sensor alignment and can result in an accuracy of a degree or two. A gyroscope-based tool, whose use is increasing, may improve the accuracy by an order of magnitude.*

Figure 8. *A completed PASSCAL-style installation. This site is actually a prototype USArray installation near the PASSCAL Instrument Center in Socorro, New Mexico.*

earthquake aftershock arrays, the PASSCAL instrument pool has allowed for rapid growth of an entirely new type of experiment, the passive-source broadband experiment. Prior to PASSCAL, broadband instruments were strictly the domain of permanent observatories. Through acquisition of an instrument pool based on new, rugged, low-power 24-bit digitizers and portable broadband seismometers, PASSCAL allows collection of essentially observatory quality data anywhere in the world. As a result, the deep structure of the continental lithosphere is but one of many targets that are the focus of PASSCAL deployments that span the globe (Figure 4).

A successful PASSCAL broadband experiment requires a good design and a lot of hard work. Broadband PASSCAL experiments depend on the rate and distribution of global seismicity. Companion articles by James, and Aster and Wilson in this issue outline the ways in which the academic community is using distant, or teleseismic, earthquakes to image the earth's lithosphere. To design an experiment to exploit global seismicity requires consideration of the location of the major source regions, primarily the Pacific Rim, relative to the subsurface targets. Teleseismic P- and S-waves sample the crust-mantle boundary offset roughly 6-10 km laterally from the recording station in the direction of the earthquake. However, to examine the structure of the mantle transition zone at a depth of 660 km, an experiment designer must account for the ~200 km lateral offset between the station and the subsurface sampling point. By using the rate of seismicity from a previous "typical" year, the probable distribution of sampling points in the vicinity of the target of interest can be calculated and an effective experiment design developed. Although the earth will never produce the exact number and magnitude of earthquakes used in the experiment design, the overall rate and distribution rarely change drastically from year to year, so experiments can be designed with some confidence ... and with a little bit of luck, global seismicity can be very cooperative!

Deploying a PASSCAL experiment in a remote region of the world is no small feat. Roughly 250 lbs of equipment must be shipped per site from the PASSCAL Instrument Center (PIC) in Socorro, New Mexico (*www.passcal.nmt.edu*). So, a modest deployment of 20 instruments generates an outgoing shipment of more than 5000 lbs (Figure 5). Construction materials and batteries are normally bought locally. Funding realities restrict experiments to a bare-bones installation crew; most investigators are thrilled to be able to afford a crew of four people, including themselves and often a technician from the PIC. These folks handle all of the custom clearances, site permitting, site design and construction, and instrument installation (Figure 6). Depending on the terrain and local regulations, each PASSCAL site takes 3-4 days to get up and running.

A broadband PASSCAL station normally consists of two "vaults." One houses the sensor itself and is hopefully located where bedrock is covered by a meter or two of soil. Burying the vault in a thin veneer of soil provides both security and thermal stability for the sensor. Sensors themselves are sealed, triaxial units that must be carefully aligned with geographic coordinates (Figure 7). The second vault houses the digitizer, batteries, and related gear, leaving only the solar panels and the GPS antenna visible at the surface (Figure 8). Sites typically record to a hard disk and thus must be visited for servicing every 3-5 months although recent developments in telemetry capabilities are allowing more experiments to use FreeWave radio technology to transmit their data to an Internet-capable site. In these cases, the data then flow directly to the investigator's desktop for immediate analysis.

What do PASSCAL investigators get for their efforts? Data. Lots of data. Never as much as they hoped, of course, but always enough to make significant headway toward their scientific objectives. A typical experiment will record earthquakes from a wide range of distances, producing in a year or two enough data to address their problem and a wide variety of other problems in earth structure (Figure 9). Through community consensus, investigators are allowed proprietary access to the data for a period of two years. After that point, it is released to the community through the IRIS DMS for use by any interested investigator in the world.

While most PASSCAL broadband experiments are undertaken to address a key problem in earth structure, they are often located in seismically active regions as well. And, sometimes, they get very lucky. In March 1994, a PASSCAL experiment in Fiji/Tonga was ideally located above a major earthquake, a moment magnitude (Mw) ~7.6 event at about 536 km depth. This event was the largest deep earthquake in about a quarter of a century and the first major deep earthquake since the advent of high-resolution digital instrumentation. A bonanza unlikely to be repeated in our careers? Obviously; yet three months later, Bolivia was hit by an Mw=~8.3 event at 645 km depth. And, another PASSCAL experiment was sitting right on top of the epicentral area! These two remarkable strokes of serendipity supplemented by a new digital GSN re-energized the debate on the origin and rupture processes of deep earthquakes, revitalizing a field that had stagnated due to the lack of appropriate data.

