

NSF Workshop on Portable Seismic Systems and Commercial Seismic Acquisition

Workshop Report

(March 25, 2016)

Purpose of the workshop

On September 30 and October 1, 2015 a group of ~ 39 scientists, engineers, seismic industry experts, and NSF program managers (attendance list is attached) gathered for a 1 ½ day workshop to discuss future possibilities for marine seismic data acquisition by the US academic research community. The workshop was conceived as a follow-up to the recent decadal survey of ocean sciences “The Sea Change” Report, which addressed the current issue of increasing science operational costs and the growing imbalance between operational costs relative to science support. The Sea Change Report highlighted the need for marine seismic capability as critical and important for a number of the overarching decadal science priorities identified by the committee. However, its recommendation states that NSF reduce operating costs associated with the research fleet by ~ 5%. The committee noted that one option would be “immediate layup the R/V Langseth”, the primary US academic facility for marine seismic data acquisition, as a cost saving measure. At \$70,000 per day for 2-D acquisition and \$94,000 per day for 3-D acquisition, the Langseth has been the most expensive vessel to operate in the UNOLS fleet. By comparison, the second most expensive vessel in the UNOLS fleet is Alvin/Atlantis, which has operational costs of \$67,000/day. Consequently, Langseth is vulnerable to cost saving measures for NSF facilities. However, Langseth is also the only vessel rigged to acquire unique marine seismic data in the US academic fleet and loss of the Langseth would eliminate our ability to acquire 3D surveys, crustal-scale marine seismic reflection data, severely impact our ability to acquire seismic refraction data, and devastate marine geophysics operations in the US. While some alternatives exist for shallow penetration seismic imaging, since 2008 the Langseth has been by far the primary facility for US seismic acquisition for both shallow and deep penetration seismic imaging and the cornerstone of our seismic and geophysical research capability. As expressed in the NSF response to the Sea Change report, NSF is committed to a strong marine seismic program and requested this workshop to help inform their decisions with input from the marine seismic community.

The workshop was designed to consider two primary possibilities that have been proposed as potential options for maintaining the US seismic acquisition ability, while reducing cost. We met to specifically address the feasibility of: 1) acquiring a “portable system” that when needed could be installed on global class vessels currently in the UNOLS fleet, and warehoused during the interim; 2) contracting with industry to acquire seismic data with their vessels on an “as needed” basis. “Portable systems” that we would consider were those capable of crustal scale imaging, and would not overlap in imaging capability with existing short offset 2-D portable systems at Scripps and portable 3D P-cable systems. Both options were put forward as possible alternatives to reduce costs by eliminating the need to maintain Langseth year round. Determining whether these two alternatives could in practice generate significant cost savings and concomitantly enable us to address the global tectonic, geohazard and Earth history questions, topics that motivate current active source seismic research, was a primary objective of the workshop.

The workshop was designed to first assess the current science needs and how seismic facilities, such as streamer length, multiple streamer lay out, and source arrays are linked to the capabilities that are needed to examine primary science questions. We also examined the impacts on seismic imaging if alternate acquisition systems were to be used. Results of geophysical surveys using Langseth to address current science questions were presented, illustrating how the vessel's capabilities have been effective and what would be lost without Langseth. Then we discussed "portable systems" with presentations from European scientists, who use such facilities supported by their respective countries funding agencies. The types of systems they are able to use on their vessels were described as was their effectiveness at meeting science goals. To consider the possibility of deploying a portable system on UNOLS vessels, a Glosten engineer, Tim Leach, was tasked to consider requirements for a "portable seismic system" that could be operated on the R/V *Revelle*, and to determine the largest, feasible system that could be deployed. For consideration of industry contracting as an alternative to Langseth, John Sigfreid of Resource Exploration Services assessed the feasibility and costs of using large commercial contractors with vessels much more capable than Langseth, and assessed the current availability and costs of using more modest second-tier industry vessels that are closely equivalent to Langseth. This report summarizes the presentations, discussions, and presents the conclusions of this workshop.

The impacts of streamer length, source array, and multiple-streamers on science goals

Since the early days of US marine active source seismic acquisition in the late 1950 and 60s, the seismic facilities available to the research community have continually improved, enhancing our ability to address science questions and enabling new questions to be explored. The primary advances include: 1) better, and especially longer, receiver arrays, 2) more powerful and better tuned airgun arrays, and 3) the ability to deploy multiple streamers to support efficient acquisition suitable for 3D imaging of the subsurface. One of the primary considerations in the evaluation of alternatives to the current capabilities on Langseth is to preserve the benefits of these improvements over the past decades. Consequently it is critical to understand the impact of these abilities on achieving science goals.

