U.S. Marine Seismic Reflection Acquisition Needs for the Next Decade
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Reflection Acquisition Needs
for the Next Decade

October 17-19, 1999

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Figure 1. Photos of Lamont-Doherty Earth Observatory's R/V Maurice Ewing (Images courtesy of John Diebold, LDEO and Tom Shipley, UTIG).
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EXECUTIVE SUMMARY

Seismic techniques have provided key data over the past fifty years, allowing geoscientists to better understand Earth’s subsurface physical properties, stratigraphy and structure. Seismic data have also proven crucial for correlating outcrops and boreholes. In the next decade, marine earth scientists are poised to benefit from revolutionary advances in seismic technology. To assess the new technologies and their potential impact on planned major science programs, 50 academic and industry representatives with expertise in marine reflection seismology held a workshop in October 1999. An important subtheme was to explore ways to improve access to technology and data by the broader community of earth scientists.

RECOMMENDATIONS

1. Recognize that current seismic data acquisition levels will not support projected science programs. To achieve these programs’ minimum scientific objectives will require an eight-fold increase in seismic data acquisition activities over the next decade. Budgetary remedies must be explored.

2. Develop one or more facilities to support two classes of seismic operations:
   - Portable 2-D and 3-D single channel seismic (SCS) and multichannel seismic (MCS) acquisition
   - Large UNOLS single-ship 2-D and 3-D seismic acquisition

   Provide a program of technology enhancement for these facilities. Establishing such NSF facilities should help meet the basic needs for the next decade. Many present shortcomings could be addressed by consolidating management and incorporating coherent community-based input to facilities operations.

3. Develop a seismic data archive facility to improve access for the broader scientific community and students. Currently there is no central archive or standard data formats.

4. Develop a multinational collaborative program for long-term contracting of commercial multi-streamer 3-D MCS. Major cost savings accrue with 6-month or longer contracts.

Fifty scientists met for two days in October 1999 to review U.S. academic marine seismic reflection acquisition activities, to assess the current and future technologies and the infrastructure required to meet science program goals, and to recommend funding, implementation and management strategies. This was the first such meeting since the publication of the National Oceanic Reflection Profiling Organization vision in 1986 (NORPO, 1986). The recent workshop comes at an exciting time in marine geosciences. We are at a fundamental threshold of beginning to visualize Earth in three dimensions (3-D) by actively probing the physical properties of the subsurface with compressional and shear wave energy. We are moving from simpler geometrical descriptions of the subsurface to more comprehensive investigations of the physical properties and spatial and temporal changes in rock properties associated with biological, geochemical, sedimentological and tectonic processes. We are also now establishing observational capabilities relevant to geologic problems at scales from single storm deposits to entire plate margins. Geoscientists have gained substantial experience with seismic exploration of the basic Earth systems and validation of geophysical measurements from the long-running Ocean Drilling Program (ODP) and its predecessor, the Deep Sea Drilling Project (DSDP). Thus, we are ready to make effective use of the newest 3-D imaging technologies and the emerging multi-component bottom cable technologies for improved estimates of the elastic properties of the subsurface.

Scientific planning activities within the marine geology and geophysics (MG&G) and related communities have identified specific scientific goals for the next decade (e.g., MARGIN, RIDGE/NEPTUNE, EarthScope, CODC/COMPLEX and MESH). All of these programs require a healthy seismic reflection infrastructure as part of the US academic research effort. While reflection seismology is a field of science, it is also a tool for geoscientists. An underlying theme of the workshop was to develop methods of bringing this powerful tool into wider use: enfranchise more scientists in experiment design and acquisition, and place these data in an effective data library as a legacy for the entire scientific community. To meet these goals the academic community must improve quality of data collection, ease access to the fundamental seismic shared-use equipment and provide opportunities to use commercially available specialized technologies.

The report of the 1996 Future of Marine Geosciences Workshop (FUMAGES, 1998) concluded that the current funding and management model for common-use equipment has resulted in a gradual degradation of many MG&G capabilities. This is a problem for permanent shipboard equipment as well as portable equipment. The FUMAGES meeting highlighted the need to identify, maintain, and improve key capabilities and create better linkages between facilities and users. Moving in this direction was a major goal of the present workshop. A recent review of the academic research fleet (Academic Fleet Review, 1999) focused on the science systems and technical support within the UNOLS fleet. The Academic Fleet Review made a number of recommendations to the National Science Foundation (NSF) to develop higher standards for shared use facilities, to continue introducing new technologies, and to emphasize quality control. The Review also recommended trial use of commercial operators in order to better serve investigators needing special capabilities.
The workshop began by reviewing existing systems and, for the case of multichannel seismic data, their usage since 1974. We had assessments of new technological opportunities that will have a significant impact on scientific endeavors and considered how to obtain use of these technologies. We recommend funding and management methods to improve capability, quality and system performance standards for academic systems. We also considered archiving and access to data. The huge positive scientific impact of the Incorporated Research Institutions for Seismology (IRIS) model of data management, distribution and access provides an important lesson that the seismic reflection community needs to consider. The workshop discussions and recommendations are presented in subsequent sections of this report.

### RECENT SEISMIC DATA ACQUISITION ACTIVITIES

With the advent of seismic profiling in the 1960’s and particularly the invention of the compressed air “gun” at Lamont-Doherty Earth Observatory of Columbia University (Lamont), seismic profiles were collected routinely into the mid-1970’s using a towed single channel hydrophone array (SCS). The results were millions of kilometers of profiles of the thin sediments and sedimentary structures above the oceanic crust and continental and island arc margins around the world. Collection of these kinds of data rapidly diminished with changes in funding of routine underway data acquisition. Long multichannel receivers (~2 km in 1974; up to 6 km in 1999), augmented with larger air gun systems, led to deep probing of the subsurface, including the Moho, the structure of spreading ridge crests and underlying oceanic lithosphere, portions of thickly sedimented continental and island arc margins, and subduction zones. These multichannel seismic (MCS) techniques produced a wealth of new ideas about Earth’s structure and history.

<table>
<thead>
<tr>
<th>Ship</th>
<th>Year</th>
<th>Rate</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>UTIG Green</td>
<td>1974-78</td>
<td>4.2 mo/yr</td>
<td>21 months</td>
</tr>
<tr>
<td>Lamont Conrad</td>
<td>1975-89</td>
<td>2.3 mo/yr</td>
<td>35 months</td>
</tr>
<tr>
<td>SIO Washington</td>
<td>1977-80</td>
<td>2.0 mo/yr</td>
<td>8 months</td>
</tr>
<tr>
<td>UTIG Moore</td>
<td>1979-87</td>
<td>2.6 mo/yr</td>
<td>23 months</td>
</tr>
<tr>
<td>Lamont Vema</td>
<td>1980</td>
<td>5.0 mo/yr</td>
<td>5 months</td>
</tr>
<tr>
<td>Lamont Ewing</td>
<td>1990-00</td>
<td>3.3 mo/yr</td>
<td>36 months</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td></td>
<td><strong>128 months</strong></td>
</tr>
</tbody>
</table>

Note: Months refers to nominal cruise lengths of about 30 days, actual projects were more or less than a month. Short cruises have been combined in the above estimates. This table is an approximation based on information from J. Diebold (LDEO) and T. Shipley (UTIG).

UTIG is The University of Texas Institute for Geophysics; SIO is Scripps Institution of Oceanography; Lamont is Lamont-Doherty Earth Observatory.
In the late 1970’s, the earlier SCS methods were upgraded to digital recording and became important for a variety of higher spatial-resolution problems associated with paleoceanography and neotectonics when used in conjunction with new seafloor swath-mapping tools. Academic use of digital SCS and updated versions of short multichannel receivers peaked at about six months per year during 1982-1988; today’s use has dropped to only a few months per year. Use of MCS data systems is easier to track because fewer ships were equipped for this work (Table 1; Figure 2). MCS acquisition reached a maximum of about nine months per year between 1975 and 1980. In 1981 it dropped to about 3.4 months per year for two decades, where it has languished, fluctuating between zero and seven months per year. An additional activity that needs to be considered is the use of chartered commercial, higher performance MCS acquisition systems. Since 1973 there have been at least seven such instances, the last occurring ten years ago (Table 2).

