Out of Africa

Adapting the AfricaArray Model
– Building Capacity Around the World

Cover Photo

With an area of 1500 square kilometers and a population of 13 million growing by 4% annually, Dhaka City, Bangladesh, is an example of rapid urbanization in a region at risk of major earthquakes. Courtesy of Syed Humayun Akhter, University of Dhaka.

About the Workshop

The NSF Office of International Science and Engineering (OISE) and Division of Earth Sciences (EAR) jointly funded IRIS to convene a workshop on transitioning networks of earthquake monitoring stations in developing countries into fully sustainable networks of advanced seismic observatories.

Held in conjunction with the Annual Meeting of the American Association for the Advancement of Science, the workshop brought together key members of the IRIS community in the US and in Southeast Asia, South America, Central America and the Caribbean Sea Region to build strategies for transitioning networks of earthquake monitoring stations in developing countries into fully sustainable networks of advanced geophysical observatories.

Modern observatory networks can support international research and educational collaborations through standards-driven data acquisition, data management and open data exchange. The US seismology community is poised to foster geophysical networks outside the US for several reasons, including

- AfricaArray's demonstration that developing a permanent seismic network can provide critical new data for imaging Earth structure while also supporting scientific capacity building and strengthening hazard monitoring,
- IRIS's initial investment in several regional networks through its long-term loan program of refurbished seismic instruments providing a successful model on which we can build.

The goals of the workshop were to

- Enumerate leading regional science objectives that require long time series of high-fidelity seismological waveform records,
- Identify broader regional social benefits from improved seismological capacity and sophisticated data products,
- Suggest mechanisms for assessing the technical capacities and performance of new and existing regional and national networks,
- Introduce development experts and aid providers to the need for integrated network solutions.

Out of Africa

Adapting the AfricaArray Model – Building Capacity Around the World

A workshop on transitioning networks of earthquake monitoring stations into fully sustainable networks of advanced geophysical observatories.

Held February 17–19, 2008

Contents

Workshop Agenda

SUNDAY 17 FEBRUARY

AAAS Annual Meeting, Hynes Convention Center, Room 208

10:30 **Building Science Capacity with Linked Observation Systems: Seismological Perspectives**

Roger Bilham	Earthquake Risk in Developing Countries
Paul Dirks	Building Capacity for Africa's Natural Resources Sector
Gerardo Suarez	The FDSN and Sustainable Regional Seismic Networks

Hyatt Regency Hotel, One Avenue De Lafayette (+1 617 422-5516)

18:00 **Reception, Dedham Room**

MONDAY 18 FEBRUARY

8:00	**Continental Breakfast, Nantucket Room**

Introduction and Workshop Goals

8:45	Ray Willemann	Welcome
9:00	Art Lerner-Lam	Long-term instruments loans – Linking capacity building with geophysical monitoring
9:30	Göran Ekström	Training workshops – Successes and an outlook for improvements

10:00	**Break**

Lessons from AfricaArray

10:30	Andy Nyblade	Envisioning AfricaArray
11:00	Paul Dirks	Building an academic program on a geophysical observing network
11:30	Gerhard Graham	Gaining societal and governmental “buy-in” to sustain a program
12:00	Discussion	

12:30	**Buffet Lunch**

Identifying Existing Infrastructure and Needs in …

13:30	Gerardo Suarez	Mexico, Caribbean and Central America
14:00	Sergio Barrientos	South America
14:30	Fauzi	Southeast Asia
15:00	Break	

Breakout Sessions, 15:30 – 18:00

Room	*Chairpeople*	*Region*
Sturbridge	Marino Protti/Karen Fischer	Mexico, Caribbean, Central America
Plymouth	Edmundo Norabuena/Susan Beck	South America
Marlborough	Humayun Akhter/Steve Roecker	Southeast Asia

18:00	**Adjourn**

Group Dinner, 19:00, Restaurant TBD

TUESDAY 19 FEBRUARY

8:00	**Continental Breakfast, Nantucket Room**	

Some Successful First Steps

9:00	Marino Protti	Quality Monitoring and science in a developing country: Nicoya Peninsula, Costa Rica, and the success of effective strategic alliances
9:30	Jerry Carter	Global capacity building by the Comprehensive Test Ban Treaty Organization
10:00	Susan Beck	Mutual benefits from graduate education at US universities
10:30	*Break*	
11:00	Humayun Akhter	Leveraging temporary deployments to advance permanent networks
11:30	Richard Allen	Earthquake early warning: Adding societal value to regional networks and station clusters
12:00	Discussion	

12:30	**Buffet Lunch**	

Reports from Breakout Sessions: Outlining a Way Forward

(Each interval includes a 20-minute presentation and a 40-minute discussion.)

