Project Number: 900907

Project Start: Jan. 1, 2009 **Project Duration (in years):** 2

Please indicate what type of project is being proposed (mark only one).

[ ]	[X]	[ ]	[ ]	[ ]
Feasibility/Scoping [Less than 100 days effort]	**Development**[1]	**Research**	**Infrastructure**[1]	**Education**
	[ ]	[ ]		
	Time Series	**Institute Initiative**		

Project Manager[2]: David Caress

Principal Investigator: David Caress

Lead Scientist: David Caress

Lead Engineer: Richard Henthorn

Project Title:
High-Resolution Near-Surface Seismic Refraction Tomography

[1] Development and infrastructure projects must complete the risk matrix (see item #5 at the end of the proposal form).
[2] Not all projects will require all four titles to be filled in. Please indicate individuals only for those titles that are appropriate for your project.

1) ABSTRACT (new projects only)

We propose a two-year development project to develop a high-resolution seismic refraction capability to image the shallow structure of the seafloor subsurface. The technique will include a swept-frequency (chirp) acoustic source mounted on an ROV and multiple ocean bottom hydrophones (OBHs). To conduct an experiment, we will use the ROV to deploy the OBHs in a desired configuration, run profile lines along the seafloor while pinging the source, and then recover the OBHs. The OBH data will be match filtered ("de-chirped") using the source signal to yield seismic refraction record sections. Once refracted arrivals are identified and travel times are picked, tomographic inversion can be used to yield 2D or 3D models of the subsurface compressional seismic velocity structure. By using a 1-6 kHz sweep, we expect to observe refracted arrivals to ranges in excess of 1 km, depending on the material and the subsurface velocity gradients, allowing penetration and imaging of structure to depths of as much as 200 m.

During year 1 we will purchase the source and two OBHs, integrate the source with ROV Ventana, develop the necessary software, and conduct three one-day test experiments to refine the technique. In the course of the testing, we will investigate the shallow seismic velocity structure of the flat shelf and of the axis of upper Monterey Canyon. The canyon refraction experiment will measure the thickness of the sands moving down axis, an observation important to our understanding of sediment transport processes in submarine canyons. During year 2 we will purchase additional OBHs and conduct a major field experiment at one of two methane hydrate deposits that have been previously investigated by MBARI using ROVs and the Mapping AUV (Barkley Canyon and Santa Monica Basin). Imaging the subsurface structure of actively forming hydrate deposits will provide new constraints on models for the formation and evolution of these features.

The proposed development is novel in that no comparable capability for imaging the shallow seismic velocity structure in the deep ocean presently exists, but low risk because all of the involved technologies (ROVs, OBHs, chirp processing) are mature. The technique will be applicable to wide variety of socially relevant and scientifically significant problems, and this capability will be readily exportable to other oceanographic institutions operating ROVs.

2) PROPOSAL

a) <u>New Projects</u>

Statement of the problem, why it is important

In recent years MBARI has developed an impressive suite of technologies for conducting fine-scale geological investigations of the deep-ocean seafloor. ROVs enable visual mapping and precisely located rock and surficial sediment sampling. ROV-mounted vibracoring allows the collection of precisely located sediment cores 2+ m