An informal survey was conducted of existing academic systems capable of digital recording of SCS and MCS data. Tables 3-5 summarize the characteristics of some of the larger systems in the U.S. Included are estimates of how often they are used, annual costs (in addition to the basic ship costs), and age of the systems. The R/V Ewing is the stalwart of the US academic capability following in the long tradition of Lamont ships that have conducted geophysical investigations around the world. Academic scientists from the US as well as other countries routinely use the R/V Ewing. One single-streamer 3-D program was conducted on the R/V Moore in 1987 and three have been completed on the R/V Ewing. Two 3-D programs are scheduled for 2000, one on the R/V Ewing and one using the Lamont portable system on the R/V Thompson. The Antarctic Science Associates R/V Palmer, supported through NSF’s Office of Polar Programs (O PP), is a system used only in the hostile ice conditions of Antarctic seas. The United States Geological Survey (USGS) has a suite of instruments that is available for use in formal joint projects with academic scientists and in other cooperative arrangements, but at present has no ship. The USGS seismic gear was used in a USGS/academic collaborative effort in the Puget Basin in 1998.
<table>
<thead>
<tr>
<th>Location</th>
<th>Year</th>
<th>Channels</th>
<th>Depth</th>
<th>Air Gun Array</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nazca Plate Peru-Chile Margin</td>
<td>1973</td>
<td>24</td>
<td>1600 m</td>
<td>4600 cubic inch array of 4 air guns</td>
</tr>
<tr>
<td>IPO D-USGS Cape Hatteras to Mid-Atlantic Ridge</td>
<td>1974</td>
<td>48</td>
<td>1700 cubic inch array of 23 air guns</td>
<td></td>
</tr>
<tr>
<td>EDGE Central California</td>
<td>1986</td>
<td>180</td>
<td>4500 m</td>
<td>6000 cubic inches</td>
</tr>
<tr>
<td>EDGE Eastern Aleutian</td>
<td>1988</td>
<td>240</td>
<td></td>
<td>7800 cubic inch air gun array</td>
</tr>
<tr>
<td>Carolina Trough</td>
<td>1988</td>
<td>240</td>
<td>6000 m</td>
<td>10800 cubic inches in array of 36 air guns</td>
</tr>
<tr>
<td>Cascadia</td>
<td>1989</td>
<td>144</td>
<td></td>
<td>4560 cubic inch air gun array</td>
</tr>
<tr>
<td>EDGE Mid-Atlantic</td>
<td>1990</td>
<td>240</td>
<td>6000 m</td>
<td>10800 cubic inch array of 36 air guns</td>
</tr>
<tr>
<td>SOURCE</td>
<td>Lamont-Columbia Ewing MCS</td>
<td>Lamont-Columbia Ewing High Res</td>
<td>Lamont-Columbia High Res Portable</td>
<td></td>
</tr>
<tr>
<td>--------</td>
<td>---------------------------</td>
<td>-------------------------------</td>
<td>---------------------------------</td>
<td></td>
</tr>
<tr>
<td>COMPRESSORS</td>
<td>20 air guns 2 subarrays 8500 in³ nominal 11000 in³ max</td>
<td>2 GI generator Injection (GI) guns 150 in³ each</td>
<td>2 GI guns 150 in³ each</td>
<td></td>
</tr>
<tr>
<td>STREAMER</td>
<td>2150 cfm nominal 3 x LMF 1075 cfm Ewing</td>
<td>275 cfm Price Ewing</td>
<td>135 cfm Price Portable</td>
<td></td>
</tr>
<tr>
<td>ACQUISITION SYSTEM</td>
<td>Syntron Syntrak SEGD</td>
<td>Syntron Syntrak SEGD</td>
<td>OYO DAS-1 SEGD</td>
<td></td>
</tr>
<tr>
<td>Equip. Funding</td>
<td>NSF, Columbia</td>
<td>NSF, Columbia</td>
<td>DOD, NSF</td>
<td></td>
</tr>
<tr>
<td>Operations Funding</td>
<td>NSF, ONR, Ind., +</td>
<td>NSF</td>
<td>ONR, NSF</td>
<td></td>
</tr>
<tr>
<td>Mean Usage</td>
<td>4 months/yr</td>
<td>1 month/yr</td>
<td>1 month/yr</td>
<td></td>
</tr>
<tr>
<td>Monthly Ops Cost</td>
<td>~$220 k/mo</td>
<td>~$75 k/mo</td>
<td>~$147 k/mo</td>
<td></td>
</tr>
<tr>
<td>Annual Ops Cost</td>
<td>~$880 k/yr</td>
<td>~$75 k/yr</td>
<td>~$147 k/yr</td>
<td></td>
</tr>
</tbody>
</table>
### Table 4: Other Digital Acquisition Systems in the Academic Community

<table>
<thead>
<tr>
<th>Source</th>
<th>Compressors</th>
<th>Streamer</th>
<th>Acquisition System</th>
<th>Acquisition Date</th>
<th>Equip. Funding</th>
<th>Operations Funding</th>
<th>Mean Usage</th>
<th>Monthly Ops Cost</th>
<th>Annual Ops Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scripps High-Speed SCS</td>
<td>3-waterguns 80 in³ 2-GI guns to 410 in³ 8-airgun array 45-4450 in³</td>
<td>analog AMD, Teledyne 3 x 1-channel 4-channel, 200 m</td>
<td>Univ. Hawaii A2D system 8 channels SEG Y</td>
<td>~1992</td>
<td>NSF, Scripps</td>
<td>mainly N SF</td>
<td>3 months/yr</td>
<td>~$36.7 k/mo</td>
<td>~$110 k/yr</td>
</tr>
<tr>
<td>W HO I Subscan</td>
<td>X-star sonar chirp 0.5-16 kHz</td>
<td>analog hydrophone array</td>
<td>EdgeTech Sparc20 SEG Y</td>
<td>1998</td>
<td>DOD</td>
<td>N SF</td>
<td>3 months/yr</td>
<td>~$20 k/mo</td>
<td>~$60 k/yr</td>
</tr>
<tr>
<td>Duke R/V Hatteras</td>
<td>airguns 1 to 40 in³</td>
<td>3 x analog ITI varying, short</td>
<td>Univ. Hawaii A2D system</td>
<td>1995</td>
<td>NSF</td>
<td>mainly N SF</td>
<td>once since 1995</td>
<td>$6-13 k/mo refurb.</td>
<td>$5-10 k/yr refurb.</td>
</tr>
<tr>
<td>University of Hawaii</td>
<td>2-airguns to 300 in³ 1-watergun 80 in³</td>
<td>analog AMG 6-channel, 150 m</td>
<td>Univ. Hawaii A2D system 1-8 channels SEG Y</td>
<td>1990-1999</td>
<td>DOD</td>
<td>various</td>
<td>0.75 months/yr</td>
<td>$60 k/yr</td>
<td>$2 k/yr</td>
</tr>
<tr>
<td>Cal State Long Beach</td>
<td></td>
<td>analog 2 x 1-channel</td>
<td>Univ. Hawaii A2D system 1 channel SEG Y</td>
<td>1993</td>
<td>NSF, state</td>
<td>N SF, state</td>
<td>0.3 months/yr</td>
<td>$5 k/mo</td>
<td>$2 k/mo</td>
</tr>
<tr>
<td>SOURCE</td>
<td>COMPRESSORS</td>
<td>STREAMER</td>
<td>ACQUISITION SYSTEM</td>
<td>ACQUISITION DATE</td>
<td>Equip. Funding</td>
<td>Operations Funding</td>
<td>Mean Usage</td>
<td>Monthly Ops Cost</td>
<td>Annual Ops Cost</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
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<td>------------------</td>
<td>---------------</td>
<td>-------------------</td>
<td>------------</td>
<td>------------------</td>
<td>-----------------</td>
</tr>
<tr>
<td>Antarctic Sci. R/V Palmer</td>
<td>6-air gun array of 5000 in³ 3 small airguns 7 GI guns</td>
<td>1200 cfm 2 LMF 1200 cfm</td>
<td>Analog ITI 2 single channel 48 chan 300 m 48 chan 1200 m</td>
<td>1994-1998</td>
<td>NSF</td>
<td>NSF</td>
<td>3 months/yr</td>
<td>~$67 k/mo</td>
<td>~$200 k/yr</td>
</tr>
<tr>
<td>Texas A&amp;M ODP</td>
<td>4 waterguns 80 in³ 2 waterguns 200 in³ 1 watergun 400 in³ 1 airgun to 1000 in³</td>
<td>Drillship</td>
<td>Analog 3 Teledyne 1 chan</td>
<td>1985-1994</td>
<td>ODP-N NSF</td>
<td>Industry</td>
<td>0.25 months/yr</td>
<td>~$67 k/mo</td>
<td>~$150 k/mo</td>
</tr>
<tr>
<td>Rice University</td>
<td>1-watergun 15 in³ 3 sleeve guns (10,20,40 in³)</td>
<td>50 cfm portable</td>
<td>Analog 1 ea ITI, Benthos, Teledyne all single channel 1 x 12 channel</td>
<td>1989-1996</td>
<td>ODP-N NSF</td>
<td>Industry</td>
<td>1 month/yr</td>
<td>~$150 k/mo</td>
<td>~$150 k/yr</td>
</tr>
<tr>
<td>USGS MCS Portable</td>
<td>16 airgun array (fits Thompson) chambers 80 to 1000 in³</td>
<td>600 cfm diesel 300 cfm electric</td>
<td>Analog Teledyne 96 chan 2400 m</td>
<td>mostly early 80's</td>
<td>Industry</td>
<td>USGS</td>
<td>0.25 months/yr</td>
<td></td>
<td></td>
</tr>
<tr>
<td>USGS High Res</td>
<td>2 GI guns 2 waterguns 14 airguns</td>
<td>50 cfm, 30 cfm Bauer 3000 psi portable</td>
<td>Analog ITI 24 chan 150 m 24 chan 250 m</td>
<td>USGS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
AVAILABLE TECHNOLOGIES

A series of workshop presentations reviewed past, present and emerging technologies. Reviewed first was the information provided in Tables 3 to 5 on the historical use and types of systems available in the US academic research fleet. A series of presentations and discussions covered newer and emerging technologies crucial for many identified scientific objectives of the next decade. Workshop attendees discussed several important concepts, including: survey nesting at a variety of overlapping spatial scales of resolution for 2-D and 3-D visualization of the subsurface; Ocean Bottom Seismometers/Hydrophones (OBS/H) for large-scale subsurface velocity control; and bottom cables for compressional and converted shear observations.