	Rapporteurs	*Region*
13:30	Rod Stewart/Jay Pulliam	Mexico, Caribbean, Central America
14:30	Daniel Huaco/Gary Pavlis	South America
15:30	Break	
16:00	Fauzi/Nano Seeber	Southeast Asia

Concluding Remarks and Discussion

17:00	Rick Aster	Next steps

18:00	**Adjourn**	

Executive Summary

The US seismology community is poised to foster geophysical networks outside the US, building on technological advances, nascent success, and previous investments. With an overall goal of building strategies for transitioning networks of earthquake monitoring stations in developing countries into fully sustainable networks of advanced geophysical observatories, the workshop brought together key members of the academic seismology community in the US, Southeast Asia, South America, and Middle America.

The number of fully educated geophysicists is insufficient in all three geographic regions on which the workshop focused, with deleterious effects on natural hazard monitoring and resource exploration. A broad range of education initiatives will be required to address the scarcity of fully educated geophysicists.

> RECOMMENDATION: *Strong existing geophysical educational programs in ought to be expanded to include students from neighboring countries. US universities with ongoing international geophysical research ought to establish strategic partnerships with foreign educational institutions and engage in coordinated "cluster" admissions to jointly create a critical mass of young, educated geophysicists in selected countries. Geophysical summer field course programs ought to be established with US participation as teachers and students.*

Training for specific skills is a critical need in many countries, partly because of the scarcity of broadly and fully educated geophysicists. There are several international training programs in seismology, but coordination between the programs is all but nonexistent, most of them serve any given location too intermittently to build capacity, and some of them are not well focused on achieving clearly stated objectives.

> RECOMMENDATION: *International regional organizations (such as MIDAS and CERESIS) ought to conduct surveys of existing capabilities and publish summaries of regional training requirements. Organizations that operate international training programs ought to compare the objectives and content of the different programs and offer complementary courses in selected geographic regions that cumulatively build capacity toward clearly stated goals.*

Recent advances in instrumentation bring significantly better capabilities within the grasp of seismologists everywhere. Nevertheless, there are challenges in making best use of modern instrumentation that are aggravated by inadequate training and more frequent instrument failures in tropical environments.

> RECOMMENDATION: *Regional development agencies ought to fund projects to develop versions of instrumentation that would perform more reliably in different environmental conditions, analogous to the US program to develop cold systems for the IPY. High-income countries ought to provide standardized sets of instrumentation to low- and middle-income countries, coupled to cooperation in training, education, research, and commitments to open data.*

Network processing packages offer "complete solutions" for routine operations, including data collection and management and computation of earthquake locations and magnitudes. Some packages are costly, even by the standards of US academics. The choice of the network processing package can make it difficult to use the data in certain other programs, which are developed continuously by loosely coordinated investigators and which are often required to produce important new products.

RECOMMENDATION: *Owners of proprietary software ought to provide no-cost or low-cost licenses to users in low- and middle-income countries. Documentation for a specialized product program ought to include advice on using the program with different network processing packages.*

Just as in the US, moving towards more open data exchange would probably progress gradually in a process that includes governments and other funding organizations growing accustomed to evaluating the network operators by how widely the data are used. Confidence building measures might demonstrate advantages to open data, but risk both "complacency" (the measures might be misperceived as acceptable long-term arrangements) and a "slippery slope" (progressively more networks might adopt restrictive data policies). There might be less resistance to freely distributing data through regional centers, perhaps one within each of South America, Middle America and Southeast Asia to share data.

RECOMMENDATION: *An international seismological organization representing consensus among network operators in each of South America, Middle America, and Southeast Asia ought to propose confidence building measures for archiving data at the IRIS DMC that address the risks of complacency and a slippery slope. In parallel, seismological network operators within each of South America, Middle America and Southeast Asia ought to make plans for regional management of open data.*

Motivation

→ DHAKA CITYSCAPE FROM AKHTER: Explosive urban growth of cities such a Dhaka, Bangladesh, exposes larger populations to earthquake hazard and makes them more vulnerable to disruption of essential services.

→ PHOTO OF A TRANSPORTABLE ARRAY VAULT: Each cutting-edge seismic station of the EarthScope project in the US requires only about $25,000 of instrumentation.

Over the past quarter century, the U.S. National Science Foundation has made large investments in global seismological infrastructure and the support of facilities for data management services and temporary network deployments. In addition, the NSF has supported a globally distributed program of fundamental research in seismology and related fields, along with innovative educational projects, and often with the express collaboration and financial commitments of international partners.

Moreover, U.S. mission agencies, most notably the U.S. Geological Survey, have matched these investments with operational support and earthquake information products with a focus on earthquake hazard reduction. Many stakeholders, including emergency responders and humanitarian aid agencies, as well as research scientists, use these products, many of which are produced in near real time as the result of stable real-time telecommunications, quality control, data streaming and analytical tools.

There are similar efforts with varying objectives, spatial coverage, performance, and stakeholder base in many nations and regions. The International Federation of Digital Seismic Networks acts as a portal for information on and collaboration among global, national and regional earthquake monitoring networks and operations, and has status as a commission within the International Association of Seismology and Physics of the Earth's Interior. Many of the networks participating in the FDSN have research, operational and stakeholder bases that mirror those of U.S. funded networks. In many cases, earthquake-monitoring networks were capitalized and deployed as a result of a major earthquake disaster, with funding and technical assistance coming from international development institutions and national aid agencies.

