Current and future trends in seismological investigations of the continental lithosphere

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The pioneering discoveries in seismology over the last century have been made by those scientists fortunate to have access to key observations. In past eras, exchange of information has been limited by technology and sometimes by other restrictions on data sharing. This situation often created an artificial barrier between the ideas and curiosity of individual researchers and the data necessary to test those ideas. However, now we are seeing extensive databases of seismological data growing rapidly and becoming increasingly available via the Internet. Continued improvements in telecommunications technology are making global seismic data increasingly available in near-real time. These developments make possible a Virtual Seismic Network from which any seismologist with an Internet connection can access any data worldwide, in order to test a scientific idea. The guiding principles of such a system include: (i) Maintain open access to all recorded data; (ii) Maintain an open source software development philosophy; and (iii) Leverage advances in information technology and telecommunications to improve the reliability and speed of both data recovery and processing. One result of this improved research infrastructure will be the advancement of our understanding of the origin and evolution of the continental lithosphere.

Introduction

In the last third of the previous century, the earth sciences were dominated by the plate tectonics revolution. During this period, concepts on the origin, evolution, and destruction of oceanic plates were born and have grown into a mature understanding of oceanic plate tectonics. The rapid growth of our understanding of the evolution of oceanic lithosphere owes its success to the consistency and relative simplicity of the process of formation and consumption of oceanic plates. Large-scale features created over a period of several million years can be observed almost in their entirety and can be explained to a large degree by the classical laws of rigid plate motions.

In contrast, earth scientists have observed and pondered the origin of the continents for centuries and many of the processes remain enigmatic. The challenge of unravelling the evolutionary history of the continents owes its complexity to the age of the continents and the diversity of the processes that have shaped them over more than 4 billion years. Early chemical differentiation of our planet, followed by deformation and accretion of continental fragments through billions of years of plate interactions has led to the assembly of continents that are a collage of fragments. On spatial scales, these fragments are an order of magnitude smaller than observed in the ocean and represent an order of magnitude more of earth history than the oceanic lithosphere. Thus, despite its accessibility relative to oceanic lithosphere, the difficulty of deciphering the evolutionary history of the continental lithosphere is perhaps not surprising.

Seismological studies provide a means to develop a crucial view of the variation of the continental lithosphere at depth. Proper interpretation of this view requires correlation of seismological parameters with geologic, geochemical and experimental studies. In this paper, I will not attempt to summarize the vast scope of seismological studies that are utilized in investigating the continental lithosphere. The ideas of individual researchers are endless and an adequate summary is an impossible task. Instead, I will comment on changes in the research infrastructure that currently, or in the future, are likely to enhance the opportunity of individual researchers to pursue their own ideas for new and innovative analyses. Ultimately, these opportunities are the means by which our understanding of the continental lithosphere will advance.

Three-dimensional structural geology

Seismological studies of the continental lithosphere attempt to extend structural and chemical analysis of rocks into a three-dimensional image. Our success in this attempt largely depends on our ability to resolve lateral and vertical changes in subsurface structure on a scale comparable to the variations in structure observed at the surface. At the upper and middle crustal level, we have seen considerable success in the last decade, at correlating surface and subsurface features with active source profiling in areas where sufficiently dense instrumentation could be deployed over distances of tens to a hundred kilometers. This resolution is improving, but is still

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somewhat limited, when the depth of investigation is extended to the crust–mantle boundary, largely because both active and passive profiling methods have had to sacrifice station density with profile length due to limited availability of instrumentation. Finally, our ability to simply resolve lateral variations in the mantle lithosphere and interpret them in terms of structural and compositional variations has been very limited. Yet, this region may, in fact, be the key to understanding continental evolution as it is the strongest rheological element of the lithosphere. There is increasing evidence that the deformation of the lithospheric mantle is preserved in shear wave anisotropy and that there is a correlation between inferred deep deformational structures and present or past surface deformation[1].