VERY HIGH RESOLUTION SYSTEMS

Two workshop presentations focused on high-resolution systems. These systems employ several different types of sources, including 3.5 kHz hull-mounted and towed systems, chirp technology in the 0.5 to 16 kHz range (Subscan), Uniboom, Sparker, generator-injector (GI) guns, water guns, and air guns (Tables 4 and 5). These high-resolution systems are coupled to a variety of receivers, including transducers and short hydrophone arrays. The 3.5 kHz systems have resurfaced as a useful tool for high speed surveying in support of paleoceanographic objectives. An example of a digitally recorded and minimally processed 3.5 kHz record showed significant promise for correlating piston and hydraulic piston core samples to seismic profiles (Figure 3).

LOW-FOLD HIGH SPEED SCS

One of the “old” technologies still of great importance is the low-fold 2-D single-channel seismic work needed to support paleoceanographic programs and other marine geology programs at relatively high (~8 kt), or very high ship speed (> 10 kt). This technology is rapidly disappearing in the UNOLS fleet, largely because the reflection seismologists are now concentrating on other scientific problems using other systems. Yet, low-fold 2-D seismic reflection is a critical geological tool that needs to be maintained for academic users. It has been more than a decade since these systems were upgraded. The systems were first made digital at Scripps, with continuing evolution up to the early 1990’s at the University of Texas and University of Hawaii. Relatively simple incremental improvements are possible that would allow for easier operations and minimize the need to use precious ship time for repair of outdated systems when the science program is mainly for other purposes such as sampling or seafloor surveying.

Fig. 3. Digital enhancement of Ewing 3.5 kHz records near ODP Site 1014 in the Tanner Basin (Janik et al., 1999).
A related class of instrumentation is the so-called high-resolution system at Lamont. This system is a portable, 48-channel, 600-m long array that can be coupled with a variety of broadband sources to collect data for objectives in shallow or deep water (Figure 4a). It currently represents the system of choice for high-quality, moderate ship speed, surface-towed systems. Its use is anticipated to increase in the next decade. A basic extension of this technology is used for high-resolution 3-D surveys with four to six very short streamers using an appropriate broadband source (Figure 4b). A typical geometry in shallow water is six streamers, each with 30-m separation, and shots every 15-m. One commercial example of such a system, a turnkey operation including ship and processing, costs about $26,000 per day. Surveying a 30 km² area would cost about $233,000 plus mobilization with a resulting 3-D spatial resolution appropriate for sediment “event” detection, such as storm deposits. A variety of these systems are used in shallow water engineering and hazard surveys. There are basic research needs for hazard surveys for shallow water drilling, for shallow water neotectonic and sedimentary processes studies, and in deep water for a variety of deep-sea biological, sedimentation, fluid flow, and tectonics studies.
CONVENTIONAL 2-D AND 3-D MCS

Conventional MCS acquisition, with continued upgrading, will remain the key component of mesoscale marine geophysical studies over the next decade. These studies require an acquisition system with a 6-km or longer streamer and the ability to deploy air gun arrays with capacities over 10,000 in³. This role is currently filled in the UNOLS fleet by the R/V Ewing, with the support of NSF and Lamont. Two-dimensional and three-dimensional surveying on the Ewing remains a cost-effective alternative to short-term commercial contracts (Academic Fleet Review, 1999). Having access to a ship such as the Ewing, scheduled by UNOLS, provides the flexibility needed to plan complicated programs involving multiple ships and instruments. The continued operation of the Ewing as a general-purpose ship helps reduce transit times between MCS programs spread around the world.
Commercial 3-D MCS

Acquisition of 3-D MCS data by the US academic community is expected to increase over the next decade (see discussion in Scientific Objectives and Planning section). Current 3-D MCS acquisition technology for commercial projects is vastly superior to academic efforts, and provides a possible model for future growth. A presentation on commercial 3-D work provided insights into the utility and operating methods of major oil companies contracting for surveys. Typical acquisition in 1997-1998 used multiple source arrays and six to eight streamers. Typical bin spacings are 30 x 25-m using 4000-m long streamers. Current short-term costs are $100,000 to $200,000 per day and provide data shot to detailed contract specifications. Longer-term contracts (six months or longer) are about $75,000 per day but with reduced specifications. Costs do not include mobilization, turn times, or processing (except quality control and final navigation). A 700 km² area survey, typical of the size currently being funded by NSF, would cost about $2.6 million at $75,000 per day. The presentation showed some of the improvements in economies and spatial resolution made possible by using multi-streamer ships.

Industry spends considerable effort balancing system performance with post-processing methods to compensate for acquisition problems. This is similar to what academic scientists do in 2-D work. A difference is the level of effort devoted to monitoring the acquisition so that intelligent decisions about acceptable deviations from the primary specifications are possible.

Companies work hard to combine projects in close proximity and work with other companies in adjacent blocks to reduce mobilization costs. The mobilization costs associated with commercial ships would, in all but the most opportune circumstances, preclude their use for a single academic experiment. This is particularly true for areas of scientific interest that lie outside the regions currently being commercially explored.

Fig. 6. On-board analysis shows noise associated with depth and compass units attached to the streamer. More importantly, the absolute amplitudes of the background noise are determined. ARCO uses these kinds of data to decide whether to continue data acquisition. If post-cruise processing can attenuate noise to acceptable levels, they continue acquiring data (courtesy of Mervyn Parry, ARCO).
Ocean Bottom Seismographs and Vertical Cables

Ocean Bottom Seismographs and Hydrophones (OBS/H) are an important component of seismic investigations. There is a continuing need for MCS and OBS/H projects because, when used together, they are powerful tools to explore the Earth. An Ocean Bottom Seismograph Instrument Pool (OBSIP) has been formed to enhance the availability of modern OBS/H with the initial participation of Scripps and Woods Hole working through cooperative agreements with the NSF. Additional information is available at http://victory.ucsd.edu/obsip.html. With the introduction of the large R/V Ewing source array it has become possible to complete profiles with OBS/H and land instruments to examine the crustal structure across entire continental or island arc margins. Another related technology is the vertical cable, which has become practical with recent improvements in storage capacity and power efficiencies. The vertical cable is a 10’s to 100’s of meters long hydrophone cable that is attached to a seafloor recording device (an OBS is easily modified). Its power is the ability to separate the downgoing and upgoing ray paths, which then provide the ability to greatly attenuate seafloor to sea surface multiples. The oil industry has been using these in hard-bottom, shallow water settings. Another potential advantage of this technique is the ability to image steeply dipping structures (e.g., vertical faults), which is impossible to achieve with surface-towed, normal-incidence systems.

Fig. 7. Two types of four-component cables systems showing different types of shipboard handling gear. Current systems are capable to 3000-m water depth (courtesy of Schlumberger).
FOUR-COMPONENT BOTTOM CABLES

The newest emerging technology is ocean bottom four-component cables (Figure 7). These are 3-component geophone assemblies plus a hydrophone (and thus called 4-C). This is similar to the OBS/H single instruments. The important difference is that the spacing of sensors is typically 25 to 50 m, similar to surface-towed MCS.

A ship can shoot a 3-D pattern to the sensors before the cable is picked up and moved. Resulting compressional (P) wave images are remarkably similar to those collected with surface-towed equipment. Questions about coupling were of such concern during the first deployments of bottom cables that submersibles and remotely operated vehicles were used to plant geophones. This type of deployment now appears unnecessary for most mud-covered seafloors. Converted shear (S) waves detected on the geophones produce record sections like the P sections, but with greater resolution because of the slower propagation velocity (Figure 8). Differences in the P and S sections are exploited for hydrocarbon detection. Additionally, the data can be analyzed for amplitude variations with offset in P and S, and produce good estimates of density. Thus, we have the ability to determine three of the important elastic parameters describing physical properties of the sediments and rocks.

To date, approximately 2500 km of 4-C data have been collected in the Gulf of Mexico and other hydrocarbon areas around the world. Approximately 60% of these surveys were to improve imaging, while the remainder was for physical property determinations. Present cables can be up to 6 km long and set in water as deep as 1000 m. A logging technology cable has already been tested to 3000 m depths. Bottom cable technology is improving rapidly with several major companies involved in development (Maxwell, 1999). It is feasible that sensor packages will soon shrink significantly (for example, the Mars “seismometer-on-a-chip” is the size of a thumb) opening up basic research in all water depths. The processing and interpretation techniques are still being developed and are formidable. However, given the potential power of these observations, the future is bright.
After the presentations on technology, Working Group One examined the broad outline of science objectives for the next decade plus the technology that will be needed to meet these objectives. The group also estimated the level of effort that will be required to carry out these programs (see Appendix 3 for details). The scientific rationales for these programs have been documented in a series of workshop reports, including those carried out under MARGINS, RIDGE/NEPTUNE, EarthScope, COMPLEX/CONCORD, and STRATAFORM. We also attempted to estimate needs of science programs that historically are funded from the “core” of NSF’s MG&G Program (hereafter referred to as core) based on existing and projected needs. A summary of the acquisition requirements is presented in Table 6.