Combined, this availability of high-quality seismological instrumentation has led to transformative research in the earth sciences as well as a renewed emphasis on providing real-time information in the event of an earthquake emergency. Additionally, the improvements in earthquake monitoring have led to improvements in the quality of earthquake databases, leading to better understanding of active earthquake faults, variability in ground motion, and the space-time variation in earthquake hazard.

Despite these advances in seismological infrastructure, there is evidence that the U.S academic community, colleagues in foreign universities, and the various government agencies involved in regional, national and international earthquake monitoring are not taking full advantage of common opportunities and the leverage provided by the infrastructure base. International partnerships clearly are a growing mode of scientific collaboration. In seismology, as in other sciences, the details of those partnerships often depend on the technical and research capacities of host institutions, regardless of whether they are academic or government organizations. Furthermore, in many countries (as in the US), seismological networks are dual use, having both basic research and hazard reduction objectives. There are few templates for matching the episodic nature of US experiment funding with the continuous and growing need for providing an evidence base for national and regional earthquake hazard reduction strategies. The same could be said for other objectives, such as need to educate a local, technical workforce for the mining and resource exploration industries.

There is also an argument to be made that global seismological infrastructure is not being used to leverage sustainable investments in basic and applied research in developing countries, and the capacity to use enhanced earthquake monitoring for improving human well-being. Among the global science investments made by developed countries, seismological infrastructure stands apart in its distributed geographic footprint, its use of high-bandwidth advanced telecommunications, and its importance to stakeholders outside the basic research community. Relatively speaking, the deployment of a single seismological station is not difficult or excessively expensive, and the marginal costs of including it in existing global and regional networks and sharing its data are minimal. However, it is very difficult and relatively expensive to establish and operate a national or regional earthquake-monitoring center that can inform the hazard reduction discussions in individual nations. Agencies such as the USGS, and consortia such as IRIS and the FDSN contain a wealth of expertise and capacity that could be shared, if the pathways for doing so were clear.

The NSF's Program in International Research and Education (PIRE) provides an opportunity to explore such pathways that leverage international seismological infrastructure to satisfy objectives in international scientific collaboration, capacity building and social and economic development. One of the first large earth science projects funded by the PIRE panel was AfricaArray. The question before the workshop is how models such as AfricaArray can be applied in other situations.

But the "AfricaArray" project appears to be expanding a sustainable geophysical community in sub-Saharan Africa. The project is geophysical in a broad sense – potentially extending to a multidisciplinary program to study the atmosphere as well as the solid earth – but the origin of AfricaArray's observational component is a network of broadband seismographic observatories.

In some ways, broadband seismology is a surprising start for a project aimed at wider societal goals in southern Africa, since capabilities that are unique to these systems serve principally to study large earthquakes and sub-crustal earth structure. With an original observation system directed towards a hazard that is not the greatest in the region and towards earth structure at depths too great to hold exploitable resources, the source of AfricaArray's success must be found elsewhere.

US-based seismologists have several motivations for seeking to identify features of AfricaArray that contribute to its success, and using that knowledge to develop similarly successful projects elsewhere. They have an empathetic desire to help improve the lives of foreign colleagues. They have a professional responsibility to use seismology to mitigate earthquake hazard and discover resources. But the motivation that may be most likely to support a sustained commitment is that these lessons could enable greater scientific achievement, both individually and as a community.

Format and Goals

The US seismology community is poised to foster geophysical networks outside the US for several reasons, including

- Modern facilities, such as IRIS's, support international collaborations in research and education through standards-driven acquisition, management and open exchange of data.
- AfricaArray's demonstration that developing a permanent seismic network can provide critical new data for imaging Earth structure while also supporting scientific capacity building and strengthening hazard monitoring,

→ STATION PHOTO INCLUDING PEOPLE FROM NYBLADE: Researchers and students in southern Africa are gaining experience with modern seismological instrumentation as a result of the AfricaArray project.

- IRIS's initial investment in several regional networks through its long-term loan program of refurbished seismic instruments providing a successful model on which to build.

We convened a workshop with an overall goal of building strategies for transitioning networks of earthquake monitoring stations in developing countries into fully sustainable networks of advanced geophysical observatories. We brought together key members of the academic seismology community in the US and from three geographic regions: Southeast Asia, South America, and Middle America (Mexico, Central America and the Caribbean Region). The IRIS Consortium organized the workshop with funding from the US National Science Foundation Office of International Science and Engineering (OISE) and Division of Earth Sciences (EAR), and it was held in conjunction with the Annual Meeting of the American Association for the Advancement of Science.

Our specific objectives were to

- Enumerate leading regional science objectives that require long time series of high-fidelity seismological waveform records,
- Identify broader regional social benefits from improved seismological capacity and sophisticated data products,
- Suggest mechanisms for assessing the technical capacities and performance of new and existing regional and national networks,
- Introduce development experts and aid providers to the need for integrated network solutions and the benefits that they would enable.

