An introduction—Solid-earth seismology: Initiatives from IRIS

This special section on solid-earth seismology consists of papers about studies associated with IRIS, the Incorporated Research Institutions for Seismology. This is not an arbitrary choice; the recent advances made by IRIS groups have begun to have an impact on exploration seismology—particularly in passive seismic imaging, imaging of converted transmissions, and velocity analysis of long-offset diving waves. Nevertheless, we feel the impact would be larger if more explorationists were aware of these advances.

Many geophysicists find that their careers and education are dynamic rather than static. Most of us obtained our education in a solid-earth type of geology department and are now working in reflection seismology for exploration; others of us, including two of those writing this introduction, spent a large part of our careers in exploration and have since moved into academia. But for most of us, the cross-fertilization that is possible by keeping up with our neighboring disciplines has gradually become less and less of a reality, as we find ourselves occupied increasingly with our own work. Of course, each discipline itself is far from static; the field of exploration seismology hardly resembles what it was a couple of decades ago, and the same is true for solid-earth seismology.

We have therefore enlisted our IRIS peers to contribute articles dealing with the crust and upper mantle that we believe will be of considerable interest to the *TLE* readership. In particular, many projects highlighted in these articles are forerunners to a major new initiative in earth science known as "EarthScope," which should garner the attention of earth scientists throughout the world over the next decade. We expect that some articles will interest you as exploration geophysicists. We expect others will interest you as residents of the planet Earth. A discussion that took place in the Round Table of the August 1992 *TLE* foresaw the potential of some of the techniques presented here; the opinions expressed in that exchange are intriguing in light of the advances made in the ensuing decade.

IRIS. The Incorporated Research Institutions for Seismology (*http://www.iris.edu*) "is a university research consortium dedicated to exploring the Earth's interior through the collection and distribution of seismographic data." It is U.S.-based, and interested U.S. universities can become full members or affiliates; non-U.S. groups can join as foreign affiliates. At present, IRIS has 100 full-member universities and many educational- and foreign-affiliate members. Largely with support from the U.S. National Science Foundation, IRIS has developed a network of standard seismograph stations around the world, centralized its data gathering and distribution, and has created a pool of more than 1000 transportable seismograph systems (PASSCAL) from which researchers may draw for their own projects much as library patrons check out books to read. The research, as seen from the examples in this section, need not be centered on U.S. targets and may include participants from anywhere in the world. IRIS is also strongly involved in education and outreach.

The creation of IRIS has led to a major change in the way that academic seismology is conducted. It has allowed the "small" scientist to do innovative seismology just like those at major research institutions. In particular, the creation of the Global Seismograph Network (GSN) and the free availability of such data via the IRIS Data Management Center (DMC) allow anyone with Internet access to "do" global seismology. The creation of DMC also led to standardization of formats for data exchange and software. The "open data" policy for all data collected using IRIS facilities has become a community-wide philosophy that nurtures collaboration and sharing. The PASSCAL instrument pool allows anyone, even at a small college or university, to do field work, without the expense of purchasing the systems. Because of these changes, academic seismology has undergone rejuvenation with fresh data and new ideas. Many of these ideas may benefit exploration seismology almost as much as they benefit solid-earth seismology.

There are organizations in other countries that cooperate closely with IRIS, or that conduct their own work with multi-institutional research efforts. One global organization is the Federation of Digital Seismograph Networks (*http://www.fdsn.org*). A European group that works to coordinate large-scale experiments is ORFEUS, Observatories and Research Facilities for European Seismology (*http://orfeus.knmi.nl*). A good listing of Web sites and organizations at *http://www.ess.washington.edu/seismosurfing.html* includes a number of organizations and Web sites not described here, such as organizations in Asia, Latin America, Africa, and Australia. We hope that future issues of *TLE* will include articles describing recent interesting advances from some of these groups.

Solid-earth seismology and exploration seismology. Solid-earth seismology has been moving progressively to denser arrays, to the point where the wavefield is not always undersampled and aliased. At the same time, exploration seismology has begun experimenting with permanent arrays of sensors, time-lapse monitoring of reservoirs, mapping of fractures with shear-wave splitting, extremely long-offset recording, and so on. Both fields, while expanding their areas of inquiry, have been increasingly approaching each other in many ways. We hope that the papers in this section will help exploration seismologists to understand those areas of solid-earth seismology that may most affect their own work or their interest in earth structure.

The instrumentation available for permanent and/or temporary experiments consists of a variety of seismometers, including broadband ones capable of recording distant earthquakes and local explosions, and recording units that can operate for weeks or months without intervention, continuously or in triggered mode. Accurate timing, which used to plague field operations, is now accomplished through GPS reception. The paper by Owens and Fowler "New instrumentation drives discovery of the earth's deep interior," describes this new generation of equipment and some of its applications.

One approach to imaging the subsurface is through the stacking of seismograms from different source locations, recorded at stationary receiver locations. The stacking process removes the variations due to source and travel-path differences, but reinforces the forward-scattered converted phases (P to S) beneath each receiver. Because this is essentially the transfer function at the receiver location, it is referred to as the "receiver function." Set up enough receiver locations, and the receiver functions essentially image the crust and upper mantle beneath the array ... of course, it isn't quite as easy as that ... multiples interfere (don't they always?), and one must use care to avoid some other pitfalls. But the researchers involved in this seem to have mastered the science and the art. The overall technique and a few of the details are described in the paper by Pavlis, "Imaging the earth with passive seismic arrays." He credits the use of these methods to improvements in data quality due to good portable broadband digital seismographs, and to an increase in data density due to the availability of these instruments through IRIS/PASSCAL and other groups.