**Table 6: Projected Seismic Acquisition Needs for the Next Decade**

<table>
<thead>
<tr>
<th>Summary (usage months)</th>
<th>Core</th>
<th>IODP Riser</th>
<th>IODP Non-Riser</th>
<th>MARGINS</th>
<th>MESH</th>
<th>RIDGE/NEPTUNE</th>
<th>EarthScope</th>
<th>Total Months</th>
<th>$ K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chirp</td>
<td>0</td>
<td>5</td>
<td>2.5</td>
<td>2</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>16.5</td>
<td>330</td>
</tr>
<tr>
<td>High-resolution MCS</td>
<td>10</td>
<td>7</td>
<td>2</td>
<td>10</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>32</td>
<td>3,520</td>
</tr>
<tr>
<td>High-resolution 3-D SCS (30 km²)</td>
<td>0</td>
<td>7</td>
<td>2</td>
<td>6</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>15</td>
<td>3,495</td>
</tr>
<tr>
<td>High-speed SCS</td>
<td>15</td>
<td>0</td>
<td>10</td>
<td>0</td>
<td>20</td>
<td>12</td>
<td>0</td>
<td>57</td>
<td>2,052</td>
</tr>
<tr>
<td>2-D MCS Ewing</td>
<td>20</td>
<td>8</td>
<td>7</td>
<td>51</td>
<td>0</td>
<td>18</td>
<td>18</td>
<td>122</td>
<td>36,600</td>
</tr>
<tr>
<td>3-D MCS Ewing (700 km²)</td>
<td>0</td>
<td>5.5</td>
<td>1</td>
<td>3</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>11.5</td>
<td>9,200</td>
</tr>
<tr>
<td>3-D MCS Commercial</td>
<td>0</td>
<td>5</td>
<td>0</td>
<td>5</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>13</td>
<td>34,125</td>
</tr>
<tr>
<td>4-C Bottom Cables</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>6</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>9</td>
<td>4,500</td>
</tr>
<tr>
<td><strong>TOTAL ($K)</strong></td>
<td>7,640</td>
<td>22,426</td>
<td>4,496</td>
<td>36,443</td>
<td>1,110</td>
<td>11,882</td>
<td>9,825</td>
<td>276</td>
<td><strong>93,822</strong></td>
</tr>
</tbody>
</table>

Note: The estimated total annual costs in this table is approximately $9.4 million, almost an eight-fold increase over the $1.2 million reported in Tables 2 and 3 for current activities. See Appendix 3 for details of this table’s construction.
CORE NATIONAL SCIENCE FOUNDATION PROGRAMS

Over the next decade traditionally funded NSF MG&G core projects will continue to need access to the broadest variety of technologies, but with more emphasis on higher resolution, 3-D and full elastic imaging, and physical properties. A few of the anticipated projects that may be expected in the next decade are listed below; there will surely be other programs requiring seismic reflection use that are not listed here because core science originates by unsolicited proposals. Table 6 summarizes the potential activity levels for the next ten years. The estimate uses one-half the present-day annual NSF use shown in Tables 2 and 3. We use a factor of one-half because approximately half of the current activities are funded from non-core special programs such as RIDGE.

LARGE IGNEOUS PROVINCES, OLD OCEANIC CRUST

Large areas of the oceans are not specifically covered in focused NSF programs. Many important problems related to Earth’s history of mantle dynamics, large igneous provinces (LIPS), and associated environmental changes, and Cretaceous-Jurassic crust remain virtually unexplored. This is primarily because the geophysical tools have not been particularly effective and the other major alternative, drilling, requires excellent regional and site specific characterization for effective use. To improve this situation will require significantly longer offset data, to 8 km, to obtain more continuous profiles of compressional velocity structure of the uppermost crust coordinated with OBS/H experiments. For a few potential deep-drilling sites, 3-D imaging will be required for 600-900 km² area.

GAS HYDRATES

Methane gas hydrates are common across many environments. Our perception of their significance grows as we discover how common they are, recognize their potential impact on environmental change, and appreciate their potential as an energy source and as a hazard to shallow drilling. Gas hydrate investigations will continue within other scientific programs but will also be focused into several sites that already have substantial geophysical and sampling programs. For instance, an existing 2-D seismic survey of Hydrate Ridge near the base of the Oregon accretionary prism suggests a complex subsurface plumbing system associated with hydrates there (Figure 9). During 2000, 3-D seismic data will be acquired to link the subsurface plumbing to active seafloor venting observed for the first time by Alvin during summer, 1999. The other NSF-funded 3-D seismic survey planned for 2000 is also imaging a gas hydrate system. In general, a better understanding of the dynamics of marine gas hydrate systems will require high-resolution broadband images of sedimentary architecture to about 1000 m below the seafloor. As the geographical areas are focused, nested scales of 3-D experiments over 100 x 200 km areas will be required. These will include shear-wave experiments that will require 4-C technology, including OBSs, ocean-bottom cables, and drill hole sensors.
EARTHQUAKE HAZARD STUDIES

Earthquake studies require observation of the geometry, style, and slip rates of active and recent faulting onshore and offshore. Many faults, such as the Santa Monica and Palos Verdes faults in California and the North Anatolian fault in Turkey, extend from offshore directly into densely populated areas. Seismic reflection data required to image the strata that record the activity of faults and related folds ranges from the highest possible resolution (1-5 m) to the greatest possible penetration (100 m to 10+ km). Three-dimensional data are required to correctly image complex 3-D geometry and the steep dips that are common around active faults. Many offshore studies will also require 4-D MCS data and/or OBS/H refraction/microseismicity programs. Deep imaging with long streamers and 3-D acquisition technology are needed to more accurately define the character and geometry of the seismogenic source region. Bottom cables and other “transition-zone” technology will allow observations across the shoreline to image active structure in the coastal zone.

HIGH-LATITUDE STUDIES

Arctic and Antarctic research is an area that has unique scientific questions and logistical problems. They are also regions with relatively little regional characterization compared to other ocean basins. These activities are largely supported by the NSF Office of Polar Programs but share some of the equipment and technology problems of work conducted at lower latitudes. Historically, there have been about 1-2 months per year for Antarctic seismic surveying, and almost none in the Arctic. These studies are not included in our analysis.
MARINE ASPECTS OF EARTH SYSTEM HISTORY (MESH)

Paleoceanographers have developed an ongoing, internationally coordinated effort to understand the natural variability of the Earth system through preserved geo-biologic records. The geologists are contributing to a broad, interdisciplinary program on global change. The anticipated use is on ships of opportunity underway between stations largely for assessing the sediment thickness and for high-resolution core correlation to depths of 50-100 m. Occasional targets will require deep-towed instruments for optimal resolution. Neogene drilling targets need high resolution (1-10 m) data in the upper 500 m while Cenozoic and Mesozoic studies need deeper penetration with the same resolution. Seismic lines are needed to identify intact sedimentary sections that will yield high-resolution, hi-fidelity records for paleoceanographic sampling — sites with hiatuses and slumps must be identified and avoided.

CONCORD/COMPLEX AND THE INTEGRATED OCEAN DRILLING PROGRAM (IODP)

The Ocean Drilling Program is a major component of marine geological research and is scheduled to end in 2003. A new program is being developed to provide a more integrated set of tools to explore the most important scientific issues. Two major planning conferences have been held: one in Japan, the Conference on Cooperative Ocean Riser Drilling (CONCORD), and one in Canada, the Conference on Multi-platform Exploration of the Ocean (COMPLEX). Both conferences addressed the subset of scientific questions related to the technology under consideration but focused on the deep biosphere, gas hydrates, rapid climate change, extreme climates, oceanic lithosphere architecture, earthquakes, rifting and large igneous provinces. The current plan, still under development, envisions two platforms in continuous use in low- and medium-latitude, deep-water regions, plus "fit-to-mission" platforms for high-latitude and shallow-water drilling.

All drilling requires site characterization, with a level of detail that depends on the geologic setting and potential drilling hazards. Sites need to be placed into a regional context for correlation purposes and chosen to minimize drilling time. A wide range of seismic investigations will be required to support drilling, and drilling in turn will allow for more powerful scientific conclusions to be drawn from the site and regional geophysical surveys. Table 6 includes only one-half the potential surveying needed to properly support drilling. It is expected that the other half will be conducted by international partners or be part of regional geophysical surveys conducted as parts of other science programs.
Continental margins and island arcs are regions of particular significance to society because of the concentration of populations, earthquakes, volcanic hazards and hydrocarbon and mineral resources in these areas. The US MARGINS program is formulated to stimulate new levels of research activities focused on understanding the processes that control the structure and evolution of these margins, including lithospheric deformation, magmatism and mass flux, sedimentation dynamics and fluid flow regimes. The objective is to combine theoretical, experimental and observational work on these problems. The MARGINS program, now international with the INTERMARGINS program, currently includes the Seismogenic Zone Experiment (SEIZE) and the Subduction Factory Experiment. Recent workshops were held to define the Sediment Dynamics and Continental Rifting experiments.

Fig. 10. Image of the 1987 3-D reflection project off the Pacific coast of Costa Rica (Shipley et al., 1992). The seafloor mound is a 100-m high mud volcano/diapir. The subsurface shows some fluid conduits extending through the slope sediments from the wedge but they are discontinuous. Diving found a seep community on the seafloor (McAdoo, 1996).
SEIZE

The SEIZE experiment focuses on understanding the seismogenic zone in subduction settings. The objectives are to understand the evolution of a margin and the physical properties changes that control sediment and rock rheology and, ultimately, stress and strain across the entire convergent margin. SEIZE has identified two major regions for observational work, the Japan Island Arc margins (Japan Trench and Nankai Trough) and the Pacific continental margins of Nicaragua-Costa Rica (Figure 10).

This program requires nested scales of 2-D, 3-D, and 4-D MCS data encompassing areas of 300 km x 150 km and smaller. While many data already exist, the regions are large and complex, requiring significant additional 2-D characterization. This will be the basis for several 3-D surveys, the first of which was completed off Southwest Japan in 1999. It is expected that at least three additional 3-D surveys (each on the order of 700 km²) will be required, plus some repeat nested surveys at higher resolution. Physical property characterization requires both compressional and shear wave information, though some can be obtained from 2-D surface-towed MCS and OBS instrumentation. A series of targeted projects using the bottom cable technology will be invaluable when it becomes available.