Thus, the mantle lithosphere is arguably the next frontier of exploration of the continental lithosphere. It is also a region that will be understood through the application of new, interdisciplinary approaches to seismological studies. A decade ago, seismological tools were classified as active and passive source methods, the implicit distinction being that the former methods were largely restricted to the study of crustal processes, while sublithospheric processes belonged to the latter domain. The mantle lithosphere was beyond the reach of active source profiling, while passive source methods typically employed large station spacing and thus could not provide good resolution (except perhaps within seismogenic zones). Developments in the 1990s suggest that seismologists have broken through these observational restrictions and that future integration of active and passive profiling holds great promise for advancing our understanding of the mantle lithosphere. There is an increasing body of evidence to suggest that distinct reflectors exist in the mantle lithosphere[2], while at the same time receiver functions derived from dense recordings of teleseismic earthquakes are producing much higher resolution of deep lithospheric structure[3,4]. These observational tools now provide a broad spectrum of techniques that, when combined, present the opportunity to dramatically improve our understanding of the structure and evolution of the continental lithosphere in the next decade.

An increasingly important tool in the study of the mantle lithosphere in the last decade has been the deployment of networks of temporary, portable, digital broadband seismograph stations within regions of interest. Deployments of 20–40 instruments from instrument pools in both North America and Europe are now relatively common. There is an increasing interest in deploying ever greater numbers of instruments at closer spacing to improve resolution in the mantle, although present instrument pools are too small to allow extremely dense two-dimensional instrument arrays of significant lateral dimensions. However, the potential for such deployments can be easily understood by examining results from more modest two-dimensional arrays.

For example, the 1994–95 Tanzania Broadband Seismic Experiment[5] had 20 instruments deployed in two linear arrays across the Tanzania Craton and surrounding mobile belts. Instrument spacing of 80–150 km along each array was chosen to allow reconnaissance profiling of the region. However, in the centre of the network, teleseismic body waves provide substantial lateral coverage in the upper mantle. Modification of the reflection-style processing technique of common depth point stacking to teleseismic P-to-S converted phases generated at upper mantle depths can be used to generate 'common conversion point' images of the upper mantle beneath the Tanzania Craton[6] (Figure 1). The subsurface sampling of teleseismic P and PP phases allows for stacking of 30 or more rays from at least 4 stations for common conversion point bins of less than 0.50° radius, for a large part of the central craton and easternmost margin (Figure 1 *a*). The noise reduction from this stacking results in very clear images of the variation of mantle discontinuities (Figure 1 *b–d*). Depth differences between the 410 and 660 km discontinuities, primarily due to a broad dip in the 410-discontinuity along the eastern margin of the craton, have been interpreted as evidence for a plume origin of the plateaus and rifts of East Africa[6,7].

Perhaps most intriguing when considering future prospects for imaging the subcrustal lithosphere, is the emergence of an apparent discontinuity at 250–300 km depth. The origin of this feature is enigmatic as we cannot rule out chemical or deformational (shear wave velocity anisotropy) explanations at this point. Observations of a discontinuity at this depth are becoming more common as profiles with smaller station spacing are conducted[4,8,9]. Thus, we can expect to see, in the near future, detailed investigations of structures between the crust and the 410-discontinuity for which observational evidence had been quite elusive in the past. As station spacing becomes smaller and active source and passive source methods are applied in spatially coincident investigations, the prospects for major improvements of our understanding of the subcrustal continental lithosphere are excellent.

Importance of research infrastructure

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 scientific investigations. One hundred years later, we have vastly expanded the quantity and availability of high-quality seismological data. We are beginning to establish the infrastructure to deliver these data to practising seismologists in a manner that recaptures the critical real-time, catalytic element of our science. Current and emerging technologies allow us to deliver seismological data to an individual's desktop from a worldwide network of stations in near-real time.

These developments can be thought of as a 'democratization' of seismology. We are moving toward an environment where any seismologist in the world with an Internet connection can receive data from any seismic station worldwide. The potential of this advance in infrastructure is profound as it eliminates artificial barriers to