While this third revolution in seismic instrumentation will continue to result in new discoveries about the earth through deployments around the globe, we can look forward to

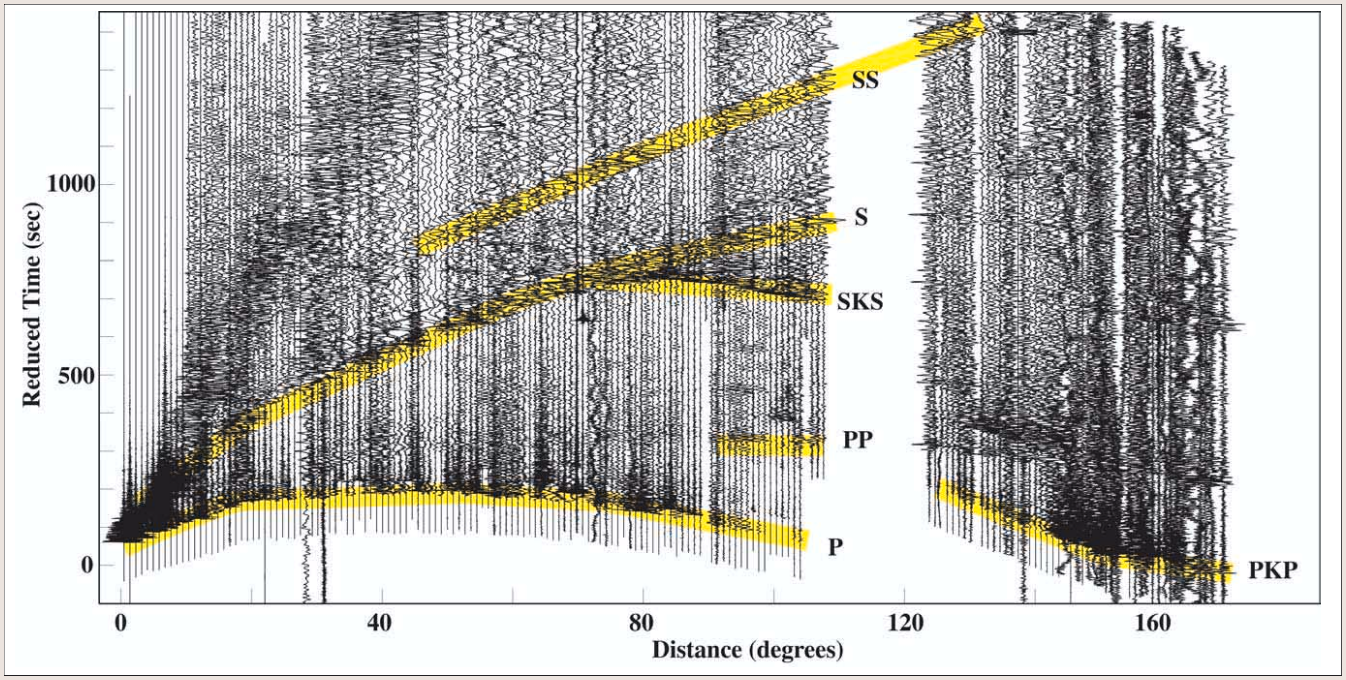

Figure 9. *A composite global record section from the 1991-92 Tibetan Plateau Seismic Experiment. The section was assembled by selection of the highest signal-to-noise ratio seismogram from each 100-km distance bin. Some bins had no seismograms, others had more than 100. The seismograms were then adjusted to a common depth and plotted with a reducing velocity of 13.8 km/s. Reduced time equals arrival time—distance/Vr, where Vr is the reducing velocity. 1° = about 111.19 km. Energy from a number of seismic phases is used by PASSCAL researchers to investigate earth structure.*

USArray, described in a companion article by Meltzer, as perhaps the fourth revolution in seismic instrumentation. That revolution is driven primarily by numbers of instruments, integration with other geologic and geophysical observations, and a focus on a "local" problem—the evolution of the North American continent! TLE

Corresponding author: owens@seis.sc.edu