SUBDUCTION FACTORY

The subduction factory objectives include the role of subduction parameters as forcing functions in regulating chemical cycling and crustal growth, the volatile cycle through subduction zones, and understanding mass balance and continental growth. To a large extent the observational needs are similar to the SEIZE experiments, and one of the focus areas is shared with SEIZE (Nicaragua-Costa Rica). The other identified focus area is the Izu-Bonin-Mariana Island Arc margin, an immense area with few modern seismic surveys. It is expected that three months per year of 2-D MCS will be required for several years. Nested scales for seafloor venting of fluids, serpentinite vents, serpentization within the mantle wedge, and mass flux at depths of 15 km or more will require a series of surveys at several resolutions.

SOURCE-TO-SINK

The MARGINS sediment dynamic objectives are to understand the paths followed by sediments from their source to their ultimate depository and the impacts of these processes on the environment. The resultant stratigraphy on margins is a high-fidelity tape recording of Earth history. Seismic surveys across continental margins need to include imaging systems with different resolving capabilities in order to examine stratigraphic sequences at a variety of spatial scales. Multiple surveys with overlapping ranges of frequencies are needed to determine the origin of seismic reflectors, quantify reflection coefficients, and assess the spatial variability of reflectors. By acquiring high-resolution seismic images of the stratigraphy across continental margins and sedimentary basins at a variety of scales (i.e., nested surveys) in conjunction with swath mapping, lithologic, and physical properties data, it will be possible to examine the link between formative geologic processes and the resulting stratigraphy (Figure 11).

The nested survey approach employed by ONR's STRATAFORM program and potentially by the Source-to-Sink experiment requires a number of seismic imaging systems from chirps and high-frequency boomer to single channel seismics with GI guns to high-resolution, deep penetration multichannel seismic data. The major objectives of these programs will require many 2-D surveys (two to three months per year), limited 3-D surveys (one month every 2 years), and rare 4-D surveys (one month after a substantial event, e.g., flood or earthquake).
Continental Rifting

The continental rifting component of MARGINS focuses on active rifting processes—deformation and magma production. The MARGINS program has identified the deformation of the continental lithosphere at unexpectedly low stress magnitudes as an example of the misunderstanding of some of the most basic properties of the lithosphere. There are two major focus areas for this program: the Gulf of California and the Gulf of Suez/northern Red Sea. The observational part of these programs requires much better determinations of stress and strain and their spatial and temporal variations. Ultimately this is perhaps the biggest challenge to our suite of seismic techniques. It will require nested scales of 2-D MCS, 3-D MCS, and possibly 4-D MCS data starting at scales on order of 300 km x 150 km areas. There are few modern studies of continental rifting so there is a need for more general characterization using conventional 2-D MCS acquisition of about 3 months per year before selecting smaller areas for more focused nesting and 3-D work. Deep penetration will be required with active-source imaging coordinated with OBS/H and earthquake studies.
RIDGE/NEPTUNE

The RIDGE Program focuses on oceanic ridge crest processes, and is scheduled to end in 2001. The recent wave of technological advancement with 3-D and ultra long-offset 2-D seismic will be needed to continue exploration of fundamental ridge crest-related processes. A new initiative is being developed that may require MCS on slow- and intermediate-spreading ridges. For slow-spreading ridges 3-D will be required to image low-angle faults over areas of 600-900 km² coordinated with OBS/H programs. Four-dimensional (temporal 3-D) MCS may be the appropriate tool for monitoring changes in axial magma chambers. In addition, a new initiative, NEPTUNE, is being planned for placing long-term observatories on the seafloor. The NEPTUNE project, which will include a variety of seafloor observatories linked by a fiber optic cable encompassing the entire Juan de Fuca plate system, will have nodes dedicated to plate boundary (ridge, transform and subduction) and intraplate biogeochemical processes. To fully exploit long-term time-series data related to biological, tectonic and fluid flow processes that would be acquired during the NEPTUNE program requires seismic reflection imaging at multiple scales to characterize the subsurface structure. An important component of both the site location and site characterization will be 3-D MCS surveys. These new programs are likely to require three months per site over six to eight years.

EARTHSCOPE

A new program, EarthScope, is moving rapidly through the planning and funding process (Henyey et al., 2000). A major objective of this program is to provide the ability to collect seismic data at high spatial resolution across the entire continental US and its margins. The expectation is that the spatial density will provide resolution of structure within the upper mantle and crust at scales of ~10 km. The USAarray instrumentation and facilities support, a component of this program, is currently being considered as a potential Major Research Equipment project (Meltzer et al., 1999). If this project is successful there will be a need for substantial work offshore with both ocean bottom seismographs, 2-D multichannel, and active sources in the adjacent ocean margins to fully probe the structure of the continental margins.

SUMMARY OF USE NEEDS

Table 6 is a minimal estimate of the needed seismic activities over the next decade. Even at this level, many of the programs already underway and in the late stages of planning will be unable to fully meet their science plans, resulting in slowed scientific progress and many disappointed scientists. There is almost an 8-fold mismatch between current and needed funding. The workshop thus makes the following recommendation:

- Recognize that current seismic data acquisition levels will not support projected science programs. To achieve these programs’ minimum scientific objectives will require an eight-fold increase in seismic data acquisition activities over the next decade. Budgetary remedies must be explored.
The preceding sections provided the scientific rationale for the kinds of technology we need now, likely future technology development, and a basis for how much these systems will be used. The workshop then considered issues of access and the best choices among traditional and nontraditional alternatives (e.g., contractors, NSF-facilities, individual PI initiatives, cooperative agreements with other federal agencies and other countries). A key element was to consider what kinds of changes and innovations would improve access by a wider range of geoscientists than currently use seismic reflection tools. To achieve this, seismic equipment and services must be better coordinated, scheduling must become more transparent, and the barriers to use must be reduced. The level of acquisition technical expertise required by the research scientist can and should be greatly reduced; investigators should be free to concentrate on scientific analysis and interpretation.

**Recommendations for Specific Systems**

**Very-High Resolution**

The quality and value of 3.5 kHz data can be enhanced with relatively straightforward processing and display. Digitizing typical windowed data (possible on multibeam-equipped ships) might accumulate 300-600 MB per day, no longer a significant volume. It would be desirable for multibeam-equipped ships in the UNOLS fleet to move to digital recording of 3.5 kHz echo sounder data. Eventually it would be desirable for these ships that have not already done so, to add chirp systems for improved resolution.

Very high-resolution systems are generally small, portable, and operated by individual scientists or technicians. Concern was expressed that there are still many users of analog systems in coastal and shallow water environments that are not capable of supporting digital systems. This is principally a case of the ‘tool’ mode of operations. More support is required for maintenance of and accessibility of these systems for the class of users who do not use UNOLS large vessels or do not reside at one of the major oceanographic centers.

**Low-Fold, High Speed**

Reliability is the primary need for low-fold, high-speed data acquisition. Reliability can be accomplished by improving streamers and sources that can be towed at relatively high speeds (~12 knots) collecting as good quality data as possible in conjunction with swath bathymetry or underway between stations. At least one such system should be available on both the west and east coasts.
CONVENTIONAL 2-D AND 3-D MCS

The R/V Ewing is our only academic seismic vessel, so we should strive to make it the best possible acquisition platform with as much flexibility as possible. Cost-effective, short-term commercial operations usually mean giving up long-term planning and collaboration for experiment synergy, often a major factor in previous R/V Ewing programs. Having an updated Ewing-style capability within the UNOLS fleet provides the flexibility in location and scheduling needed to ensure that scientific rather than logistical considerations are paramount in the selection of field programs.

One important Ewing enhancement would be to increase the maximum offset of the streamer to 8 km, benefiting studies of deep targets. This increase would enhance the ability to do continuous velocity profiling of the upper crust in deep water and to do amplitude-versus-offset studies of important reflectors. A second important enhancement would be to configure the MCS acquisition system so that it could deploy the long streamer used for 2-D acquisition as two or more streamers and also two source arrays. This arrangement, by alternate firing of the source arrays, allows the collection of four in-lines (closely spaced, parallel common midpoint lines) of 3-D data on each sail line. This procedure is particularly effective for shallow targets and shallow water depths. In deep water or for deep targets, long recording lengths would lead to a potential shot spacing of 100 m. In this case three streamers and a single source might be a better option, producing three CMP lines per sail line. Flexibility of multi-streamer operations would be a considerable improvement over current practice of using a single streamer, allowing more efficient collection of better quality 3-D data with improved cross-line spacing. In particular, as the exploration industry learned over a decade ago, a significant amount of the time spent on a 3-D seismic survey was downtime during the turns from one sail line to the next. The cost-effectiveness of 3-D seismic surveys increased dramatically when multistreamer technology was utilized.

Based on the needs outlined above, there is a clear strategy for improving the R/V Ewing’s capabilities. There are many tradeoffs to consider, including cost, reliability and feasibility for a ship the size of the Ewing. Therefore, a facilities committee should investigate these issues and provide recommendations before substantial upgrades are made. In summary, some possibilities are:

1. Incorporate the latest solid-state streamer technology. This should provide the flexibility to tow a single 8-km streamer or eventually up to four shorter streamers. At the same time, the airgun arrays need to be modified to allow for firing of alternate arrays. This would allow us to conduct small-scale, multi-streamer 3-D surveys with dual source arrays, or to conduct a 2-D survey with an 8-km streamer and a single source array.