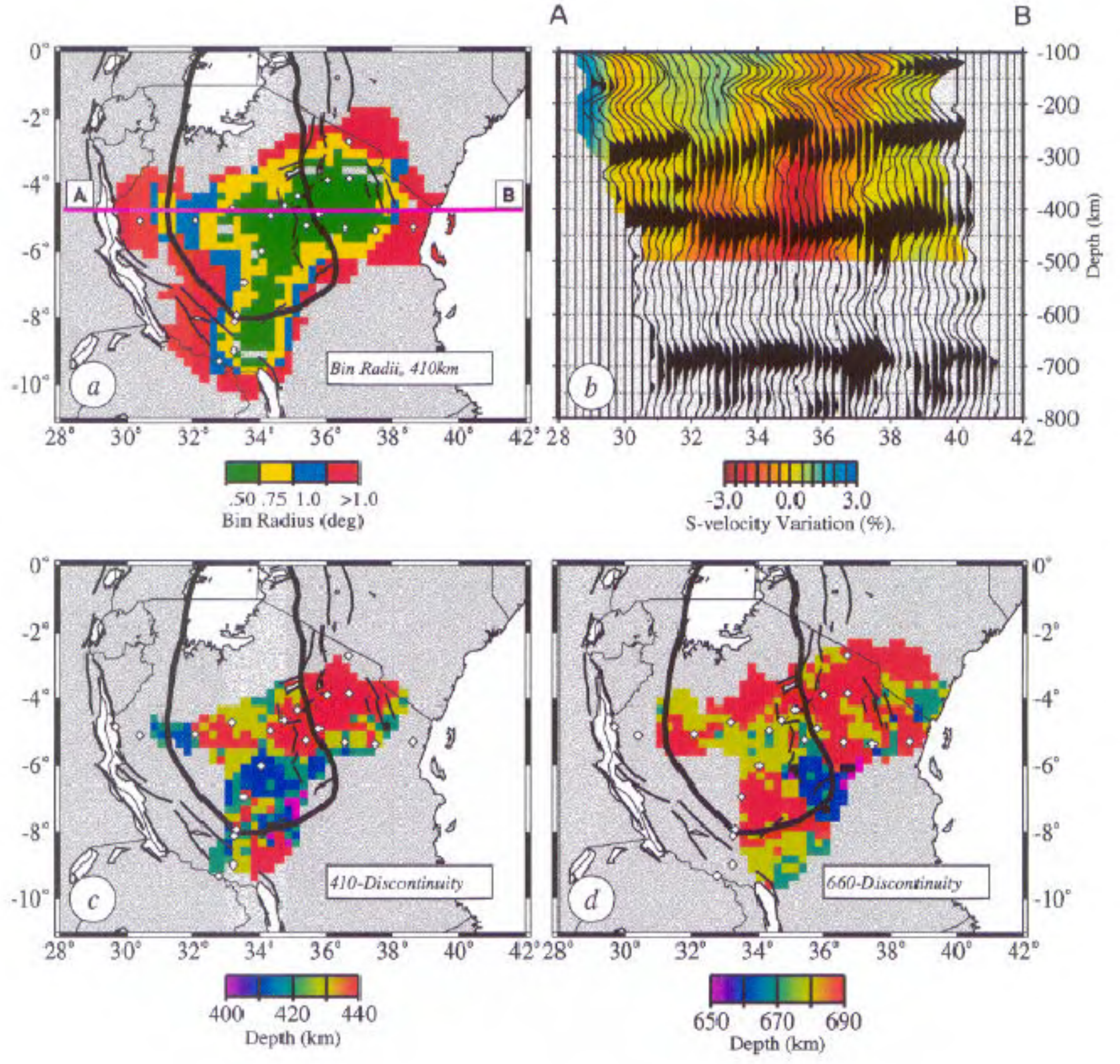

Figure 1. ***a***, Map showing the stacking bin radius at 410 km depth. Stacking criteria are that a circular bin must contain at least 30 traces from at least 4 stations. Bin radius is increased until these criteria are met. Colours show radius of stacking bin at each node in the image area. Nodes are spaced 0.25 degree apart. Red region is the area where only one of the two stacking criteria (normally the number of traces) was met for a bin radius of 1.0 degree. Grey and white areas on the periphery of the region did not meet either stacking criteria for bin radii of 1.0 degree or less; ***b***, Cross-section across a region of greatest ray density. Location of section is shown in ***a***. Positive amplitudes are shaded black. Regions where neither stacking criteria were met in bins of 1.0 degree radius or less are muted to zero amplitude. Background image and colour scale shown to the left of the figure are per cent velocity variations (from IASPI91 reference model) for the shear wave velocity model[13]. Background model was only plotted to 500 km depth, as this is the region of best resolution in the tomographic model; ***c***, Depth to the 410 discontinuity. Region shown is for only those areas for which both the minimum number of stations and minimum number of traces criteria were satisfied in bins between 0.50 and 1.00 degree radius; ***d***, Depth to the 660 discontinuity. Region shown is for only those areas for which both the minimum number of stations and minimum number of traces criteria were satisfied in bins between 0.50 and 1.00 degree radius.