The length of the receiver array (streamer) is a key factor for seismic imaging because it determines the maximum source-to-receiver offsets, critical for several aspects of image processing and for the determination of crustal structure, tectonics and rock properties. As the source-receiver offset increases, primary reflections arrive at times that are distinct from multiples. Consequently, longer streamers enable multiples to effectively be filtered out whereas in most instances with relatively short streamers, multiples cannot be effectively removed. Furthermore, as source-receiver offsets increase, the travel time vs. source-receiver offset curves (traveltime curves) become more precisely defined given the finite signal width of band limited source signals and the presence of noise. Consequently streamer length controls the accuracy of the seismic velocity that can be estimated from the data. Long streamers are also critical for other velocity determination techniques such as amplitude versus offset (AVO) and full waveform inversion (FWI), which exploit reflection and refraction characteristics beyond simple analysis of reflection traveltime curves. Seismic velocity is needed for both rock property interpretation and signal processing for seismic imaging. Accurate velocity estimation requires source-receiver offsets approximately equal to at least the depth of the seismic imaging target, and is always improved with larger ranges. Langseth has provided 8 km receiver arrays for 2D imaging, and 4 x 6 km arrays for 3D surveys of crustal targets of 5-15 km depth. One of the goals of a portable system would be to enable the deployment of sufficiently long streamers to image crustal scale targets of similar depth range. Streamer length is a critical consideration for portable systems because of the potential difficulties with handling large, heavy streamer reels and the need for adequate storage space for

streamer sections that cannot fit on reels. Portable systems are increasingly more difficult to handle, deploy, and store as streamer lengths increase, and streamer length is also a factor in weight distribution aboard ship.

The seismic source is a key element to imaging because of its ability to allow relevant-scale seismic wave interaction with the sub-seafloor geologic structure. The source signal frequency range determines the resolution of structures, and the source output amplitude determines the signal strength relative to noise on seismic images, which decreases with the depth of penetration and with lower and lower magnitude of the impedance boundaries. The source tuning determines how clearly structures can be seen without interference from bubble pulse artifacts. All of these factors contribute to how accurate and how much of the geology can be seen in seismic images, especially in settings with deep targets and complex geology where resolution needs to be especially high.

One of the largest improvements in marine seismic imaging over the past ~30 years has come from the improved seismic source signal generated by the airguns, in terms of signal strength, tuning and frequency content. Signal strength is directly proportional to the sum of the cube root of the airgun size, and consequently signal strength of the seismic array is better with a large number of airguns instead of fewer guns even if the total air volume is less with more guns. The tuning (defined by the bubble pulse amplitude relative to the peak amplitude) improves by increasing the number of airguns, the range of airgun sizes and selecting the best firing sequence. The Langseth seismic array has the sharpest and strongest seismic input signal and best airgun tuning of all academic seismic sources because of her ability to tow four 9-gun arrays (36 guns of varying sizes). These are better seismic source parameters than what is available on any academic vessel globally and are similar to current seismic industry standards. A portable system without the ability to tow large seismic arrays with a large number of airguns would be a serious compromise and a downgrade from our current capability.

The capability to acquire data with multiple closely-spaced, long streamers for 3D imaging improves our ability to visualize the subsurface and decipher geologic processes because of two primary factors. Data acquired with multiple streamers allow us to recover energy that is scattered in all directions and with 3D processing techniques, relocate this scattered energy into its true subsurface position. With 2D imaging the scattered energy can only be recovered if it falls onto the 2D imaging plane, and cannot be properly relocated if it is scattered from sources outside the 2D plane. The result is that geologic structures, especially complex deformational structures that produce a great deal of scattered energy, can be imaged much more completely, without horizontal breaks in continuity and with fewer “out of line” artifacts obscuring the primary structures. In addition to the sharper images obtained from 3D data, structures can be traced in all directions, which enables interpreters to identify structures that are broadly continuous and significant from features that stand out on a single 2D profile but are too localized to be broadly significant. For many complex structural settings, such as compressional margins where mega-earthquakes are generated, the three-dimensional seismic imaging supported by the Langseth has been transformative and losing it would be a substantial setback for the US marine seismic community.

Science achievements made possible because of Langseth capabilities

Marine seismic reflection and refraction are key tools for studies within the decadal priorities identified in the SeaChange Report of Ocean Basin-Global tectonics, GeoHazards, and Subsurface environments, as well as Sealevel change. Many grand challenges in Earth science such as earthquake

processes, tsunamogenesis, volcanism, and the global plate tectonic processes that drive these geohazards, as well as understanding the chemical and energy fluxes across the seafloor, require the ability to probe and image the subsurface at the resolution that can be uniquely achieved with active source marine seismic studies. Other challenges, such as understanding past sea level change as a benchmark for anticipated sealevel rise in the coming centuries, also depend on having excellent seismic imaging capabilities to infer sealevel fluctuations from seismically imaged depositional systems. A prior report described the scientific questions that active source seismic data uniquely address (Incline Village Report, 2011). Here we emphasize only the most recent advances, in order to illustrate how Langseth's capabilities have increased our ability to image structure that records key geologic processes.