The workshop participants met in plenary session to review the objectives, to learn details about AfricaArray from pivotal African contributors, and to prepare draft summaries of regional infrastructure and needs. The participants then formed breakout groups for planning specific to the three geographic regions on which the workshop focused. On the second day, the workshop re-convened in plenary session to learn about successful international scientific capacity building other than AfricaArray and to discuss reports from the breakout groups. The workshop concluded with discussion of particular next steps.

Regional Breakout Groups

MIDDLE AMERICA

“Middle America”, the geographic area that includes the northernmost South America, southernmost North America and everything in between, including the Caribbean, has been the site of great plate tectonic activity in the most recent 35 million years. The region continues to be highly geologically active today as the Caribbean tectonic plate advances to the east, and the Pacific, Cocos and Nazca plates subduct to the west. Type examples of many key features of plate tectonics—subducting lithosphere, deep trenches, transform faults, pull-apart basins, subduction-to-strike-slip transitions, subduction-related volcanics, and volcano-free subduction zones—exist in a relatively small geographical area.

Because of the limited geographic extent of many countries in the region, and the far-flung distribution of its island nations, international data exchange and scientific collaboration are especially important. However, challenges to international cooperation – the desire to be autonomous, the need to justify spending to local governments, and the wish to avoid conflicting reports – are no less than elsewhere. Indeed, with Spanish, English and French each predominant in different countries, there are special challenges.

Discussion of regional needs in Middle America focused on four themes: better coordination of existing data collection, the expansion of broadband station coverage, enhancement of regional training and education opportunities, and the development of international collaborations that would facilitate an evolution from routine monitoring to research-mode science.

→ MAP OF MIDDLE AMERICA WITH STATIONS CURRENTLY ARCHIVED AT THE DMC: Permanent seismic stations in Middle America that use the IRIS Data Management Center to exchange are too sparsely distributed for many research and monitoring applications.

Data Coordination

The region boasts a significant number of national networks that were funded by local governments, aid organizations, and has also been the site of seismic arrays geared to particular research projects. These networks have recorded significant data needed to study critical features of regional structure, tectonics and geodynamics. Unfortunately, relatively few of these data have been analyzed at all, and there has been no coordinated and sufficiently long-term effort to aggregate, validate, and jointly analyze data from the numerous networks. Until such an effort is made, we will not learn some of the important things we want to know, researchers will not have access to these data, and we run the risk of duplicating efforts.

Some regional structures for data exchange exist, for example the Central America Seismic Center (CASC) at the University of Costa Rica. The Middle America Seismology Partnership (MIDAS) is an international organization among earthquake monitoring agencies. However, MIDAS does not include universities without a monitoring mission. Data from some stations are telemetered in near-real-time to the newly-established Caribbean Tsunami Warning System (CTWS) at the University of Puerto Rico, Mayaguez (UPRM), but currently these data are not being archived.

Some local operators will likely be unenthusiastic about "giving their data away." However, these concerns may be mitigated by forming a regional data center that has an oversight board made up of regional representatives. With such a center clearly identified, the data could actually reside at a central location such as the IRIS DMC. This latter option would be attractive as a low-cost (no-cost?) opportunity to back up data securely, organize metadata, and distribute data and metadata back to networks and their associated researchers. A multi-tier data release policy should be considered (e.g., data for events above a certain threshold would be released immediately, other data would be released after 2-3 years). Access to other opportunities (research collaborations, communications upgrades, etc.) could be tied to a commitment to contribute data under this policy.

Densifying Broadband Coverage

Despite existing networks, significant gaps in spatial coverage remain, and data collected in some regions, particularly those dominated by short-period networks, are not sufficient for state-of-the-art broadband analyses. A number of options for densifying broadband station coverage were discussed. A regional pool of portable broadband instruments was in general viewed as a very attractive solution. In addition, some countries in the region would greatly benefit from greater access to training and support in the operation and maintenance of permanent broadband stations. Given the many island nations, ocean-based monitoring and investigations are more important in Middle America than in some other regions. Thus, there is a need for ocean bottom seismometer (OBS) systems and for access to the time of drill ships and other research vessels. Denser arrays of GPS sites are also required to address key regional science questions.

Increasing Regional Geophysical Expertise

The number of scientists with seismological training varies greatly across the region. Some countries, for example Mexico and Costa Rica, have multiple institutions with active research-focused seismology groups, as does Puerto Rico. However, although earthquake and volcano hazards are high throughout Middle America, many national governments employ only a few geophysicists at monitoring agencies. In addition, although strong geophysical education programs exist, for example at the Universidad Nacional Autónoma de México (UNAM) and the University of Puerto Rico Mayagüez (UPRM), they are relatively few in number, and opportunities for graduate-level training are especially scarce.

Discussions of education and training issues were wide-ranging. However, broad support was expressed for internship programs and field camps that would be conducted in the region and available to participants from across the region. Potential industrial funding sources include the oil companies in Mexico, Venezuela, and Trinidad and Tobago who would benefit from a well-trained regional workforce.