individual scientists' ability to pursue their ideas. Seismologists from any institution in any country will be able to access the data and analysis tools necessary to test their ideas. Undoubtedly, the experiments that have advanced our understanding of the continental lithosphere were driven by the individual or collective curiosity of the seismologists who designed and conducted them. Thus, it is easy to see how improved access to seismological data will open up our science to the ideas of more individuals and, in the long run, improve our understanding of lithospheric processes.

The opportunities we can now see as imminent have been made possible by advances in information technology, largely outside the control of seismologists, coupled with substantial changes in the research infrastructure in several countries, including the United States, Germany, France, Canada, Australia and perhaps others. These countries have each made significant investments in infrastructure over the last decade that position our community to more easily pursue our seismological curiosity. Beyond the substantially improved instrumentation that is now available, the important guiding principles of most of these infrastructure investments have been: (i) Maintain open access to the recorded data; and (ii) Leverage advances in the information technology and telecommunications industries to improve the reliability and speed of data recovery.

The impact of the above principles on the activities of individual seismologists can be illustrated using Incorporated Research Institutions for Seismology (IRIS) as an example. IRIS is a federally-funded consortium of research universities in the United States charged with providing both permanent and portable instruments for the seismological community. PASSCAL is the program within IRIS that maintains portable instrumentation for both active and passive source recording. Investigators who use PASSCAL instruments are required to release all recorded data to the community through the IRIS Data Management Center (DMC) within two years of the end of the experiment. Although a major departure from the proprietary nature of data from seismic experiments in the pre-IRIS era, the community has adjusted to, in fact entirely embraced, this open data policy.

The Tanzanian Broadband Seismic Experiment is an example of a major experiment that used instruments from the IRIS–PASSCAL pool in the United States. Project participants spent many person-years collecting the data and had two years of proprietary access to that data. The original participants have published at least 10 papers on their analysis of this data. More importantly, since its release to the community in 1997, other seismologists have made 438 requests for data from this experiment from the IRIS DMC (pers. commun. Tim Ahern, DMC Program Manager). Most of these requests are serviced automatically via the Internet. A total of nearly 109,000 seismograms from the Tanzania deployment have been delivered to requesting seismologists around the world in the last 3 years! Many of these requests are made based on search criteria such as distance, depth, and/or magnitude for any qualifying data. Thus, some researchers may not even know that their data originated from a PASSCAL experiment that other investigators proposed and carried out to test hypotheses on the origin of the Tanzania Craton. They receive the data because, it satisfies the criteria they have defined in order to test their own hypotheses that may be wholly unrelated to the original intent of the experiment. In this new era of data sharing, future researchers need not know when or why the original experiment took place nor do the original investigators need to make special efforts to service requests for their data. Centralized, community supported, data centres handle these tasks, freeing seismologists to pursue their individual ideas.

The Tanzania example clearly illustrates the advantage of the open data philosophy from the point of view of those accessing data from multiple open sources. This philosophy also has equally clear advantages for the data provider. Open data policies raise the community's awareness of specific experiments as others recognize the potential applications of that experiment's data to problems of interest to them. Suggestions and encouragement from the community can result in a better experiment design to meet both the original goals of the project as well as potential peripheral goals. This awareness raises the profile of the individual experimenters and their institutions as they gain a reputation for well-designed experiments and a willingness to share the resulting data. As a data sharing culture emerges, this in turn encourages others to reciprocate by making their data available as well. It is easy to imagine that, in a competitive funding environment, an institution that shares its data will find it easier to support its research programmes. This is simply because external reviews can judge their projects not only in terms of their specific proposed objectives, but also by the potential long-term benefit of having that data available as a permanent community resource. Of course, ultimately, the best justification for an open data philosophy is the long-term advancement of our scientific knowledge. In a global community of seismologists, it is unrealistic to expect that the relatively small number of scientists who collect seismic data will forever be the sole source of the best ideas of how to use that data to uncover the mysteries of the earth's interior and the earthquake process. By opening our data to the eyes, minds and ideas of others, we will benefit from their contributions to our understanding of the earth.