Mid-ocean ridges. Mid-ocean ridges (MOR) are the birthplace of the oceanic lithosphere that comprises much of the global tectonic plates, covering two-thirds of the surface of our planet. They are the locus of the majority of volcanism occurring on Earth, where heat and mass from Earth's interior is transferred to Earth's surface during the formation of oceanic crust. They are also sites of abundant hydrothermal circulation of seawater within oceanic crust that supports complex chemosynthetic ecosystems that may be linked to the origin of life. Active source seismic techniques are important tools for the investigation of crustal formation at mid-ocean ridges. Reflection seismic imaging has been used to detect and map magma reservoirs in the crust, other intra-crustal events, and the crust/mantle interface, which is much more complex than previously described. Seismic refraction methods have been used to obtain first-order constraints on the distribution of melt within the crust and underlying mantle. Mid-ocean ridges are challenging environments for seismic studies due to scattering of the seismic wavefield by rough seafloor topography and the presence of magma, which has a dramatically different seismic velocity than the surrounding rocks and strongly attenuates seismic waves. Key to the improvements achieved in imaging in this challenging environment has been the availability of long offset streamers, a powerful tuned source, the development of new advanced processing techniques, and access to improved 3D imaging capability.

Langseth's first 3D multi-source, multi-streamer seismic study was conducted on a unique portion of the East Pacific Rise where two volcanic eruptions have been detected and abundant hydrothermal venting is ongoing. The detailed picture of the interior of the East Pacific Rise achieved from this study has led to new discoveries that challenge prior conceptions of fast-spreading mid-ocean ridge magma reservoirs. Rather than a single magma sill above a crystal mush zone in the lower crust, the new images reveal that multiple vertically stacked magma sills are present beneath the ridge axis at different levels and that these lenses may be hydraulically connected such that magma may ascend from one sill to another during a volcanic eruption. The Langseth's well-tuned and broadband source was essential in the ability to identify these deeper sills and rule out source ringing effects present in older 2D data. The long-offset streamers used for this investigation have supported detailed AVO studies of the melt content within the magma reservoir and reveal short length scale variations with significant implications for eruption dynamics and distribution of hydrothermal venting on the seafloor above. The high spatial density and the ability to migrate the seismic wavefield in three dimensions, has led to the discovery of numerous magma sills located off-axis, indicating that delivery of mantle melts to the ridge axis is not as narrowly focused as previously believed. In contrast to the patchy imaging of the crust-mantle boundary (Moho) achieved in similar studies using older generation seismic systems, an almost complete image of the Moho surface is achieved within the survey area revealing coherent spatial variations in the nature of the Moho reflection linked to melt delivery from the mantle.

Other major seismic experiments conducted at mid-ocean ridges using Langseth include an extensive regional refraction study of Lau Basin and a combined refraction/reflection study at the

Rainbow non-transform offset of the Mid-Atlantic Ridge, which includes the ultramafic-hosted high-temperature Rainbow hydrothermal field. Here, the powerful tuned seismic source of the Langseth used in conjunction with a network of ocean bottom seismometers has allowed mapping of the large-scale distribution of mantle outcrops. This seismic structure has been combined with the Langseth long-streamer seismic reflection data to image, for the first time, a magmatic system within an ultramafic setting. This magmatic system consists of multiple, small, partially molten sills extending down to at least 10 km below the seafloor (the deepest melt sills ever observed at a MOR), and it is the energy source that mobilizes fluids in the Rainbow hydrothermal field. This magma-driven fluid flow drives serpentinization of the surrounding mantle rocks and produces hydrothermal outflow with unusually high methane and hydrogen concentrations.

As with earlier studies using *Ewing*, the deep crustal seismic imaging of mid-ocean ridges obtained using the *Langseth*, supports a wide range of complementary multi-disciplinary studies including biological and geochemical studies of the hydrothermal system, volcanological studies of eruption dynamics, tectonic studies of deformation of the lithosphere, and geochemical and modelling studies of melting and melt transport in the crust and mantle below. These investigations all make use of and build from the first-order unique constraints on the architecture of MOR faults and magmatic systems determined by seismic imaging.