Key Science Issues and Regional Research Initiatives

→ Middle America Tectonic Map from Protti: *Diverse interplate faults and intraplate deformation in Middle America contribute to high levels of earthquake, volcanic and other natural hazards, as well as opportunities for geophysical research.*

Due to the active and diverse tectonic processes in the region, many opportunities exist for geophysical research that simultaneously addresses fundamental earth science questions and improves the scientific basis for hazard mitigation. For example, a better understanding of faulting in the upper plate would not only contribute to subduction zone lithospheric deformation models, it also would help to quantify earthquake hazards close to population centers. High resolution bathymetry would better characterize the properties of the subducting lithosphere, but it is also needed for tsunami forecasting.

An overarching science theme for the region is to better understand how a complex, segmented subducting plate dynamically couples to the upper plate and contributes to its longterm tectonic and chemical evolution. These issues have been explored in certain portions of the region. For example, Costa Rica is a focus site for the Seismogenic Zone Initiative of the NSF

MARGINS program, and Nicaragua and Costa Rica are a focus site for the MARGINS Subduction Factory Initiative. However, much of the region's complex plate boundaries remain to be studied in detail.

Specific questions of interest include:

- How are upper plate deformation patterns linked to the properties of a subducting plate, which varies in morphology, age, and seamount density? What is the role of plate coupling across the seismogenic zone? What do links between interplate earthquakes and subsequent upper plate events several months later tells us about stress propagation within the earth? What are the processes that lead to flat subduction?
- What is the origin of the Caribbean plate and what is the nature of its lower crust? How has it been altered by subduction zone magmatism? What do these processes tell us about the creation of continental crust on a more global basis?

The group expressed the need for greater intra-regional scientific cooperation, as opposed to relying on bilateral research projects with researchers from outside the region. However, funding for such endeavors will require some creativity. Within the region, Mexico and Venezuela appear to be the only countries with significant internal funding for "NSF-style" projects. However, while these budgets can be significant, up to roughly $500,000 in Mexico from the National Council for Science and Technology, they are not long-term, and these sources are unlikely to fund region-wide initiatives.

Overall recommendations

A key recommendation was to form a regional consortium that would conduct regional science workshops, provide robust, documented software, coordinate data exchanges/archiving, and provide consultation for networks and related equipment. Models for developing this consortium require further exploration. Options to be examined include drawing on existing organizations, such as MIDAS, CASC, or CEPREDENAC. Alternatively, with additional resources, one of the national networks, such as the PRSN (Puerto Rico) or SRU (Trinidad and Tobago) could expand their role.

Action item

Hold a workshop to discuss science targets, stimulate interest, and formulate a plan to move forward to address the highest priorities among the targets that are identified. Ensure broad participation by facilitating travel to the meeting and by including key representatives from the region's major networks, educational institutions, and governmental organizations on the workshop's organizing committee.

SOUTH AMERICA

The fundamental earth science questions that can be addressed in South America arise from its role as the archetype example of sub-continental subduction. Processes of subduction zone orogenesis and evolution of continental shields are arguably more accessible to geophysical observation in this region than anywhere else in the world. Several initial efforts have been carried out at a relatively large scale, but more continuous initiatives involving more than two countries in the region need to be advanced. There is no doubt that regional collaboration should be expanded in many areas of the earth sciences, particularly in those disciplines that can shed light on minimizing the effects of earthquakes, tsunamis, landslides, etc. Even though academic exchange is fostered under research programs, it should be extended to other aspects of observational practice.

The different earth sciences/seismological institutions in South America have come a long way in data exchange; however, more can be done by taking advantage of the rapid development of Internet facilities in recent years. Even though this media might not be considered a safe, reliable, robust, or earthquake-proof ways to transmit data, it may well resolve, in the near future, the difficulties that large distances pose to open data exchange.

As in most regions elsewhere, geophysical educational programs in South America exhibit a variety of development levels in different countries. In some cases, they are almost non-existent. In other cases, they are very well developed, particularly as joint programs with private industry or where governments have made a commitment to support research and development activities. Most of geophysics graduate students are offered careers in mining and petroleum industries. Unfortunately those with academic interests are not able to pursue their research interests in universities because of lack of stable academic position. We must keep in mind that in several countries more than 90% of research is carried out by universities, sometimes with no more than a couple of earth scientists in charge of the entire program.

National seismological observatories in South America may be associated with universities, part of government agencies, or depend from private initiatives; therefore their objectives do not always point to the same purpose, particularly in research activities. Moreover, the possibilities of generating joint proposals for inter-country research are diminished because of different orientations and emphases of research activities and because of lack of international funding agencies ready to support these efforts.

CERESIS (Centro de Sismología para América del Sur) is a South American international organization – created in 1966 and based in Lima, Peru – under the auspices of UNESCO with the goal of facilitating seismological activities and exchange among the different South American seismological institutions. This long-lived organization may well support and coordinate not only research activities but also exchange programs within the region.

SOUTHEAST ASIA

The scientific and societal benefits of geophysical collaboration in Southeast Asia are abundantly clear. The region offers the full spectrum of large-scale convergent tectonic environments for academic study, and the associated societal hazards posed by earthquakes, volcanoes, and tsunamis demand the coordinated efforts of the international geophysical community in sharing of data and analysis. Indeed, the lack of any such coordination prior to 2005 was a key contributor to the widespread devastation caused by the tsunami that followed the December 2004 Sumatran earthquake.