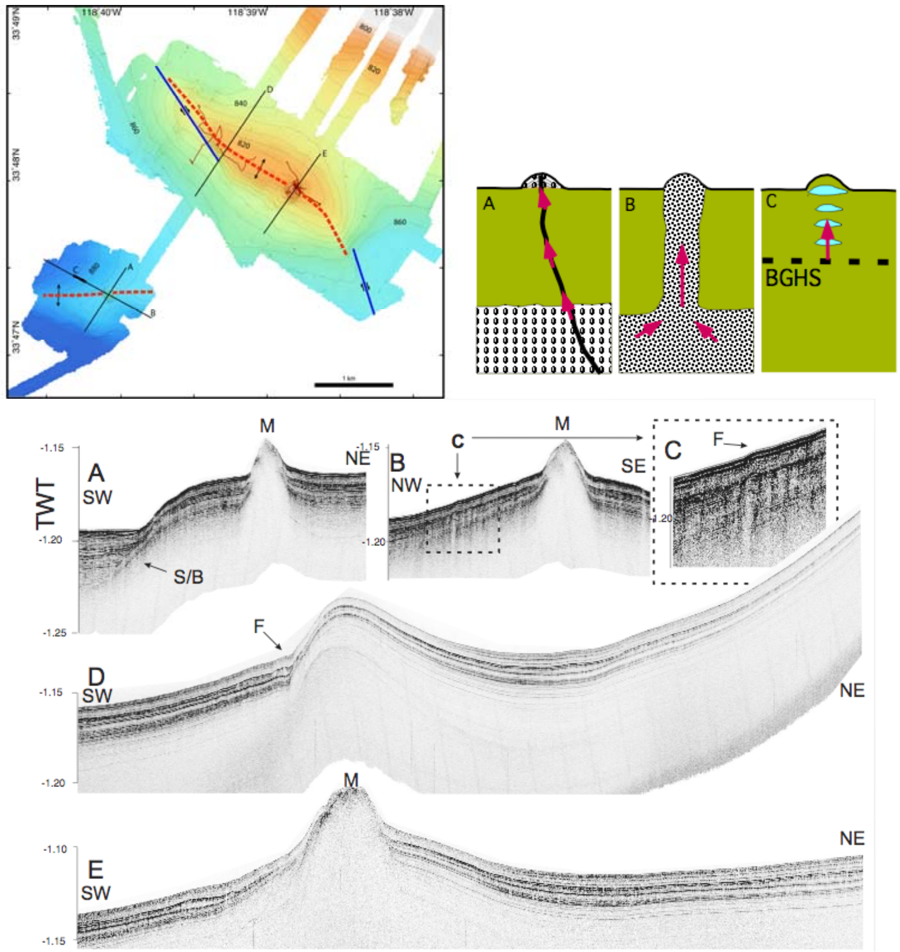

Figure 1. Results from Mapping AUV survey and ROV dives on Santa Monica gas seep mounds (Paull et al., 2007). (Top right) Bathymetric map generated by AUV multibeam surveys across the NE and SW mounds and swells shown at 5 m contour interval. Location of chirp seismic profile sections illustrated in A-E are indicated (black lines). Locations of ROV dives (thin red lines), the axial trace of the anticline (red dashed line) and inferred strike slip faults (blue line) are also indicated. (Bottom) High-resolution seismic-reflection profiles of the Santa Monica Mounds and swells collected using the chirp system on MBARI's mapping AUV. Profile A extends NE-SW across the SW Mound and illustrates that this topographic high is associated with an anticline. Profile B extends NW-SE along the crest of the swell and crosses the SW Mound. The reflection profile does not resolve internal structure of the mound. Profile C is an expanded view of part of profile B and shows several small normal faults (F) on its NW limb. Profile D shows a crossing of the NE Swell and shows faulting (F) on its southwest limb. Profile E crosses the NE Mound. (Top right) Cartoon showing the three possible mechanisms for producing seafloor mounds. Part A represents a mud volcano where the topography is composed of reconstituted material extruded as a slurry from the subsurface. Part B represents a diapir where the solids have flowed upward and deform the seafloor. Part C illustrates the effect of expansion associated with the growth and accumulation of gas hydrate in the subsurface. Paull et al. (2007) prefer C, but the existing data do not conclusively distinguish between these models.

in length. The Mapping AUV allows us to efficiently map the deep-ocean seafloor bathymetry with a 1 m lateral resolution and a ~0.3 m vertical precision, and also collects similar resolution sidescan imagery. In addition, the Mapping AUV images subsurface sedimentary structure using a chirp subbottom profiler, penetrating up to 60 m in soft, well stratified sediments. These tools are used to investigate a variety of geological problems, including