Rifted margins. Rifted margins record the processes of continental breakup that occurs as continental crust is ripped apart and the mantle upwells into the growing void. Eventually extension of the continental crust and upwelling of the mantle leads to generation of new ocean crust at seafloor spreading centers. Given the nature of crustal scale processes, critical science questions along rifted margins have focused on large scale crustal deformational structures and tectonic activity. In the past, studies have relied on 2D seismic imaging of rifted crust, major extensional fault systems, and sedimentary deposits within developing basins for interpreting rifting process, with constraints from drilling to determine rock compositions and the timing of rift activity. Studies have been limited to 2D seismic data because of the large scale of rifted margins and the assumption that crustal structure variation along strike is small enough that widely spaced 2D lines are adequate to characterize these margins. However, accurately linking deformed crustal blocks, connecting major fault systems, identifying transfer faults that make connections between stratigraphic layers using sparse 2D profiles, proved to be too ambiguous to accurately map rifted margin structures to the extent needed to depict rifting processes.

Accurate depiction of rifted margin structures is well-suited for 3D seismic imaging that accurately reveals rifted margin structure in sufficient detail to fully interpret rift tectonics. The primary advantage of seismic imaging in 3D is that it allows detailed mapping of individual extended blocks to interpret block rotation in all dimensions, which is necessary for fully assessing continental thinning and relative timing of major rifts. Furthermore, 3D imaging of extensional fault systems helps assure a block rifting model is consistent with both the fault geometry and block continuity and identification of eventual postrift erosion. One of the relationships that reveals the rifting process is the spatial linkage between faults that separate crustal blocks and their interaction with the main crustal detachment fault at the base of the rift zone. Mapping the main basal detachment fault in 3D shows both the geometry and relation with connecting crustal faults. Critical clues to the physical properties of rocks and fluids that lie along the crustal fault zone can be extracted and interpreted by accurate mapping of its seismic reflectivity with 3D data. Basal detachment faults are possible fluid migration pathways that can weaken the basal detachment and feed into and thus weaken other overlying crustal faults. The fault system can

also promote shallow mantle serpentinization by directing fluids into the mantle. 3D seismic imaging in combination with seismic velocity constraints from ocean bottom seismometers provide opportunities for mapping fault properties and detecting fluids, and estimating the degree of alteration of upper mantle by serpentinization.

Subduction zones. Subduction zones produce Earth's largest and most powerful earthquakes and tsunamis. Recent events such as the Tohoku, Sumatra, and Chile earthquakes are vivid reminders of these hazards. These earthquakes are typically generated at deep (>6 km) levels and are consequently inherently inaccessible. However, seismic imaging is one of the primary ways to probe these settings and image the subduction megathrust. This allows researchers to examine the evolution of these faults, and related structural and tectonic development that can be investigated within the framework of earthquake patterns and fault slip characteristics. These are settings that are intensely deformed due to the ongoing plate collision; the complex structure makes imaging deep subduction zone fault structure particularly challenging.

Subduction zones are also settings of very active fluid migration due to consolidation of subducted sediment, thickened accretionary wedges undergoing horizontal compression, and mineral dehydration reactions as materials are heated and compressed during subduction. These fluid systems are critical for understanding fault slip due to the role of pore fluid pressure in regulating effective stress. In recent years, seismic studies have provided a means to broadly characterize fluid budgets using seismic velocities, and to identify fluid-filled migration pathways along fault systems.

Central to the recent progress has been the ability to record long source-receiver offsets signals on ocean bottom seismometers, the availability of long streamers (>8 km) for deep penetration 2-D seismic imaging, and deployment of multiple streamers for efficient deep-penetration 3D acquisition and imaging. All three approaches, and especially imaging, have benefited greatly from Langseth's well-tuned powerful seismic source that has minimal interference from bubble reverberations, and is powerful enough to penetrate to seismogenic depths.

Recent surveys using such facilities have made significant progress in imaging and characterizing the subduction megathrust. The 2011 Aleut project on the Langseth was able to image the entire forearc and follows the plate-boundary thrust from the trench to more than 50 km depth. These data show more clearly than ever previously seen that the fault evolves from a sharp, highly-reflective interface 100s of m thick along the seismogenic zone into a broad km thick zone 3-5 km thick, as the fault enters the mantle wedge and transitions from brittle to ductile behavior. In comparison, older seismic data acquired with short-offset acquisition systems, have strong multiples and weak signals; the fault reflections are too weak or absent and are unable to reveal the downdip evolution of the megathrust as it evolves from the trench into the seismogenic zone and into the mantle. With extra-long offset data (15 km) from Sumatra (acquired by a commercial contractor, CGGVeritas) greater details show the role of seamounts and deep sediment subduction on upper plate evolution and subduction thrust development.