Since the 2004 tsunami, awareness of the need for monitoring and early warning, and the recognition of the role of international collaboration in the mitigation of future disasters has increased dramatically. Nevertheless, the response to this disaster thus far has been uneven. Some countries, like Indonesia, have taken on a leadership role and are investing heavily in training and equipment as well as initiating meetings with countries in the region to promote data exchanges. Others, like Bangladesh, are receptive to improved collaborative links but are strained for resources. International organizations like the 10 countries in the Association of Southeast Asian Nations (ASEAN), largely in response to initiatives put forth by Indonesian scientists, have embraced the concept of improved data sharing mechanisms. Hence, there is a clear potential for a broader collaboration among countries in the region. Moreover, there is an abundance of educational and governmental institutions within ASEAN that could benefit from a partnership with geophysical programs at US universities; for example there are 28 accredited universities in Indonesia alone.

Despite increased awareness, however, many key countries in the region have not been receptive to the concept of increased collaboration. The reasons for this recalcitrance appear to be due to a combination of a lack of funds, a lack of political will, and, in some cases, an active aversion to sharing data. While daunting, none of these limitations appear insurmountable and could be addressed by a concerted effort to identify needs and concerns along with potential means to satisfy them. For example, seismologists in Bangladesh recently augmented their data collection capabilities by taking advantage of equipment donated by IRIS. To some extent the aversion to cooperation exhibited by other countries appears to be born out of a lack of true understanding of the costs and benefits of data sharing, and hence could be addressed by education and outreach programs.

To summarize the current situation: Southeast Asia is fertile ground for an international organization built on the Africa Array model, but the interests and abilities of potential collaborators are at present profoundly asymmetric. A considerable amount of prep work, involving discussions with individual institutions, and assessment of the needs and resources of potential collaborators, needs to be done before a “Southeast Asia Array” can become a reality.

Conclusions

EDUCATION

Seismological education is an open-ended process that aims to impart broad knowledge sufficient to help build or guide a program in exploring for mineral resources, collecting and analyzing data for seismic hazard analysis, or conducting research to advance the state of the science. There is a scarcity of fully educated seismologists in all three geographic regions on which the workshop focused. One result is that many earthquake-monitoring agencies continue to focus on narrowly defined missions even though new services could make important contributions to mitigating earthquake effects and averting disasters. Furthermore, except in a few large countries of Latin America, geophysical education programs are nearly non-existent even at the undergraduate university level. Many students who came to the US for advanced education in seismology originally intend to return home but, because of limited opportunities at home, in the end only individuals more dedicated to societal issues than to academic concerns actually repatriate. Reinvigorating one effective education program in South Africa is a key element of AfricaArray, but establishing this as a regional center that draws about half of its students from other countries in the region was essential to both the education program and the overall AfricaArray project.

> RECOMMENDATION E1: *Existing geophysical educational programs in South America and Mexico ought to be expanded to include students from neighboring countries and a regional geophysical education program ought to be established in Southeast Asia, in each case with partial funding from regional development banks or intergovernmental organizations.*

> RECOMMENDATION E2: *US universities with ongoing international geophysical research ought to establish strategic partnerships with educational institutions in the workshop focus regions, and make it possible for students to come to the US for several visits of one or two semesters in the course of earning an advanced degree while mostly working in their home country.*

> RECOMMENDATION E3: *US universities ought to engage in coordinated "cluster" admissions to jointly create a critical mass of young, educated geophysicists in selected countries, and this should be complemented by US foreign aid to facilitate research by post-doctoral scientists repatriated after their graduate education, in collaboration with US-based investigators.*

> RECOMMENDATION E4: *Geophysical summer field course programs ought to be established in Middle America and South America. US university faculty members and graduate students ought to teach in these field courses and encourage undergraduates, especially Latinos, to satisfy a field requirement for a degree in geophysics by attending the foreign courses.*

Students who are well-educated by the standards of high-income countries might still lack skills required after returning home, because universities in low- and middle-income countries are often more integrated with governmental agencies doing applied seismology, with a less elaborate system of supporting technicians.

> RECOMMENDATION E5: *US universities ought to partner with the USGS and resource discovery companies so that foreign graduate students can complete internships that teach them applied skills while they earn credit towards advanced degrees.*

TRAINING

Seismological training aims to impart specific capabilities in a short period of time. Training is a critical need in many countries because of the scarcity of fully-educated geophysicists. There are several international training programs in seismology, but coordination between the programs is all but nonexistent, most of them serve any given location too intermittently to build capacity, and some of them are not well focused on achieving clearly stated objectives. The existing training programs include

- A program operated by GFZ, Potsdam, and funded by the national government of Germany, with additional contributions from UNESCO.
- A program operated by BRI, Japan, funded by the national government of Japan.
- A program operated Provisional Technical Secretariat for the Comprehensive Test Ban Treaty and funded by the CTBT Preparatory Commission.
- A program operated by IRIS and funded by the US National Science Foundation.