- Marine hydrate deposits (Santa Monica Basin (Figure 1) – Paull, Normark (USGS), Ussler, Caress; Barkley Canyon – Brewer and Caress)
- Offshore faulting (California Borderlands – Paull, Normark, Caress)
- Volcanic seamounts (offshore seamounts - Clague), mid-ocean ridges (Axial Seamount – Clague, Chadwick (OSU), Caress)
- Submarine canyon processes (Paull, Normark, Ussler, Caress)

While yielding novel and important scientific contributions, these geological projects also expose a limited ability to constrain subsurface structure at scales similar to the surficial sampling and mapping. In the case of subbottom profiles of stratified sediments, the thickness of units and the depth of penetration are poorly understood because we do not know the compressional seismic velocity of the imaged sediments. In the case of more complex structures where lateral variations in seismic velocity are likely (e.g., Figure 1), the subbottom images are likely distorted, further hindering accurate interpretation. In cases of a hard rock bottom or a shallow basement, subbottom profiling yields no penetration beyond the hard interface, and therefore no knowledge of the subsurface. At present, this shortfall is most limiting to our studies of hydrate deposits in Santa Monica Basin (Figure 1) and Barkley Canyon. At both sites we are unable to test hypotheses for the formation of these complex structures because the subbottom data alone provides inadequate information of the subsurface structure.

Approach to the problem

The geophysical technique of seismic refraction uses widely spaced active sources and passive receivers to observe compressional seismic (acoustic) energy propagating laterally through the subsurface. The general tendency of seismic velocity to increase with depth refracts the waves back towards the surface after sampling within the Earth; the path taken between a particular source and receiver is calculated using geometrical ray theory (Snell's Law). Observations of refracted arrival travel times associated with these raypaths constrain the seismic velocity structure. If refraction experiments are conducted with many closely spaced sources and receivers, a tomographic inversion can be applied to image the subsurface seismic velocity structure.

In order to address our internal scientific needs, and to provide the oceanographic community with a needed capability, we propose a two-year effort to develop a new technique for high-resolution seismic refraction imaging of shallow sub-seafloor compressional seismic velocity structure. We will package an ROV-mounted acoustic chirp source operating in a frequency range slightly lower than that of chirp subbottom profilers, within the range from 1 - 6 kHz. We will also obtain ROV-deployable ocean bottom hydrophones (OBHs) to receive and record refracted arrivals from the ROV-mounted source. Our seismic refraction experiments (Figure 2) will involve deploying an array of OBHs on the seafloor, and then generate closely spaced sources by pinging as the ROV flies lines at low altitude. We will collect refraction traveltime datasets that densely sample the target volume, allowing tomographic imaging of the subsurface seismic velocity structure (e.g. Burnett et al., 1989; Caress et al., 1992; Bjarnason et al., 1993; Caress et al., 1995).