Three-dimensional imaging further improves the characterization of the reflectivity of the plate interface and allows us to map surfaces beneath the seafloor at comparable resolution to typical seafloor mapping. Comparisons of 2-D vs. 3-D images of the plate interface in the Nankai subduction zone shows improved horizontal connectivity of reflectors, sufficient to see that the plate-interface beneath the outer accretionary wedge at ~5 km subseafloor is substantially shallower (~ 2km shallower)

that previously interpreted from 2D images. The thickness of sediment subducted into the seismogenic zone at ~ 8-10 km seafloor is measured at more than 1 km. These results correct the previous inference of nearly no subducting sediments based on analysis of the 2D data. This revised interpretation substantially increases the role of available pore fluids on the evolution of the plate interface in the shallow subduction zone because of the greater volume of fluid produced from the correctly interpreted thick section of subducting sediment. Mapping the effects of possible seamount or basement structure subduction was virtually impossible without the ability to map in 3D. Finally, mapping folds, unconformities, and stratal relations of sedimentary sequences within the upper plate along the Costa Rica margin provides a link between the subducting basement structures and the upper plate evolution that is critical for understanding the hydrogeology of the upper plate and the development of the subduction megathrust.

Intra-plate structures and processes. Science questions within the interiors of plates require both seismic reflection and refraction data for deep penetration into the crust and mantle, and for interpreting shallow structure of intraplate regions. Current topics are broad ranging; from upper mantle structure at large target depths, to the evolution of oceanic crust as it ages, to fluid and gas migration in shallow sediment.

In the upper most mantle, constraints on seismic p-wave and shear-wave velocity structure are critical for assessing the role of melt generation and extraction from the mantle during decompression melting generated by mantle flow, which ultimately controls the genesis of the crust at mid ocean regions and evolution of the lithosphere between seafloor spreading centers and subduction zones. Furthermore, seismic studies are very effective for measuring anisotropy to assess strain related to mantle flow patterns beneath intraplate regions. The powerful, well-tuned source on the Langseth has enhanced deep penetration seismic refraction studies into the upper mantle by producing clear arrivals up to several 100 km of source-receiver offset.

At crustal scales, intraplate studies have focused on the evolution of crust from its creation at mid-ocean ridges to its destruction at subduction zones using seismic reflection and refraction studies. The evolution of crust along flow lines results from low-temperature hydrothermal circulation that is believed to continue for 10s of m.y. after crustal formation. Research focuses on distinguishing between effects of crustal evolution and differences inherited from crustal formation due to spreading rate, ridge axis magma supply, and proximity of ridge axis discontinuities. As ocean crust approaches subduction at the end of the life cycle of ocean crust, the development of faults from plate-bending into the subduction zone leads to significant alteration of crustal structure, major fluid migration pathways to the base of the crust and upper mantle, and chemical alteration, especially serpentinization of the upper mantle, that can be detected by reduced seismic velocities and seismic anisotropy in the crust and upper mantle.

Tectonic disruption within plate interiors can be inferred from the disruption of the overlying sediment cover in areas where sediment is thick enough to be imaged in detail. Seismic imaging with sufficiently good resolution shows offset and rotation of underlying crustal blocks and relative timing of tectonic disruptions.

Finally, some intraplate areas have shallow sediment fluid and gas migration that is often fault controlled and may be focused areas of gas hydrate formation. Hydrate related features produce distinctive structures in sediment, such as "VAMP" structures in the Bering Sea, while vent systems produce pockmarks and mounds on the seafloor. Hydrate concentrations and distribution can be mapped using seismic experiments by acquiring high-resolution images that show fluid migration

pathways and reflection characteristics that are distinctive of free gas and gas hydrate, as well as sediment seismic velocities that show sediment physical properties. Using high-resolution seismic data, these can be placed within the context of vent systems and seafloor structures.

Future Studies. As our “eyes” into the subsurface, marine seismic programs will continue to be the primary means to address longstanding issues related to specific tectonic processes such as those described above, along with new directions emerging from national and international scientific programs. Seismic imaging is a critical component to existing programs such as IODP for site surveys and regional geologic context of drilling results. It is a powerful tool for addressing fundamental science questions of the GeoPRISMS program, and it will play a large role as part of a suite of complementary tools and studies for new programs such as the Subduction Zone Observatory currently under development or geohazards programs such as the NSF Preevents program.

There are opportunities for both shallow and deep penetration MCS and OBS experiments. Deep penetration seismic imaging with long streamers (up to 15 km) will address crustal scale targets such as fault systems within rifted margins, magma storage and migration systems within mid-ocean ridge spreading centers, and the subduction megathrust in subduction zones. As recent experiments offshore Sumatra conducted by commercial contractors have shown, long streamers are able to image the entire forearc where previous surveys have failed because of the issues of multiple suppression. Long-offset streamers in combination with wide-angle OBS data can take advantage of new analysis techniques, such as full waveform inversion, for high resolution inversion of seismic p-wave velocity structure, along with shear-wave and density information. Because of the potential to acquire these types of data sets and new analysis techniques, opportunities for addressing crustal scale structure and tectonic processes have never been better.