2. Improve shipboard quality control by enhancing the streamer and air gun monitoring software and, perhaps, by hiring industrial consultants who are experienced in shipboard acquisition quality control. This will also require additional hardware and software to allow users to produce a shipboard brute stack and simple post-stack migration of 2-D data.

3. Upgrade the navigation system and technical support to allow users without their own technical experts to conduct quality-controlled 2-D and 3-D projects and depart the ship with a standard UKO O A navigation file.
HIGH-RESOLUTION PORTABLE 2-D AND 3-D

Unlike large, long-offset MCS systems, typical high-resolution systems are sufficiently portable that they could be installed on a UNOLS vessel for a single acquisition program. However, actual portability of such systems among ships needs to be investigated further, especially with regard to the complex acoustic navigation system needed to track the various towed components. Complete portability may be incompatible with reliable system operation, and it may be better to equip a few vessels in the UNOLS fleet with necessary acoustic navigation and 3-D system modifications. The purchase cost of a three streamer, high-resolution system for installation on a UNOLS vessel would be on the order of $1M. With such a system the same streamers and recording systems could either be operated on demand as a 3-D acquisition system or dispersed and used as 2-D streamers depending on project requirements.

In contrast, the attractions of commercial charter arrangements include access to a broader range of high-resolution systems, which might allow better tailoring to a specific project, access to the latest technology, and more comprehensive technical support for data acquisition. At present, potential users of commercial equipment tend to be at a disadvantage relative to users of UNOLS equipment, particularly because of mobilization costs.

COMMERCIAL LONG-OFFSET 3-D MCS ACQUISITION

A two-pronged approach to providing long-offset, 3-D acquisition capabilities is proposed. For large 3-D surveys, in addition to the R/V Ewing, commercial systems are necessary to cover larger areas more efficiently than possible with the UNOLS ship. These surveys would be best carried out via chartered industry vessels that can make use of eight to twelve streamers. Six-month or longer charters may reduce the cost rates by 25% or more. The most viable option is international collaboration to allow joint leasing of a vessel for periods of six months or more, perhaps biennially. The projected amount of 3-D acquisition by the US research community does not allow the US to do this alone. Collaboration in an international partnership along the lines of the Integrated Ocean Drilling Program (IODP), with the requisite planning committees is an option to explore (Coffin et al., 1998).

FOUR-COMPONENT BOTTOM CABLES

Access to 4-C bottom cables is extremely limited at present. This is an emerging technology, which will undergo substantial changes. In the next decade we do not see a compelling reason to consider UNOLS operation of its own 4-C acquisition system. Several commercial contractors are interested in working with academic groups having seafloor instrumentation and signal processing expertise. By the end of the decade, we may have specialized needs for 4-C that depart from what will be available in industry. Envisioned are extremely long cables (10’s to 100’s km) employing the latest in miniature geophone sensors. Such technology may well replace current active source OBS refraction. Cable-laying equipped ships will be needed sometime in the next decade and this should be evaluated as part of the ongoing UNOLS fleet development. Cable-laying technologies are also likely to become important to other sorts of academic marine science initiatives.
HIGH-LATITUDE TECHNOLOGY

With regard to surface towed seismic systems, the Arctic and Antarctic operations have problems similar to the rest of the UNOLS seismic operations. There is a need to improve the short, high-resolution MCS and SCS streamers in current OPP vessels, striving for less effort to maintain the over-the-side equipment and better technical support. With the new R/V Healy coming into service soon there is an opportunity to consider what seismic instrumentation will be appropriate, though an emphasis on high-resolution surveys for shallow-water drilling in Antarctica is a likely starting place.

IMPLEMENTATION STRATEGY

The workshop participants agreed that the best way to implement the above specific recommendations was to establish one or more national facilities where equipment, technical expertise and appropriate user input could lead to improved quality and services. In addition, there is a need to begin commercial contracting and planning for the UNOLS replacement for the R/V Ewing retirement expected in 2010-2015.

NATIONAL FACILITIES

There are currently no official national facilities for seismic acquisition. Establishing one or more NSF facilities for seismic acquisition should go a long way to meeting the basic needs for the next decade. Many current shortcomings could be addressed by consolidating management and incorporating coherent community-based input to facilities operations. In the current mode of seismic acquisition, an undue burden is placed on the operating institution (e.g., Lamont with the R/V Ewing). Intermittent funding makes retaining technical expertise difficult and improving services next to impossible. The academic community treats the Ewing as a national facility even though its funding is tied to specific projects. This creates problems between expectations of the scientists and the ability of the operator to satisfy these expectations. A national facility would provide the resources and capabilities necessary to meet community needs and would permit continuity of funding to sustain basic equipment, personnel, and technical knowledge even when there is a minor pause in projects (the workload for MCS operations has recently varied from 0 to 7 months in a single year). Load balancing is also a problem for low-fold, high-speed SCS operations. The objectives of a facility should be to (1) provide improved performance and reliability, (2) make access easier for more scientists, (3) advance acquisition technology through system upgrades, and (4) reduce the need for specific knowledge of details of seismic data acquisition. An external oversight committee should include the operators, industry representatives and selected principal investigators to review performance and provide guidance on standards for navigation, output formats, quality control and future directions. A number of examples of these committees extend across NSF. Facilities designation is a major commitment from the scientific community that needs to be periodically reviewed to ensure that the facility is still scientifically relevant and facilities should be open to re-competition at an interval of 5-10 years.

Generically, a seismic facility or facilities may or may not be geographically distinct. It might consist of multiple, geographically dispersed, physical entities that have cooperative agreements and plans to share equipment. There are a number of ways that entities could be grouped into a logical set of one, two or three facilities to meet the needs of the academic community. To conform to the descriptions of systems given earlier we will continue to use
that terminology. Below is one example of how two facilities, Portable Seisms and Single-Ship Seisms, could be organized. We reiterate that a number of other models would work just as well. The examples below are based in part of our expectations of use over the next decade, and some practical realities based on the management of existing systems, the rarity of well-trained technical staff and the expense of maintaining operations that are not fully subscribed. In the case of seismic reflection acquisition, many of the basic skills and knowledge are applicable across a range of distinct technologies so that opportunities for sharing technical help are good.

**PORTABLE SEISMIC FACILITY**

An academic facility for portable seismic acquisition would support seismic acquisition on a wide variety of ships. Systems supported would include conventional low-fold, high-speed SCS acquisition now conducted on the R/V’s Hatteras, Revelle, Melville, Thompson, Wecoma, and others. This same facility could also include high-resolution, short-streamer 2-D and 3-D MCS acquisition. An important function of this facility would be to provide expert services, advice and contact information for other instrumentation not run directly by the facility. The portable facility is probably most useful in the area of shallow-water and shallow-penetration geophysics, for which there is much equipment available around the country. We assume that onboard processing would usually be provided for this class of operation by the facility (the exception might be 3-D and other specialized programs). This allows for turnkey operation and final products for non-seismologist geoscientists. There is plenty of equipment spread among institutions (e.g., 13 G.I. guns, five portable compressors, and seven built-in compressor systems on the R/V’s Ewing, Revelle, Melville, Hatteras, Palmer, Thompson and D/V JOIDES Resolution). Scheduling, equipment pooling, dedicated technical support, and coherent management are currently lacking. We imagine east and west coast subdivisions of a single facility to reduce transport costs, and more importantly, to maintain expertise related to specific ships and marine operations groups that is critical for success.

The facility would be responsible for scheduling equipment and technical support. This should start at or before the time of proposal submission, helping the investigator match equipment and scientific needs. It is expected that the facility would arrange for technical support during acquisition, using either their own employees or those from UNOLS Research Vessel Technical Enhancement Committee (RVTEC), other institutions, or consultants as appropriate. Hardware would initially reside in the shared-use pool with the possibility of consolidating some equipment and technical operations to a few geographically separated locations to reduce shipping and travel costs, and upgrade the systems as described in this report with guidance from a facility oversight committee. The technical support would include providing hardware and software tools to monitor acquisition performance, and enough knowledgeable help in setting up initial parameters for such things as sample rates, anti-alias filters, and preamplifiers. The facility would also be responsible for navigation systems and software to locate the source and receiver positions as appropriate to the project.

To make these data readily available to the community, there must be a set of standard deliverables to both the principal investigator as well as the data center described in a later section. This would include standard formats for the raw data and complete navigation output into standard navigation formats.
**SINGLE-SHIP MCS SEISMIC FACILITY**

The single-ship MCS facility would support seismic acquisition on a single dedicated MCS-capable ship, although that ship need not be dedicated purely to seismic data acquisition. Similar to the portable seismic facility, the single-ship MCS facility should provide the preponderance of technical support during acquisition, including pre-proposal interaction to use the facility’s knowledge of data acquisition and matching these with scientists’ data expectations. At-sea support for seismic acquisition would include providing the tools and knowledge base to help the investigator make decisions about the acquisition performance relative to the goals of the project. This will need to include support for basic onboard processing and copying of seismic data for collaborative partners and the data center. It is also important that navigation hardware and software be supported, including information to the bridge for steering the ship in various coordinate systems, processing of navigation to produce shot and receiver locations, and producing an industry-standard navigation product. For scientists who are not seismologists or even geophysicists, there is a need for processing support. Data processing for scientists would not be the role of the facility, but it could act as a coordinator of available personnel and resources.

The workshop makes the following recommendation:

- **Develop one or more facilities to support two classes of seismic operations:**
  - Portable 2-D and 3-D single channel seismic (SCS) and multichannel seismic (MCS) acquisition
  - Large UNOLS single-ship 2-D and 3-D seismic acquisition

  Provide a program of technology enhancement for these facilities. Establishing such NSF facilities should help meet the basic needs for the next decade; many present shortcomings could be addressed by consolidating management and incorporating coherent community-based input to facilities operations.