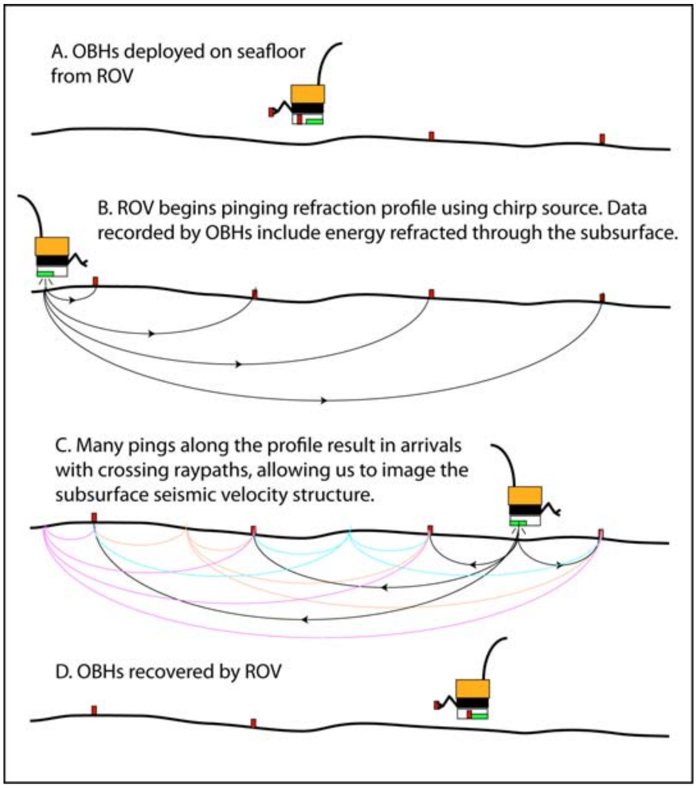

Figure 2. Cartoon of proposed high resolution seismic refraction technique.

Conventional marine seismic refraction methods use low frequency (1-100 Hz) shallow towed sources (e.g. airguns) and widely spaced seafloor receivers (e.g. ocean bottom seismometers (OBSs)) to image crustal scale structure at resolutions no better than hundreds of meters. Such experiments are common (e.g. Grevemeyer et al., 2001; Evangelidis et al., 2004), and the data analysis techniques and modeling algorithms, including tomographic inversion, are well established (McClain and Caress, 1993).

The marine geophysical community has long been interested in constraining the surficial seismic velocity structure in the deep ocean. Past efforts to develop near-bottom, shallow refraction techniques have depended on discrete explosive or implosive sources (e.g Christensen et al., 1992; Hammer et al., 1995). These approaches were operationally difficult and yielded only sparse sampling of the subsurface. More recently, advances in waveform inversion have allowed modeling of the uppermost (<200 m deep) oceanic crust using multichannel seismic data collected using shallow towed sources and hydrophone streamers (e.g. Hussenoeder et al., 2002). However, the lateral resolutions achieved with multichannel data still exceed 100 m. A different approach (such as we propose here) including closely spaced, near-seafloor sources and receivers and high frequency (~3 kHz) acoustic signals will be required to image subsurface structure at resolutions on the order of a few meters.

How does it relate/contribute to MBARI's mission and strategic plan?

At present, there is no viable technique for high-resolution imaging of shallow seismic velocity structure in the deep ocean. The proposed project will take advantage of MBARI's engineering capability and operational expertise to recast existing technologies (chirp sonar, dataloggers, ROVs) into a new technology that addresses MBARI science needs and provides a novel capability for fundamentally new observations to the oceanographic community. Because imaging shallow subsurface structure is a fundamental capability (it potentially impacts almost any sort of localized marine geological study), this development is relevant to both basic research and to many topics of societal concern (e.g. hydrate formation, seismic hazards). The initial testing will address canyon sediment transport to the deep sea and the first major experiment will address methane hydrate deposit formation, both research topics with current societal relevance.

Publications (from other projects over the last 5 years)

Paull, C.K., B. Schlining, W. Ussler III, J.B. Paduan, D. Caress, H.G. Greene, Distribution of chemosynthetic biological communities in Monterey Bay, California. *Geology* 33:2; 85-88, 2005.

Stakes, D.S., M.R. Perfit, M.A. Tivey, D.W. Caress, T.M. Ramirez, N. Maher, "The Cleft Revealed: Geologic, magnetic and morphologic evidence for construction of upper oceanic crust along the southern Juan de Fuca Ridge", Geochemistry, Geophysics, Geosystems, 7:4, Q04003, 2006.

Paull, C.K., W. Ussler III, P. J. Mitts, D. W. Caress, G. J.. West, Discordant ^{14}C-stratigraphies in Upper Monterey Canyon: A signal of anthropogenic disturbance?, *Mar. Geol.*, 233, 21-36, 2006.

McNutt, M., Caress, D. W., Hotspots and Hotspot Swells, in Seismology and the Structure of the Earth, Treatise on Geophysics, Vol. I, ed. B. Romanawicz and A. Dziewonski, Elsevier, 2007.