We also anticipate opportunities for shallow imaging and shallow OBS wide-angle refraction projects to address a broad range of topics. High resolution images of shallow stratigraphy and detailed velocity models will be critical for addressing wide ranges of topics from sea level rise, to neo tectonics, gas hydrates, landslides, and seafloor vent systems in support of programs ranging from climate to energy and mineral resources, and marine geohazards. Many of these studies will require 3D imaging and velocity models to understand complex structure and assess properties, such as free gas and gas hydrate distributions.

Lessons from existing portable systems

Portable systems are currently used by international scientists with support from their respective countries. These systems provide insight into a possible US portable system. Two of the largest, most capable systems are deployed on the Spanish vessel, the R/V Sarmiento De Gamboa, and the German vessels, the R/V Merian, R/V PolarStern, R/V Meteor and R/V Sonne. None of these relatively large systems are truly “portable” in the sense that they can be moved between vessels. A large amount of infrastructure had to be designed into their host vessels to accommodate the airguns, compressors and streamer reels. These systems are more accurately described as “removable” instead of “portable” because they are made up of modular components, many of which are stored in standard shipping containers, and are designed to be removed in port (and stored) to make space available for non-seismic operations.

The De Gamboa is capable of deploying a 6-km-long streamer and up to 20 airguns with a total capacity of 6,000 in³. Weight issues related to larger streamer reels prevent increasing streamer lengths beyond 6 km. The total weight of the removable parts of the system is 160-tons (mostly from the streamer winch and compressors), which is sufficiently large to require additional deck reinforcement and permanent, special-design structural modifications to the decks. The large weight issue consequently also requires substantial facilities in port for deployment and removal from the vessel. Compressors for running airguns are kept in containers for removal; however, one of three of the ship's built-in electric generators is used exclusively for powering the compressors and is not part of the removable equipment. This portable system requires virtually all of the available deck space for compressors, streamer reel, and airgun deployment system, which limits space for other simultaneous operations such as OBS deployment/recovery.

The German system is designed to be swapped between their four vessels, but due to the specific built in components, such as compressors, these systems cannot be deployed on other vessels. The greater portability of the German system relative to the De Gamboa is largely because of the shorter streamers and smaller airgun array and the available built-in compressors that are on all four German seismic vessels. This system typically uses a 16 G-gun source array with a total volume of 3100 in³ and can deploy a 3.5 km streamer for 2-D work on all vessels or two < 1.5 km streamers for 3D work on the R/V Meteor. These systems typically require two-days in port for both installation and removal.

A possible portable system on R/V Revelle

Given the size and weight issues of the existing “removable” seismic systems, the most capable vessels in the UNOLS fleet for such a seismic system are the AGOR vessels R/V Revelle and R/V Thompson. The marine architects, Glostén, explored a potential portable system for the Revelle, considering what maximum size system would fit on the Revelle, and what it would take to accommodate the necessary equipment, with the constraint of maintaining Revelle’s existing general purpose oceanographic capabilities.

The Glostén design for Revelle considered deck arrangements, weight distribution and ship stability, and towing capacity. In order to accommodate the volume of equipment and for stability, Glostén determined that at least one compressor would have to be installed permanently below decks, which improved both deck space and stability. Consequently, this and other modifications would mean that the Revelle would be the only vessel capable of deploying this system. Glostén also determined that the Thompson was a poor choice for installation of the portable system because the Z-Drive propulsion system on the Thompson would be stressed excessively and would produce unwanted hull noise. The Revelle would be the only viable option for a “portable” system.

The Glostén design for the Revelle would include two streamer reels with capacity for 4 km of streamer each, and room for spare streamer spools. This would enable towing a streamer of up to 8 km, but would only allow 2-D acquisition. Because of size/space, weight/balance and compressor issues, the largest source array that could be deployed would be a 3300 in³ array that could be fired at a 10 second rate. This capacity would require a single permanently installed 1800 cfm compressor below decks, and two 750 cfm compressors in removable containers that would be installed forward near the bow. The airgun system would consist of a removable airgun source container that would have rails to the stern for deployment and towing. Additional electric generating units would be needed to approximately double power production to supply power for the compressors. This system would add an estimated

187 tons and cause some stability issues depending on fuel levels, which could be compensated by emptying anti-roll tanks. It would also consume all available deck space. There was no consideration for deck space for OBS deployment and retrieval. OBS deployment may still be possible with consideration of space; however, the weight of OBSs on deck may also cause stability issues depending on the fuel levels.