**COMMERCIAL CONTRACTING**

Another issue is how to lower the hurdle for access to contractor-supplied services. One possibility would be for these facilities to act as an interface among investigators, contractors and UNOLS. As far as practicable the difference in access to commercial equipment and services should be made similar to that for shared-use equipment. For inexperienced scientists, negotiating with contractors can be a daunting hurdle. This should not, however, preclude individual contacts because special relationships between academic and commercial ventures can sometimes make key technology available at unusually low cost. Considerable experience and knowledge is required to advantageously use contractors on short-term programs. Quality control standards developed by the seismic facilities for their own use should provide an important component of the commercial contract as well as a basis for shipboard monitoring of the contractor performance.

The workshop makes the following recommendation:

- **Develop a multinational collaborative program for long-term contracting of commercial multi-streamer 3-D MCS.** Major cost savings accrue with six-month or longer contracts.
PLANNING FOR THE NEXT UNOLS SEISMIC-CAPABLE VESSEL

Sometime in the period 2010 to 2015 the R/V Ewing will be retired, having reached the end of its service life. No arguments have emerged to support completely replacing academic seismic acquisition facilities with commercial operations. There are fundamental arguments for the potential of both an academic system and a commercial operation for special parts of our future needs. There is no serious debate that 8-24 streamer MCS is a clear priority for future work and should be undertaken with commercial contracting. But the key feature of an UNOLS vessel is the ability to contain costs by linking a diverse set of scientific programs in an effective worldwide operation (e.g., fewer unproductive transits). Other important considerations include the flexibility in scheduling, coordination of complicated experiments and equipment, and the matching of scientific objectives to the best cost-effective solution.

Two forces will shape the capabilities for the next academic seismic-capable ship: the need for good quality seismic capabilities and to simultaneously fully meet the general oceanographic needs as well. We expect that in the 10-15 year time frame we should expect a seismic ship that includes the ability to do modest, but high-quality, 3-D work with four to eight shorter streamers or fewer streamers of 8 km or longer. The technology has been rapidly moving towards much smaller diameter cables without oil-based buoyancy systems. The ship will need to be of sufficient size for deck handling gear for these multiple streamers, multiple source arrays, and permanently installed compressor systems.

A second seismic technology that will need careful monitoring is the emerging 4-C bottom cable. This technology is only a few years old but it has such important ramifications to earth scientists by providing fundamentally new observations about physical properties. Currently the only instruments that measure the same phases are 3-component OBS’s, but these are not appropriate to many scales of geologic problems. Having a bottom cable up to tens of kilometers long with thousands of seismometers is not impossible within a decade.

The workshop makes the following recommendation:

- **Begin planning for a UNOLS seismic vessel anticipating the retirement of the R/V Ewing in 2010-2015.**
DATA ARCHIVING AND COMMUNITY ACCESS

Improving accessibility to seismic reflection data may be the single most important component of any strategy to increase the scientific returns from marine reflection activity in the next decade. A top priority should be to improve access to NSF-sponsored seismic reflection data sets for all sectors of the academic community by establishing a data management facility and archive. Success in this effort promises to lead to better education of earth science students and to more and better multidisciplinary research proposals, which will better prepare those students interested in careers in the hydrocarbon industry.

Many existing geophysical data sets are or could be important to investigators. These data are distributed around the nation, in the archives of oceanographic institutions and on shelves in scientists’ offices. It would be difficult to retrieve them all. Even so, submission of important data sets to the data center should be encouraged. Data sets now being collected are more manageable and it should be possible to adopt standard formats, data submission requirements, and management procedures and to advertise data availability to the scientific community.

Two kinds of seismic reflection data need to be made accessible. The first is field data, including shot gathers, navigation, geometry of the experiment, and observer logs, with normal at-sea quality control, and all in digital form. Access to these data will allow other investigators to independently reprocess and interpret data sets that are unusually important or controversial. Replications of effort will not be common in the near future but may become increasingly so with continued improvements in computers and software, and as these data sets are used in more university classrooms. It is essential that archiving of these data sets be done in a common format and with all ancillary data sets needed for independent processing, especially navigation and observer logs. It seems simplest to implement a procedure whereby it is the seismic facility operator’s responsibility to provide these data to the archive.

The second kind, processed data, should also be deposited in the data center. These data will be valuable to geologically oriented seismic interpreters using a variety of commercial software packages and thus should be in a standard format (SEG-Y seismic data format and a UKOOA navigation format). Processed products should include a zero-offset section for 2-D data, which is either migrated or stacked, and which includes a processing history that interested users of the images can understand. Equivalent products and information should be provided for 3-D and 4-D MCS, and related (bottom cable, vertical hydrophone arrays, etc.) data sets. The data center should produce images of processed data sets for online display. In addition, the data center should be responsible for maintaining an on-line data catalog which would list availability of geophysical data sets, browseable images, and when new data sets are expected to become available. Transfer of data should be over the Internet where possible, with copying to other media as appropriate.
Improved access to seismic reflection and other geophysical data sets can best be obtained by depositing them in an archive. Establishing an archive identifies a responsible data manager, and this responsibility can be expected to assure data quality, ensure efficient storage, permit economies of scale in updating mass storage and data transfer technology, expedite timely release of data, and simplify monitoring of compliance. An academic institution or IRIS Data Management Center could be designated as a national archive facility. While the data center would necessarily work with NGDC, the latter agency may not have either the expertise or close scientific liaison to be effective as the sole archive.

Research programs supported by NSF are required to make the data available after a reasonable amount of time and any data collected under NSF auspices ultimately reside in the public domain. Processing and interpretation of MCS data is a time-consuming and computer-intensive task, so the time period for releasing processed data needs to be reasonable. Even so, in the interests of maximizing access to the larger scientific community, it is recommended a period of no more than a year (following completion of the project) of data monopoly for the field data and three years for processed data.

The workshop makes the following recommendation:

- **Develop a seismic data archive facility to improve access for the broader scientific community and students. Currently there is no central archive or standard data formats.**

Normally, acquisition facilities should not be directly connected to a seismic data center because of a potential conflict of interest. While there is need for interaction in the area of quality control, the acquisition facility should be charged with providing a high-quality product for the data center. The data center should receive data from the facility and judge whether or not it meets the specified standards.
SUMMARY OF RECOMMENDATIONS

1. Recognize that current seismic data acquisition levels will not support projected science programs. To achieve these programs’ minimum scientific objectives will require an eight-fold increase in seismic data acquisition activities over the next decade. Budgetary remedies must be explored.

2. Develop one or more facilities to support two classes of seismic operations:
   - Portable 2-D and 3-D single channel seismic (SCS) and multichannel seismic (MCS) acquisition
   - Large UNOLS single-ship 2-D and 3-D seismic acquisition

   Provide a program of technology enhancement for these facilities. Establishing such NSF facilities should help meet the basic needs for the next decade, since many present shortcomings could be addressed by consolidating management and incorporating coherent community-based input to facilities operations.

3. Develop a multinational collaborative program for long-term contracting of commercial multi-streamer 3-D MCS. Major cost savings accrue with six-month or longer contracts.


5. Develop a seismic data archive facility to improve access for the broader scientific community and students. Currently there is no central archive or standard data formats.
The workshop participants are optimistic about substantially improving academic seismic studies and are united in the desire to make data more accessible to researchers, educators, and students. Participants are also keen to involve more of the scientific community in 2-D and 3-D seismic data acquisition by reducing the level of expertise needed in navigation and seismic acquisition. By shifting much of the burden for navigation and seismic acquisition to facilities, more scientists will be enfranchised in modern seismic reflection techniques. In the same way, reducing the need for detailed knowledge of standard high-speed seismic work should greatly benefit the non-seismologists who need these data as part of other geologic investigations. The workshop enjoyed a glimpse of emerging four-component bottom cable technology, which will revolutionize how we gain an understanding of sediment and rock physical properties in the next decade.
REFERENCES