Paull, C.K, Normark, W.R., Ussler III, W., Caress, D.W., Keaten, R., "Association among active seafloor deformation, mound formation, and gas hydrate growth and accumulation within the seafloor of the Santa Monica Basin, offshore California", *Marine Geology*, 250:258-275, http://dx.doi.org/10.1016/j.margeo.2008.01.011, 2008.

Caress, D.W., Thomas, H., Kirkwood, W.J., McEwen, R., Henthorn, R., Clague, D.A., Paull, C.K., Paduan, J., Maier, K.L., "High-resolution multibeam, sidescan, and subbottom surveys using the MBARI AUV *D. Allan. B.*", *Marine Habitat Mapping Technology for Alaska*, ed. J.R. Reynolds, Alaska Sea Grant, in press 2008.

Normark, W.R., C.K. Paull, D.W. Caress, W. Ussler III, and R. Sliter. 2008. Fine-scale relief related to late Holocene channel shifting within the floor of upper Redondo fan valley in San Pedro Basin, offshore southern California. Mar. Geol., submitted, 2008.

Other References

Bjarnason, I.T., W. Menke, O. G. Flovenz, and D. W. Caress, Tomographic image of the spreading center in southern Iceland, *J. Geophys. Res.*,**98**, 6607-6622, 1993.

Caress, D. W., M. S. Burnett, and J. A. Orcutt, Tomographic image of the axial low velocity zone at 12°50'N on the East Pacific Rise, *J.Geophys. Res.*, **97**, 9243-9263, 1992.

Caress, D. W., M. K. McNutt, R.S. Detrick, and J.C.Mutter, Seismic imaging of hotspot-related crustal underplating beneath the Marquesas Islands, *Nature* , **373**, 600-603, 1995.

Christeson, G.L., G.M. Purdy, and G.J. Fryer, Structure of young upper crust at the East Pacific Rise near 9°30'N, *Geophys. Res. Lett.*, *19*, 1045-1048, 1992.

Evangelidis C P, Minshull T A, Henstock T J, Three-dimensional crustal structure of Ascension Island from active source tomography. *J. Geophys. Int.* **159** 311-25, 2004.

Grevemeyer, I, Weigel, W, Schussler S, Avedik F, Crustal architecture and deep structure of the Ninetyeast Ridge hotspot trail from active-source ocean bottom seismology. *Geophys. J. Int.* **144**, 414-31, 2001.

Hammer, P. T. C., L. M. Dorman, J. A. Hildebrand, and B. D. Cornuelle, Jasper Seamount structure: Seafloor seismic refraction tomography, J. Geophys. Res., 99(B4), 6731–6752, 1994.

Hussenoeder, S. A., R. S. Detrick, G. M. Kent, H. Schouten, and A. J. Harding (2002), Fine-scale seismic structure of young upper crust at 17°20'S on the fast spreading East Pacific Rise, J. Geophys. Res.,107(B8), 2158, doi:10.1029/2001JB001688.

McClain, J.S., and D. W. Caress, Seismic tomography in marine refraction experiments,in *Seismic Tomography: Theory and Practice*, edited by H. M. Iyer and K. Hirahara, 848 pp., Chapman and Hall, London, 1993.

b) Continuing Projects

N/A

c) New and Continuing Projects: Plans for 2009

Research Activities

[Click here to enter text]

Engineering/technology development

We propose a two-year development project. During year one, we will design and construct the source system, purchase two OBHs, and conduct tests the system. During year two, we will purchase additional OBHs and conduct the first full-scale seismic refraction tomography experiment. The number of OBHs ultimately fielded will be determined following tests to optimize the ROV based operations.