> RECOMMENDATION T1*: Organizations that operate international training programs ought to meet bi-annually to compare the objectives and content of the different programs and make plans, where possible, to offer complementary courses in selected geographic regions that cumulatively build capacity toward clearly stated goals, with objective metrics of success.*

Several follow-up activities might significantly improve the training programs. Success – that is, the subsequent utility of the training – ought to be measured even though meaningful metrics are difficult to define, especially for a program that lacks clearly stated goals. Surveys of participant satisfaction do not adequately measure success, and are probably useless or even misleading if they are conducted before trainees have time to use their new skills in operations. Training programs ought to identify a person who could be contacted afterwards and have time to assist trainees in using the techniques that they had learned. Wider use of "e-learning" tools would both allow additional people to take advantage of the material and allow training program students to review the material. The version of software that people were trained to use ought to be available indefinitely so that trainees could rely on a stable and familiar tool. Tracking help desk inquiries could guide refinement of existing training materials and suggest additional areas in which training would be useful.

> RECOMMENDATION T2*: International regional organizations (such as MIDAS in Middle America and CERESIS in South America) ought to conduct detailed surveys of existing capabilities and publish summaries of regional training requirements.*

INSTRUMENTATION

Recent advances in instrumentation bring significantly better capabilities within the grasp of seismologists everywhere. Global production of broadband, wide dynamic range sensors is growing rapidly, and installation procedures that can be applied on a massive scale have been developed. High precision digitizers, which are required for many seismological products, are now widely available and can be operated under most circumstances by technicians with only modest training. Telemetry using cell phone technology and VSAT systems is now available and affordable in so many places that near-real-time monitoring is now widely feasible. Collectively, these advances extend to the possibility of calibrating attenuation curves for rapid warning systems such as AlarmS with a set of roving stations analogous to the Transportable Array, albeit at a more modest scale than in the US.

> RECOMMENDATION I1: *High-income countries ought to provide standardized sets of instrumentation to low- and middle-income countries, coupled to cooperation in training, education, research, and commitments to open data.*

Nevertheless, there are challenges in making best use of modern instrumentation. Broadband sensors will fail to perform if handled improperly or installed in the same way as older, narrow-band sensors. Digitizers occasionally require attention from highly trained engineers. Telemetry systems must be regularly maintained. All types of instrumentation break down more often in tropical environments.

> RECOMMENDATION I2: *IRIS ought to produce a summary of existing sensors, digitizers, power systems and telemetry, including features that them make suitable for particular environments.*

> RECOMMENDATION I3: *Regional development agencies ought to fund projects to develop versions of sensors, digitizers, power systems and telemetry that would perform more reliably in different environmental conditions, such analogous to the US program to develop cold systems for the International Polar Year.*

SOFTWARE

There can be no enduring solution of software to "do it all" because programs are developed continuously by loosely coordinated investigators, reflecting an open, energetic research environment. Numerous packages exist, but they have distinct roles and capabilities. Some software is costly, even by the standards of US academics. Some programs must be compiled by the end user, which may require both installation of compilers and a moderate level of computing expertise. Some are dependent on operating systems or data management systems that are often not installed on widely available computers. In general, separately acquired programs will require programming by the end user to be compatible with each other.

RECOMMENDATION S1: *Owners of proprietary software ought to provide no-cost or low-cost licenses to users in low- and middle-income countries. Given the losses from earthquake disasters and the negligible cost to copy software, refusing low-cost licenses is analogous to pharmaceutical companies withholding life-saving drugs from low-income countries.*

Network processing packages offer "complete solutions" for routine operations, including data collection and management and computation of earthquake locations and magnitudes. These packages are the most important software for a seismological network, but producing new products will require other software.

PACKAGE	DISTRIBUTOR	OPER. SYS.	REQ. SW	WEB SITE
Network Processing Packages				
Antelope	BRTT	Solaris	Datascope	http://www.brtt.com/ http://www.indiana.edu/~aug/
EarthWorm	ISTI	Any	Oracle	http://www.isti2.com/ew/
SeisAn	Univ. of Bergen	Any	None	http://www.geo.uib.no/seismo/software/seisan/seisan.html
SeisComP – Seismol. Comm. Processor	GFZ, Potsdam	Unix	None	http://www.gfz-potsdam.de/geofon/seiscomp/
NDC-in-a Box	CTBT Org.			
Data Management Systems				
Datascope	BRTT	Solaris	None	http://www.brtt.com/
PDCC	IRIS	Java	MySQL	http://www.iris.edu/manuals/pdcc_intro.htm
Ad hoc Analysis Libraries				
IASPEISeismological Software Library	SSA	Any	None	http://www.seismosoc.org/publications/IASPEI_Software.html
CPS – Comp. Progs. in Seismology	Univ. of St. Louis	Any	None	http://www.eas.slu.edu/People/RBHermann/CPS330.html
SAC – Seismic Analysis Code	IRIS	Unix	None	http://www.iris.edu/manuals/sac/
Specialized Product Programs				
MTinv, Rftn	Penn. State Univ.	Unix	SAC	http://eqseis.geosc.psu.edu/~cammon/
hypoDD	Columbia Univ.	Unix	None	http://www.ldeo.columbia.edu/~felixw/DD.html

The choice of the network processing package can make it difficult to use the data in certain other software, which may require data in different formats. Data format translators exist but many are incomplete – they fail to fill in all of the fields required to make the translated copy fully usable – and poorly supported.