GLOSSARY

Alvin ..........................................Manned Research Submersible named after Alan Vine
BSR ............................................Bottom Simulating Reflector
CMP ..........................................Common Mid-Point
C O M P L E X  ......................Conference on Multi-Platform Exploration of the Ocean
C O N C O R D  ......................Conference on Cooperative Ocean Riser Drilling
D O D ........................................Department of Defense
D S D P .....................................Deep Sea Drilling Project
EDGE ..........................A program that used seismic reflection to study continental margins
4-C .............................................Four-Component
F U M A G E S ......................Future of Marine Geology and Geophysics
GI ............................................Generator Injector
HiRes ........................................High Resolution
IRIS ........................................The Incorporated Research Institutions for Seismology
I T I ............................................Innovative Technologies Inc.
I O D P  .....................................Integrated Ocean Drilling Program
JOI .................................Joint Oceanographic Institutions, Inc.
LIPS ........................................Large Igneous Provinces
LMF ..........................................Leobersdorfer Maschinenfabrik AG
M A R G I N S .......................A geology and geophysics program studying continental margins
M C S .......................................Multichannel Seismic
M G & G  ....................................Marine Geology and Geophysics
M E S H  ......................................Marine Aspects of Earth System History
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>NGDC</td>
<td>National Geophysical Data Center</td>
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<tr>
<td>N O RPO</td>
<td>National Oceanic Reflection Profiling Organization</td>
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<tr>
<td>NSF</td>
<td>National Science Foundation</td>
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<tr>
<td>OBS/H</td>
<td>Ocean Bottom Seismometer/Hydrophone</td>
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<td>OBSIP</td>
<td>Ocean Bottom Seismometer Instrumentation Pool</td>
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<tr>
<td>ODP</td>
<td>Ocean Drilling Program</td>
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<tr>
<td>ONR</td>
<td>Office of Naval Research</td>
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<tr>
<td>OPP</td>
<td>Office of Polar Programs, National Science Foundation</td>
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<tr>
<td>P</td>
<td>Compressional Wave</td>
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<tr>
<td>RF</td>
<td>Reflectivity Front</td>
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<td>RIDGE</td>
<td>Ridge Interdisciplinary Global Experiment</td>
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<td>RVTEC</td>
<td>Research Vessel Technical Enhancement Committee (UNOLS)</td>
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<td>S</td>
<td>Shear Wave</td>
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<td>SCS</td>
<td>Single Channel Seismic</td>
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<tr>
<td>SEIZE</td>
<td>Seismogenic Zone Experiment</td>
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<tr>
<td>STRATAFORM</td>
<td>Research program sponsored by ONR to study STRATA FORMation</td>
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<tr>
<td>2-D</td>
<td>Two-Dimensional</td>
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<tr>
<td>3-D</td>
<td>Three-Dimensional</td>
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<td>UNOLS</td>
<td>University-National Oceanographic Laboratory System</td>
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<tr>
<td>UKOOA</td>
<td>United Kingdom Offshore Operators' Association</td>
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<tr>
<td>USGS</td>
<td>United States Geological Survey</td>
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APPENDIX 1

WORKSHOP PARTICIPANTS

1. John Anderson (Rice)
2. Jeff Babcock (SIO)
3. Nathan Bangs (UTIG)
4. Lou Bartek (UNC)
5. Sarah Bazin (SIO)
6. Rick Benson (IRIS)
7. Jack Caldwell (GECO)
8. Kerry Campbell (Fugro)
9. Pablo Canales (WHOI)
10. Suzanne Carbotte (LDEO)
11. Jon Childs (USGS)
12. Mike Coffin (UTIG)
13. John Diebold (LDEO)
14. Earl Doyle (Shell)
15. Neal Driscoll (WHOI)
16. Mike Enachescu (Canadian Husky)
17. Mike Fisher (USGS)
18. Alistair Harding (SIO)
19. Patrick Hart (USGS)
20. Dennis Hayes (LDEO)
21. Paul Henkart (SIO)
22. Steve Holbrook (W yoming)
23. Graham Kent (SIO)
24. Simon Klemperer (Stanford)
25. Mark Legg (Legg Geophysical)
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27. Dan Lizarralde (GA-Tech)
28. Peter Lonsdale (SIO)
29. Mitch Lyle (Boise State)
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31. David Mallinson (S. Florida)
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35. Greg Mountain (LDEO)
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42. Tom Shipley (UTIG)
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45. Stu Smith (SIO)
46. Chris Sorlien (UCSB)
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48. Brian Taylor (Hawaii)
49. Maya Tolstoy (LDEO)
50. Anne Trehu (Oregon State)
APPENDIX 2

WORKSHOP AGENDA

SUNDAY AFTERNOON, OCTOBER 17

Introduction
1:00 - 2:00 Meeting objectives — Greg Moore and Tom Shipley
FUMAGES, NO RPO 5-yr and 10-yr predictions
Review of existing academic facilities — Tom Shipley

Science Objectives:
2:00 - 2:00 MARGINS Program — Brian Taylor
2:30 - 3:00 RIDGE Program — Graham Kent
3:00 - 3:30 STRATAFO RM Program — Neal Driscoll
3:30 - 4:00 Coffee Break
4:00 - 4:30 Paleoceanography — Mitch Lyle
4:30 - 5:00 High Latitude Programs — John Anderson
5:00 - 5:30 Regional MG&G Studies — Peter Lonsdale
5:30 - 6:00 Discussion on environmental concerns — Jack Caldwell

MONDAY, OCTOBER 18

Technology
8:15 - 8:45
8:45 - 9:15 Ocean Bottom Seismometers — John Orcutt
9:15 - 10:00 3-D reflection industry practice — Mervyn Parry
10:00 - 10:30 Coffee Break
10:30 - 11:15 Bottom Cables — Jack Caldwell
11:15 - 12:00 High Resolution Techniques — Earl Doyle and Kerry Campbell
12:00 - 1:00 Lunch
1:00 - 1:30 Data Archiving and Access — IRIS model — Rick Benson
MONDAY, OCTOBER 18, CONTINUED

Working Group Themes and Charges
1:30 - 2:00 Define themes, charge to groups

Themes and Chairs:
1. Science & Technology (co-chairs Eli Silver and Steve Holbrook)
2. Access to Technology (chairs Alistair Harding)
3. Data Archiving (co-chairs Bob Stern and Paul Henkart)
2:00 - 4:30 Working groups meet
4:30 - 6:00 Reconvene with summary of discussions
6:00 - 8:00 Catered Dinner

TUESDAY MORNING

8:15 - 8:30 Session update
8:30 - 11:00 Working groups meet/draft report
11:00 - 12:30 Working groups present final reports
12:30 End of Workshop
1:30 - 5:00 Steering Committee and working group chairs meet to draft report
Appendix 3

Details of Estimates of Seismic Acquisition Needs for the Next Decade

Most of the NSF Programs have a cycle of data acquisition that spans three to four years. In the case of MARGINS there are four initiatives that will be overlapping in time. In Table 6 we examine a ten-year interval to provide an estimate to complete the planned science activities. This table is subject to various uncertainties but probably represent in terms of total dollars a minimum required to make substantial progress on all of the known science initiatives. Many will argue appropriately that this estimate is too low. However, based on established science planning it is a good minimum estimate that can be documented. None of these costs include the data processing or interpretation.

1. We assume that half of the present day usage described in the Facilities Tables 4, 5 and 6 is related to MG&G and ODP/IODP Core projects and the other half to Programs. Thus we assume there will be 10 high-resolution MCS programs, 20 2-D or 3-D MCS Ewing programs and 15 high-speed surveys in the next decade from Core assuming no increases. We note that several important scientific programs have not been formalized and thus are not included as specific programs. Two of the more significant with regard to the use of seismic techniques are the Large Igneous Provinces and Gas Hydrates. Gas hydrates are to some extent covered in MARGINS, but MARGINS focus sites are not the areas of choice for hydrate investigations.

2. OPP supports about three months of Palmer high-speed surveys per year and ONR supported the use of the chirp system for about three months per year. These are not included in this use study.

3. The MARGINS SEIZE and Subduction Factory share the Costa Rica—Nicaragua region and we subtract the SEIZE work from the Subduction Factory estimate.

4. We assume that the IODP will sponsor two drilling ships and various “fit-to-mission” platforms. We further assume that one will be like the present ship, drilling in about six regions per year. For riser drilling we assume there will be one site per year. We assume that for every riser site drilled there will need to be at least two sites prepared for informed decision making. We assume that international partners will survey half the riser and non-riser sites. So ultimately the U.S. needs to survey one riser site per year and three conventional sites per year.

5. Nominally a 3-D multi-streamer Ewing 3-D survey of 700 km² would take about two months. So the 3-D MCS Ewing 700 km² increment is actually $800,000 per two-month program.

6. OBS/H are not explicitly shown in any of the tables. It is assumed they will be part of many of the MCS programs. Some OBS/H programs do not simultaneously collect MCS and are not shown in this report. See the Future of Ocean Bottom Seismology report (Orcutt et al., 1999).
7. Cost estimates do not include UNOLS ship operations, commercial do include the total costs of ship and science acquisition. These cost estimates are all approximate and do not include significant issues such as mobilization and transit costs. “Cruise” is nominally about 30 days. Ewing costs are adjusted higher than at present to account for anticipated upgrades to the acquisition system, including multi-streamer operations for 3-D.

8. Current “rate” of $1.2M is from summing the annual NSF operating costs in tables 3-5. These are the incremental cost over basic ship operations.

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<tr>
<td>Chirp</td>
<td>$20,000 per cruise</td>
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<tr>
<td>High-resolution MCS</td>
<td>$75,000-150,000 per cruise (use $110,000)</td>
</tr>
<tr>
<td>High-resolution 3-D SCS Commercial rate</td>
<td>$233,000 per 30 km² (about 9 days), includes initial processing</td>
</tr>
<tr>
<td>High-speed SCS</td>
<td>$36,000 per cruise</td>
</tr>
<tr>
<td>2-D MCS Ewing</td>
<td>$300,000 per cruise (after upgrades, presently ~220,000)</td>
</tr>
<tr>
<td>3-D MCS Ewing 700 km²</td>
<td>$800,000 per 700 km² (a guess based on previous work) 3-D survey of 700 km² would cost 800K plus 60 days of ship time Ewing's 1999 day rate is $18,000</td>
</tr>
<tr>
<td>3-D MCS Commercial</td>
<td>$2,625,000 for 700 km² with long term (~6 months) contract</td>
</tr>
<tr>
<td>4-C Bottom Cables</td>
<td>$500,000 (assumes 2-18 km lines) Costs not well established. 4-C operation requires 2 ships</td>
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October 17-19, 1999

Held at

Cecil H. & Ida M. Green
Institute of Geophysics and Planetary Physics
Scripps Institution of Oceanography

Co-conveners

Thomas Shipley
Gregory Moore

Steering Committee

John Anderson
John Diebold
Neal Driscoll
Graham Kent
Mitchell Lyle
Gregory Moore
Thomas Shipley

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