The proposed development combines ROV-mounted transmission of a chirp acoustic signal with a roughly 1-6 kHz sweep and an array of high-frequency ocean bottom hydrophone (OBH) receivers deployed from the ROV. By having closely spaced receivers and a highly repeatable source, it will be possible to pick refracted arrival times and model the shallow seismic velocity structure using 2D or 3D tomographic inversion. The target experimental scale ranges from subsurface sections 100 m across and 20 m deep to 1 km across and 200 m deep. Given the ~3 kHz center frequency and a sub-meter shot spacing, the best achievable resolution of subsurface structure will be about 1 m, though this will be limited by the actual receiver spacing used. Although novel in the sense that no one has previously combined chirp sonar technology, high frequency OBHs, ROV operational capabilities, and tomographic inversion algorithms, all of the relevant technologies are mature, minimizing the technical risk associated with this project. This capability will be readily exportable to other oceanographic institutions operating ROVs. This project will involve the following efforts:

1. Design and construction of a ROV-mounted chirp acoustic source system. This system will incorporate a low-frequency transducer capable of outputting in the 1 kHz to 6 kHz band, and off-the-shelf electronics to generate the desired waveform and drive the transducer.

2. Build custom waveform generation unit consisting of COTS hardware and software (LabView).

3. Obtain high-frequency OBHs for recording a broadband hydrophone output at sampling rates up to 15 kHz or more. Since experiments will require receiver operation for no more than 48 hours, the electronics need not be optimized for low power. However, size should be minimized to allow many instruments to be deployed by ROV in a single dive (possibly using an elevator).

   An excellent candidate OBH has been identified which fits the requirements of the project. Bill Burgess, a former MBARI postdoc now working for Greeneridge Sciences, has designed a compact recording hydrophone. The device, called a B-Probe, can record at 20 kHz for weeks. Its small package (20 cm long and 3.2 cm in diameter) could be configured with a syntactic foam float and anchor weight to be deployed much like our standalone HomerPro beacons. Bill is willing to make small changes to the code to support our project, although no changes are anticipated. No hardware or software development on MBARI's part will be required.

4. Software development to de-correlate chirp signals recorded by the OBHs. The algorithms for match filtering of chirp signals are well established. We will implement these algorithms to be operated in a post-processing context.

5. Software development for refraction arrival time picking, forward modeling, and tomographic inverse modeling of the compressional seismic velocity structure. We have software in hand for these purposes, but the code will require updating and improvement.

Our first year (2009) project plan is summarized here:

1. Design the experiments and variations
   a. Plan/Review goals, procedures, desired results of experiment
   b. Design reviews
2. Acquire acoustic source and integrate into Ventana
   a. Purchase electronics and housing from vendor (EdgeTech)
   b. Develop signal source electronics kit (LabView)
   c. Design and fabricate toolsled chassis
   d. Test/Integrate into Ventana
3. Acquire two OBH/Loggers suitable for the experiment
   a. Purchase Greeneridge system
   b. Test OBH units and integrate dataflow
4. Develop software tools necessary to analyze OBH data
   a. Integrate source timing with logged data
   b. Apply match filtering to raw data (“de-chirping”) to extract impulse response seismograms.
   c. Update existing software for record section display, arrival picking, and forward/inverse modeling of 2D and 3D refraction data.
5. Perform the experiments and process/analyze the data
   a. Engineering test experiments (3 Lobos days + 3 mob days)

6. Publish Oceans paper
7. Design multiple OBH field deployment based on test experience
8. Design data management system for multiple OBH/Loggers
    a. Spec system to automate data analysis from multiple units

Field programs (detail ship requirements/deployments)

Initial testing will occur during year one (2009) in Monterey Bay, and will require the use of the Pt. Lobos and ROV Ventana for three sea-days and three mob-days in the April and May timeframe. The testing will include experiments both on the flat shelf near Moss Landing and in the axis of upper Monterey Canyon. The latter experiments will measure the thickness of the sands along the canyon axis, resolving a major unknown in the Continental Margins Project study of sediment transport down Monterey Canyon.