The guiding principles, adopted by much of the global seismological community in the last decade, position the seismological community to create a *Virtual Seismic Network* (VSN) capable of delivering data from different countries and network operators to any computer with an Internet connection. Steps in this direction have been taken by several organizations. For example, the United States Geological Survey makes global seismic data available through their Live Internet Seismic Server (www.liss.org). Many regional seismic networks have similar facilities to share their data. Figure 2 illustrates the conceptual elements of a VSN. At present throughout the world, many different agencies and institutions operate seismic networks designed to collect data in support of both applied and basic science goals. More and more of these networks are collecting fully digital data in real-time. Thus, the first element of the VSN is already in place and evolving quickly[10]. To assemble these data for wide distribution, the heterogeneous data types and formats must be integrated via one or more 'Cooperative Data Collection Centers' (CDCC, Figure 2). These centres must be formed with and by the network operators, each of whom would receive data relevant to their own mission in return for contributing data from their network. This concept is also beginning to evolve as nearby networks in areas with good Internet capabilities are increasingly exchanging waveform data and automated phase picks in real time. With time, these individual collaborations are growing and can be expected to continue to grow.

With these developments rapidly proceeding, we must ask the question: What does the individual seismologist need to fully benefit from the availability of large quantities of seismic data via the Internet? In the United States, IRIS has recognized that many of its members are not fully capable of taking advantage of this emerging opportunity, largely due to the inability of existing earthquake processing software to handle the potentially enormous data volumes. It is safe to assume that the situation is similar elsewhere in the world. Thus, the remaining elements of the VSN that are still relatively undeveloped include: (i) the hardware and software of an Internet Data Distribution System (IDDS, Figure 2) that delivers seismograms to the individual scientist, and (ii) a Data Handling Infrastructure that helps seismologists manage that data and, in essence, minimize the time it takes them to test their scientific ideas using that data. The first element of this system would consist of many Internet-based nodes that automatically share and exchange their data holdings. Existing national and collaborative, multinational data centres can be considered as a preliminary framework from which to build this framework. While this system is beginning to evolve naturally as the global seismological community sees both the opportunity and the benefit provided by open data exchange, the true real-time elements of the IDDS have not yet been developed. Nodes must be able to exchange data automatically and be operated in a coordinated manner such that the load on any given node does not exceed its capacity to service user requests.

Once the IDDS is implemented in many places, it will clearly be capable of delivering more seismic data to