RECOMMENDATION S2: *Developers of both proprietary and open-source software ought to provide documentation on what fields in data formats need to be filled in order to perform specified analyses. A translator between two data formats should be open-source and run under widely available operating systems, and ought to be developed jointly by the two organizations owning the data analysis programs between which the translation is done.*

RECOMMENDATION S3: *Documentation for a specialized product program ought to include advice on using the program with different network processing packages.*

DATA DISTRIBUTION

In many low- and middle-income countries, reluctance to share data freely is widespread among operators of seismographic networks, who view many uses of their data by others as missed opportunities for undertaking similar projects themselves. Nevertheless, experience in the US suggests that seismology might advance more quickly in other countries that embrace more open data practices.

As in the US, moving towards more open data exchange would probably progress over tens of years in a process that includes governments and other funding organizations growing accustomed to evaluating the network operators by how widely the data are used. Confidence building measures might demonstrate that releasing data increases opportunities for interagency and international collaboration rather than exclusively freeing people from outside of the network to work independently of the operators. Such measures could include releasing

- continuous data in near-real-time from 10% to 50% of the stations in a network,
- multi-hour segments of data promptly for events larger than some threshold,
- continuous data from all stations three months to three years after it is collected,
- metadata to aid in data discovery and referral to the network operator.

The risks in undertaking confidence building measures include "complacency" (the measures might be misperceived as acceptable long-term arrangements) and a "slippery slope" (progressively more networks might adopt restrictive data policies).

> RECOMMENDATION D1: *An international seismological organization representing consensus among network operators in each of South America, Middle America, and Southeast Asia ought to propose confidence building measures for archiving data at the IRIS DMC that address the risks of complacency and a slippery slope.*

There might be less resistance to freely distributing data through regional centers, perhaps one within each of South America, Middle America and Southeast Asia to share data. This approach should ensure that intraregional agencies build capacity in data management technologies. At a finer scale, each regional center could be comprised of nodes in several different countries. A multimode approach is technologically more challenging and risks that only incomplete data might be available at times. The technological challenge might be addressed by leveraging systems used for distributed seismological data centers in the US and in Europe. The risk of incomplete data might be by firm commitments to allow storage of back-up copies at other nodes and distribution from the back-ups when the primary copy is inaccessible.

> RECOMMENDATION D2: *Seismological network operators within each of South America, Middle America and Southeast Asia ought to make plans for a regional data management center, possibly comprised of geographically distributed nodes.*

PRIVATE-SECTOR PARTNERSHIPS

Private industry is a key partner in any scheme for economic development – and seismologists and geophysicists find natural partners in the private sector in the petroleum and mining industries. These industries can take advantage of the skills of seismologists to discover and efficiently map mineral resources, they develop new methods and tools that can be adapted by other seismologists for academic goals, they require a steady supply of newly educated geophysicists, and they are often organized on a sufficiently large scale to form effective alliances with university consortia and government agencies. Petroleum and mining companies based in Africa and Europe have made essential contributions to AfricaArray – out of legitimate self-interest rather than exclusively from altruism – and it is likely that companies based throughout Asia and the Americas would have similar motivations to participate in a multi-faceted geophysical development effort in Southeast Asia, South America or Middle America.

> RECOMMENDATION P1: *Workshop participants from each of Middle America, South America and Southeast Asia ought to seek industrial partnerships in their own regions and in other countries with strategic interest in their regions.*

Mitigating earthquake hazards provides opportunities for capacity building. Modern, real-time monitoring systems are based on cutting-edge computer and communications technology, so their use could entail training technicians in these fields with a concrete objective of operating the systems with a high degree of reliability while also providing an opportunity for the trainees to gain pragmatic post-training experience. Once hazards begin to be well measured, there is a natural demand for more advanced engineering and urban planning to ensure that populations are properly protected.

> RECOMMENDATION P2: *International aid projects the fund purchases of seismographic instrumentation should include funding for sustained training and collaboration – over five years or more – to provide a reasonable likelihood that the systems can be operated and maintained indefinitely.*

NEXT STEPS

While this workshop with its extremely broad geographic scope was able to elucidate many of the steps that could lead to coupled geophysical monitoring and economic development, it was not possible to include representatives from the numerous government agencies and universities from each region that are involved in geophysical monitoring and education. Successful plans will require more comprehensive engagement of a larger cross-section of the communities in each geographic region.

> RECOMMENDATION N1: *Workshop participants from South America, Southeast Asia and Middle America should host regional workshops to develop more complete plans. Workshop participants from the US with research interests in each region should seek US funding at least for their own participation in regional workshops.*

Participants

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