The first major field experiment will be conducted in year two (2010) at either the northern Santa Monica Basin gas hydrate mound or the Barkley Canyon hydrate outcrops. Both sites have been investigated using ROVs and the Mapping AUV, are known to feature actively forming near surface and surficial hydrate deposits, and have an unknown but likely fault-related subsurface structure. We view both sites as being of sufficient interest to justify a major field experiment, and we expect to choose the 2010 experiment site based on ship availability and logistical considerations.

Specific deliverables

- Acoustic source, including electronics housing, transducer, and cabling
- OBH units from Greeneridge Sciences
- Experimental data
- Publication of method and results
- Open source distribution of chirp processing and data analysis software

Milestones

As indicated by the milestone chart below, our intent is to perform the hardware integration, software development, and testing during the first half of 2009. The second half of the year will be devoted to data analysis, software improvement, and planning for the 2010 field experiment.

Budget justification

Description	Amount
ROV Toolsled Chassis for Acoustic Source	1,500
ROV Mounting hardware	1,000
Miscellaneous Electronics	1,500
EdgeTech Acoustic Source with housing	15,000
Ocean Bottom Hydrophone	14,000
Spare OBH	14,000
Batteries	500
Cables and Connectors	4,000
LabView acoustic signal generator electronics kit	4,500
Signal generator electronics housing	10,000

Equipment Total	**$66,000**
Miscellaneous hardware	2,000
Computer Hardware Total	**$2,000**
LabView Development Suite license	2,500
LabView Waveform editor	900
Miscellaneous software	600
Computer Software Total	**$4,000**
1 Oceans Conference, Biloxi, MS	2,800
2 AGU Conference, SFO	3,000
Travel Total	**$5,800**
Budget Total	**$77,800**

Project team

- David Caress: Principle Investigator and Project Manager
- Rich Henthorn: Lead Engineer, Software Engineer
- Paul McGill: Electrical Engineer
- Bill Kirkwood: Mechanical Engineer
- Charlie Paull: Scientist

Scientists with interest in field programs utilizing the proposed high-resolution seismic refraction capability:

- Charlie Paull (Hydrate deposits, faults, canyon sediments)
- Peter Brewer (Barkley Canyon hydrate outcrops)
- David Clague (Hawaiian reef structure)

Project lab space

Project lab space for instrument assembly and testing will be required. Caress does not presently have any designated lab space.

Data availability outside project team, uniqueness

The processed seismic refraction record sections will be generated in the community-standard SEGY/SIOSEIS and SEGY/PASSCAL formats. These data will be submitted with supporting metadata for archiving to the IRIS Data Management Center in the same fashion as data from refraction experiments conducted using instruments from the NSF-funded national Ocean Bottom Seismograph Instrument Pool (OBSIP) centers.

The chirp processing and data analysis software developed for this project will be packaged and documented for distribution as open source under the GPL license, similar to the MB-System software already distributed from MBARI.

Risk matrix (development and infrastructure projects only)

	Technical Risk	Organizational Risk	Tech Transfer Risk	Labor Estimate Risk
High				
Medium	X			

Low		X	X	X

3) MILESTONES (new and continuing projects)

	Milestone 1	Milestone 2	Milestone 3	Milestone 4	Milestone 5	**Total Resources**[3] for each resource category for all milestones listed here
Milestone Date	**1st Qtr**	**1st Qtr**	**2nd Qtr**	**2nd Qtr**	**4th Qtr**	
Milestone Description	**Experiment Design/Engineering Design & Development**	**Obtain/Integrate Acoustic Source and OBH**	**Engineering Tests and Deployment**	**Analyze the data/internal report**	**Publish phase 1 results**	
EE	**24**	**96**	**130**	**16**	**24**	**290**
SE	**80**	**160**	**120**	**16**	**24**	**400**
ME	**24**	**10**	**120**	**16**	**24**	**194**
Support Eng						
EE Tech		**120**				**120**
SE Tech						
ME Tech		**40**				**40**
Machine Shop						

[3] This number should be the same number you entered on the resource requests for this particular resource.