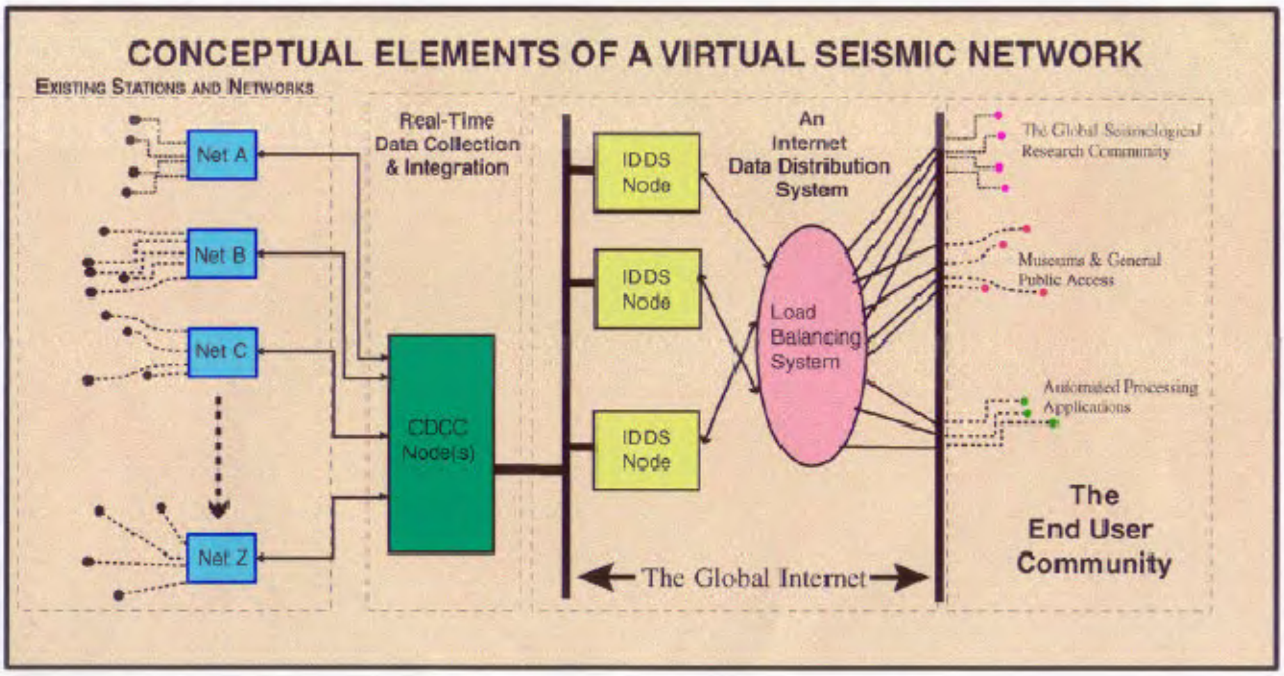

Figure 2. Conceptual elements of a Virtual Seismic Network (VSN). Data flow is from globally distributed, autonomous, heterogeneous data sources (left side of figure) to similarly diverse end users throughout the world (right side of figure). Many VSN elements are evolving naturally as telecommunications infrastructure improves. The least developed segment of the VSN is the Internet Data Distribution System, including a Data Handling Infrastructure with software to enable seismologists to fully utilize the large volumes of data that the VSN will make available in the near future.

individual seismologists than they can currently process efficiently. Thus, the end-user community must begin advocating the development of an accompanying Data Handling Infrastructure to ensure that they will be able to fully benefit from the technological advances in the rapid delivery of seismic data. The Data Handling Infrastructure cannot be explicitly represented on the VSN schematic (Figure 2) as it represents the concept of an integrated framework of software components distributed throughout the data distribution system and the end user community. This represents an area where significant infrastructure investments over the next few years are necessary and appropriate.

Drawing from the experiences of recent investments in data sharing infrastructure, the guiding principles of efforts to develop a Data Handling Infrastructure should include: (i) Maintain an open source software philosophy; and (ii) Leverage the development of software standards by the commercial software industry to minimize the time and cost needed to implement the Data Handling Infrastructure. The first guiding principle will ensure that all seismologists can benefit from and share in the software development. Adopting common exchange interfaces and object-oriented programming methods will allow seismologists to most easily share their codes with each other and to rapidly adapt those codes to suit their changing research needs. The second principle will ensure that seismologists spend most of their time doing seismology and not dealing with low-level software issues that are routinely addressed by the software industry with resources that dwarf those available in the seismological community. A Data Handling Infrastructure designed and implemented with these principles in mind will continue the progress of our community towards an environment where we are all capable of accessing and analysing seismic data and effectively pursuing our individual seismological curiosity.

Impact of the VSN on studies of the continental lithosphere

Although many of the key developments of the VSN will be driven by the need for rapid access to data from permanent seismic stations, the concept is easily extended to the portable array deployments most common in studies of the continental lithosphere. The limiting factor in portable deployments of instruments for passive seismic recording has always been the cost and effort necessary to visit the stations and recover data. VSN concepts are being applied more commonly to reduce these costs by delivering data in real-time to central recording facilities or, where telecommunications infrastructure exists, to the desktop workstation of participating scientists. Currently, these applications utilize digital radio telemetry, cellular phone communications and satellite telemetry technology depending on the availability of these technologies. In the future, these technologies and the emerging availability of Low Earth Orbit (LEO) satellite cellular technology will open the possibility to operate portable seismic deployments anywhere in the world and have full access to the recorded data in real time at reasonable cost.