Long linear arrays of receivers can be used to image a profile beneath them, using earthquakes from around the world (at appropriate distances to avoid certain complications in raypaths). The paper by Aster, Wilson, and the rest of the RISTRA Team, "Imaging crust and upper mantle seismic structure in the southwestern United States using teleseismic receiver functions," describes such a study crossing the Rio Grande rift. Their study involved 54 stations with an average separation of 18 km. They are able to make conclusions about variations in crustal thickness and the smooth topography of seismic discontinuities at 410 km and 670 km.

Not all these experiments take place in North America. James, in "Imaging crust and upper mantle beneath southern Africa: the southern Africa broadband seismic experiment," provides a good example involving diamond mines and kimberlite pipes from deep in the earth. This experiment included spatial coverage with about 100 km separation along a swath that was 1800 × 600 km, and ran for more than two years. They found evidence for high-velocity roots of cratons that extend to about 300 km depth, and lower velocity variations that seem to extend to the diamond-producing regions; they also found evidence for crustal thickening in some places, and overthrust belts atop cratonic crust in others.

The spatial sampling of the seismic wavefield for crustal and upper mantle studies is proposed to become even greater. Levander, in "USArray design implications for wavefield imaging in the lithosphere and upper mantle," describes the use of a linear array (here dense means 18 stations with average spacing of 83 km) as a prototype study for a dense spatial array in the near future. The use of receiver functions is enhanced by imaging the transmitted converted waves using a new twist on prestack Kirchhoff migration, to obtain an impressive first look at the upper mantle beneath the eastern United States.

The solid-earth seismology community uses active as well as passive sources. In a paper that straddles land and sea, Okaya et al. describe "Imaging a plate boundary using double-sided onshore-offshore seismic profiling." This experiment included land and marine sources, land and marine receivers, and what must have been a logistical nightmare in order to undershoot the coastlines. The shot-gathers or receiver-gathers cover offsets of 300 km, and are interpreted in terms of models that actually make sense, including both wide-angle reflections and refractions.

It is interesting that the highest velocities are used to image the slowest movement: the paper by Jackson describes "Geophysics at the speed of light: EarthScope and the Plate Boundary Observatory." The use of GPS stations that can measure relative (time-lapse) changes in position with accuracies approaching a fraction of a millimeter has enabled the observation of slow slip events deep in subduction zones, so-called "silent" earthquakes. Plans are to develop and deploy a huge array of stations to monitor the plate boundaries associated with the western United States, and to have a pool of portable stations that can be used in specific temporary studies.

Lastly, "EarthScope: Opportunities and challenges for earth science research and education," by Meltzer, describes a massive project proposed to improve our understanding of the solid earth and its processes through a multipronged approach. Perhaps the most ambitious component is the "Bigfoot" component of USArray, a network of seismograph stations that will slowly migrate across the United States. Potentially equally interesting to many explorationists is the deep borehole currently being drilled near (and ultimately, into) the San Andreas fault (SAFOD). Other components of EarthScope include repetitive (time-lapse) satellite radar interferometry, which could be used to monitor oil-field subsidence among other things, and dense GPS monitoring of plate boundary motions in the Plate Boundary Observatory. Because of the focus of SEG and *TLE*, the papers in this special section concentrated on the use of temporary seismographs for imaging the earth and on GPS for monitoring its deformation. But the efforts being undertaken by the solid-earth community are much broader than that.

The future, EarthScope, and the past, IGY. Preparation for development of EarthScope (and its seismological component, USArray) has taken many years. In February, the U.S. Congress initiated funding for EarthScope through the U.S. National Science Foundation's Major Research Equipment and Facilities Construction (MREFC) account. EarthScope is now poised for vigorous implementation over the next five years, with expected operation of the USArray project over the next decade. Thus, our reasons for compiling the articles in this special section are threefold:

1) We wish to inform the exploration geophysics community of recent advances in solid earth imaging of crustal and mantle features made by the academic community, with an eye toward technical cross-fertilization of ideas and methodologies.
2) We wish to enlist the exploration industry working in North America, including service companies, data brokers, and oil and mineral companies to provide maps and data that will help us optimally position the USArray sensors as well as provide "near surface corrections of the upper 5 km" that will improve imaging at depth.
3) We wish to enlist our colleagues within SEG to join us in our education and outreach effort to the next generation of geoscientists and decision makers.

One of the guest editors of this section (WDP) can recall the first time he learned the word "geophysical" and that there were such people as "geophysicists." It was in the late 1950s, and he was reading a comic book, as was appropriate for his reading level at the time. The comic book's main character "Nancy" had a friend named "Iggy." For some reason, Iggy wandered into an outdoor experiment, with the label of "IGY" for the International Geophysical Year. Of course, Iggy thought that IGY was a misspelling of his own name. The details of the story are now lost from memory, but the exciting adventures that the IGY people dragged Iggy into must have been inspiring, at least to one future geophysicist. Let's see if EarthScope can match the effect that the IGY had on the youth and the science of its time. TLE

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