The total cost to implement this design would be approximately \$2 to \$4 million, and because of additional personnel and fuel consumption, the cost of operation during a cruise would be approximately similar to the cost of 2-D operations on the Langseth. Potential cost savings would come from eliminating the need to maintain Langseth while not in operation (although the seismic technical personnel would need to be retained) and not from savings during operations.

The primary concerns with this design are substantial loss of capability relative to the Langseth. The total streamer length of 6-8 km was acceptable with this design and similar to what the Langseth has deployed until recently (as of September, 2015 Langseth can deploy a 15 km long streamer); however, the largest airgun array would be approximately half the current Langseth size depending on how many airguns can be deployed with the portable system. It would clearly be inadequate for many mid- to deep crustal imaging surveys and OBS studies. The only option for increasing capability with this system would be to use a second source vessel in a two-ship operation. This sort of operation using the portable system on the Reville and a second ship is possible, but adds considerable expense to an active source seismic program and is not an attractive approach for reducing costs in this program. The impact of integrating marine seismic studies in Reville's schedule and how the current regional model for seismic research would impact Reville operations were not discussed.

The industry option

Contracting with commercial seismic industry has several appealing possibilities as an alternative to Langseth. Contractors typically have larger data acquisition systems that include larger and more powerful airgun arrays with excellent tuning. They are able to tow more streamers with small cross-line sampling. They collect data to tight specifications, and consequently we can meet scientific goals by designing surveys to specifications. However, the main issue for using the large commercial contractors (such as CGG/Veritas and PGS) is high cost of operation of their highly capable vessels. For these high-end vessels, the cost, averaged between the market highs in 2008 and the current market low, is conservatively estimated at \$240,000/day for 3-D and \$120,000/day for 2-D acquisition. Similar costs would be incurred for mobilization and demobilization days, which create serious restrictions for all but projects with relatively short transits to the survey sites. Even with minimal transit, costs are well beyond what is currently possible with Langseth (\$70,000 per day for 2-D acquisition and \$94,000 per day for 3-D acquisition) and high-end commercial contractors are unlikely to be a viable option even in times of low oil prices. The more feasible possibilities for commercial contracting are with the smaller, less capable companies.

Smaller operators, such as Seabird, BGP and Gardline, are available for both 2-D and 3-D acquisition at costs within reasonable range of Langseth. Seabird, the most capable of the three, for example, has vessels able to tow 8 x 6 km or 6 x 8 km streamer arrays and 4,800 in³ source for 3D acquisition and 12 km streamers and 8000 in³ source systems for 2D acquisition. However, Seabird would not likely be interested in 3D acquisition unless there were multiple projects over several years, and even now in slack times they have a 3 month backlog of work. In good times, backlog is more

typically 12 months. Costs for 2D acquisition for the first quarter of 2014, were \$90,000-125,000/day and costs for 3D acquisition during the same period were \$100,000 - \$180,000/day. It was noted that one likely outcome of the current industry downturn is a broad layup of seismic vessels that may significantly impact prices and ship availability in the coming years. Another consideration is the limited geographic scope of the ports which industry currently operates from (e.g. Gulf of Mexico, Singapore, Norway) and any contracted work would need to cover transit costs associated with transit to and from these locations.

Summary and Recommendations

NSF is committed to provide the US academic research community with the needed marine seismic capability to support cutting edge research, much of which falls in areas of high priority identified in the NRC SeaChange Report. However, costs to NSF for Langseth operations need to be cut. The primary conclusions of the workshop discussions regarding the challenge and options for reducing costs are summarized below.

1. Average annual costs since 2008 for the Langseth has been about \$13.4 million, including costs of ship, technical support, seismic operations and permitting. While not all of that total was funded by NSF on an annual basis (e.g. USGS, NOAA, Taiwan projects), OCE would like to decrease NSF's contribution to the facilities cost of seismic operations to ~\$10 million annually – an amount more comparable to operation of one of the large AGORs in the UNOLS fleet. This needs to be done by increasing utilization by 3rd parties and/or contributions from other sources.
2. A review by Glosten and Associates of what would be possible for seismic operations on one of the large AGORs (Revelle as example) indicates that the space available for compressors is inadequate to allow more than about a 3500 cu³ in. source in dual gun arrays. This compares poorly to 4 source arrays and 6600 cu³ in. with 3300 cfm capacity on the Langseth. Additionally, an AGOR solution would likely limit a 2D streamer to about 6, possibly 8, kilometers length due to weight and reel size, whereas Langseth now operates up to a 15 km long streamer, as can industry. An AGOR 'removable' solution would not allow for 3D work, or to carry out a program involving an active seismic source and large numbers of Ocean Bottom Seismometers (OBSs). This type of program, which has been common program in recent years on Langseth, would likely require two vessels to allow sufficient deck space for OBS deployment.
3. A review by John Siegfried of Resource Exploration Services (industry consultant) provided pricing for seismic vessels able to carry out long offset 2D work and 3D surveys, including a good estimate of the variability of such pricing in times (like now) of low utilization, and of boom times. The average cost for 2D long-offset is \$120,000/day, vs. \$70,000/day for Langseth, depending on provider and quality of equipment. The average cost for industry 3D acquisition is \$240,000/day with peaks as high as \$280,000 to \$350,000/day, vs. \$94,000/day for Langseth, again depending on provider and quality of equipment, and this does not include multibeam seafloor mapping that is available on Langseth. The upside of commercial vessel use is that the cost is only incurred during the period of the contract, and there is no responsibility for maintaining the vessel