That these approaches are feasible on a large scale even today and appropriate for continental lithospheric investigations is evidenced by the USArray project within the EarthScope initiative (www.earthscope.org) that is under consideration in the United States[11,12]. USArray's goal is to improve the resolution of seismic images from the continental lithosphere down to the deeper mantle by an order of magnitude. Components of the prospective facility include, first, a transportable array of approximately 400 broadband seismometers that will systematically cover the entire US over a period of 5–10 years. Average station spacing will be approximately 70 km. This element will provide vastly improved deep mantle images, but will serve primarily as a reference network for more focused studies of the continental lithosphere. The second component of USArray is a pool of about 2400 seismometers of various capabilities designed for use in experiments with specific lithospheric targets within the footprint of the transportable array. These instruments would be allocated to individual scientists based on a competitive proposal review process similar to the process most scientists are familiar with around the world. The third component of USArray is a modest number of permanent seismic stations intended to improve the earthquake monitoring capabilities of the US, in coordination with the US Geological Survey's plans for an expanded national seismic network. These facilities will be combined with other geological and geophysical studies into an integrated, interdisciplinary field programme that has great potential for advancing our understanding of the continental lithosphere.

If implemented, USArray would also serve as a large-scale demonstration of the capabilities of VSN concepts. All data from the permanent seismic stations and the 400 transportable stations would be made available to seismologists worldwide in near real-time. Most (potentially all) data from the 2400 portable stations would also be available to seismologists in near real-time. This would open up data capable of exposing many secrets of the evolution of the North American continent to the ideas of all interested seismologists and create a new environment for seismological research. As a demonstration of both the technology and philosophy behind the VSN, USArray could be a model of the open data and open software ideas that seismologists around the world should work towards implementing within their own countries.

The VSN will eventually be just a small part of a revolution in how earth scientists access and process the observations that are key to advancing our science. As we enter the new millennium, it is important for earth scientists in general and seismologists in particular to recognize the enormous impact that developments in telecommunications and computer technology will continue to have on our science. Vast databases of many types of geophysical and geological information are growing rapidly and computer technology to process and aid interpretation of this information continues to improve. The Internet represents a key link between the available information and the scientists with the curiosity and ideas necessary to advance our understanding of earth processes. In this era, individual research institutions or even entire national research mechanisms that delay or resist building the infrastructure to allow their scientists to effectively participate in this opportunity will find themselves quickly left behind. Those who chose to participate can look forward to an exciting era of discovery in the earth sciences.

1. Silver, P. G., *Annu. Rev. Earth Planet. Sci.*, 1996, **24**, 385–432.
2. Steer, D. N., Knapp, J. H. and Brown, D. L., *Tectonophysics*, 1998, **286**, 111–121.
3. Nabelek, J., Li, X., Azerodo, S., Braunmiller, J., Fabritius, A., Leitner, B., Trehi, A. and Zandt, G., *EOS, Trans. Am. Geophys. Union*, 1993, **74**, 431.
4. Bostock, M. G., *J. Geophys. Res.*, 1998, **103**, 21183–21200.
5. Nyblade, A. A., Birt, C., Langston, C. A., Owens, T. J. and Last, R. J., *EOS Trans. Am. Geophys. Union*, 1996, **77**, 517–522.
6. Owens, T. J., Nyblade, A. A., Gurrola, H. and Langston, C. A., *Geophys. Res. Lett.*, 2000, **27**, 827–830.
7. Nyblade, A. A., Owens, T. J., Gurrola, H., Ritsema, J. and Langston, C. A., *Geology*, 2000, **28**, 599–602.
8. Dueker, K. G. and Sheehan, A. F., *J. Geophys. Res.*, 1997, **102**, 8313–8327.
9. Li, A., Fisher, K. M., Wysession, M. E. and Clarke, T. J., *Nature*, 1998, **395**, 160–163.
10. Vernon, F. and Wallace, T., *IRIS Newslett.*, 1999, **18,** 7–8.
11. Meltzer, A., Rudnick, R., Zeitler, P., Levander, A., Humphreys, G., Karlstrom, K., Ekstrom, G., Carlson, R., Dixon, T., Gurnis, M., Shearer, P. and van der Hilst, R., *GSA Today*, 1999, **9**, 8–10.
12. Dalton, R., *Nature*, 2000, **405**, 390–392.
13. Ritsema, J., Nyblade, A. A., Owens, T. J., Langston, C. A. and VanDecar, J. C., *J. Geophys. Res.*, 1998, **103**, 21201–21213.

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