between contracts. However, there are a lot of issues beyond just cost, that limit the feasibility of contracting for academic seismic work as an alternative to the Langseth—including availability (overall, as well as at correct location and time), the limited appeal for industry given the small size of academic contracts, the issues of long transits from the few ports used by industry, project planning, permitting, and an expected reduction in PI participation and training for students.

4. Under the new regional model for Langseth operations there are also new opportunities for potentially attracting foreign funding for research programs aboard the Langseth. With areas of operation decided in advance by several years, this should allow some foreign scientists and their funding agencies the needed time to secure funding and meet their national permitting requirements. NSF has existing international agreements under the IODP program that could be pursued to establish interagency relationships that could ease and promote paid foreign use of the vessel. Given the need for seismic studies to support ocean drilling, this is a natural connection that could be exploited.
5. NSF has advised workshop participants that they believe that in order to maintain Langseth in UNOLS fleet by increasing utilization by others (industry, other countries, etc.), future operations could benefit from a new ownership model. For example, NSF, as owner of the vessel now, believes that their ownership will be a hindrance in leasing it to industry or other 3rd parties. Options discussed were university or consortium ownership, favoring the latter. Existing consortia (COL, IRIS) or a new group solely associated with seismic acquisition, were discussed as models. NSF advised that if an appropriate ownership model were accepted, they would commit to supporting the Langseth for a significant number of days and operating costs under this newly proposed model, subject to the usual caveats of availability of funds, so that NSF science objectives and technical capabilities could be achieved.
6. Issues related to permitting any vessel undertaking seismic research on behalf of NSF funded researchers have not been explored, and need more study. It is possible that commercial charters may be difficult if companies are required to comply with the permitting requirements that come with federal funding (NMFS Section 7 consultation and EA), as there is concern that such compliance could be used as precedent to expand permitting of industry.

Recommendations (with input from the MLSOC)

1. Eliminate the “portable system” option. A portable/removable system hosted on the Revelle (the most suitable candidate) would be a significant step backward, to Ewing and pre-Ewing capability, and would be inadequate to meet current and future science needs.
2. Do not adopt an industry-only approach. Relying fully on industry contracting to conduct the current level of academic seismic research would cost more, especially if long transits were needed. Thus, less science could be accomplished for the same research dollars. While contracting industry could work for the occasional project, uncertainties

of contracting schedules and market availability would not be a feasible alternative to support an ongoing academic program in marine seismics.

3. Retain the Langseth as the facility for academic marine seismics and geophysics and search for new external support. Under the new regional model for seismic operations, there is opportunity for potentially attracting paid foreign usage for research programs aboard the Langseth. With areas of operation decided a few years in advance, foreign scientists and their funding agencies would have the time needed to secure funding and meet their permitting requirements. This avenue could be pursued under existing NSF ownership of the Langseth.
4. Pursue international facilities agreements, including MOUs, through NSF perhaps making use of the channels of communication already in place for IODP. MLSOC members are willing to reach out to international colleagues, but agency-level discussions will need to occur in tandem.
5. Immediately communicate the OCE plan for near-term marine seismics. There is currently high uncertainty about the future of Langseth, in both the US and foreign research communities, in light of the SeaChange Report and the NSF public response. Many infer that OCE will lay up Langseth soon and this impedes forefront scientific planning. OCE should determine and announce a near-term period for which Langseth will continue to serve the academic marine seismic community (something like 5 yrs), during which time international support and a potential consortia model(s) would be vigorously explored. Certainty of operations is essential for engaging foreign entities in paid usage discussions, reliability of access will be key for attracting/retaining prospective consortia members (regardless of whether/when an ownership transfer occurs), and a reduction in proposal pressure 'backlash', such as occurred in recent past times of high uncertainty for marine seismics, may be avoided.

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*Via teleconference link