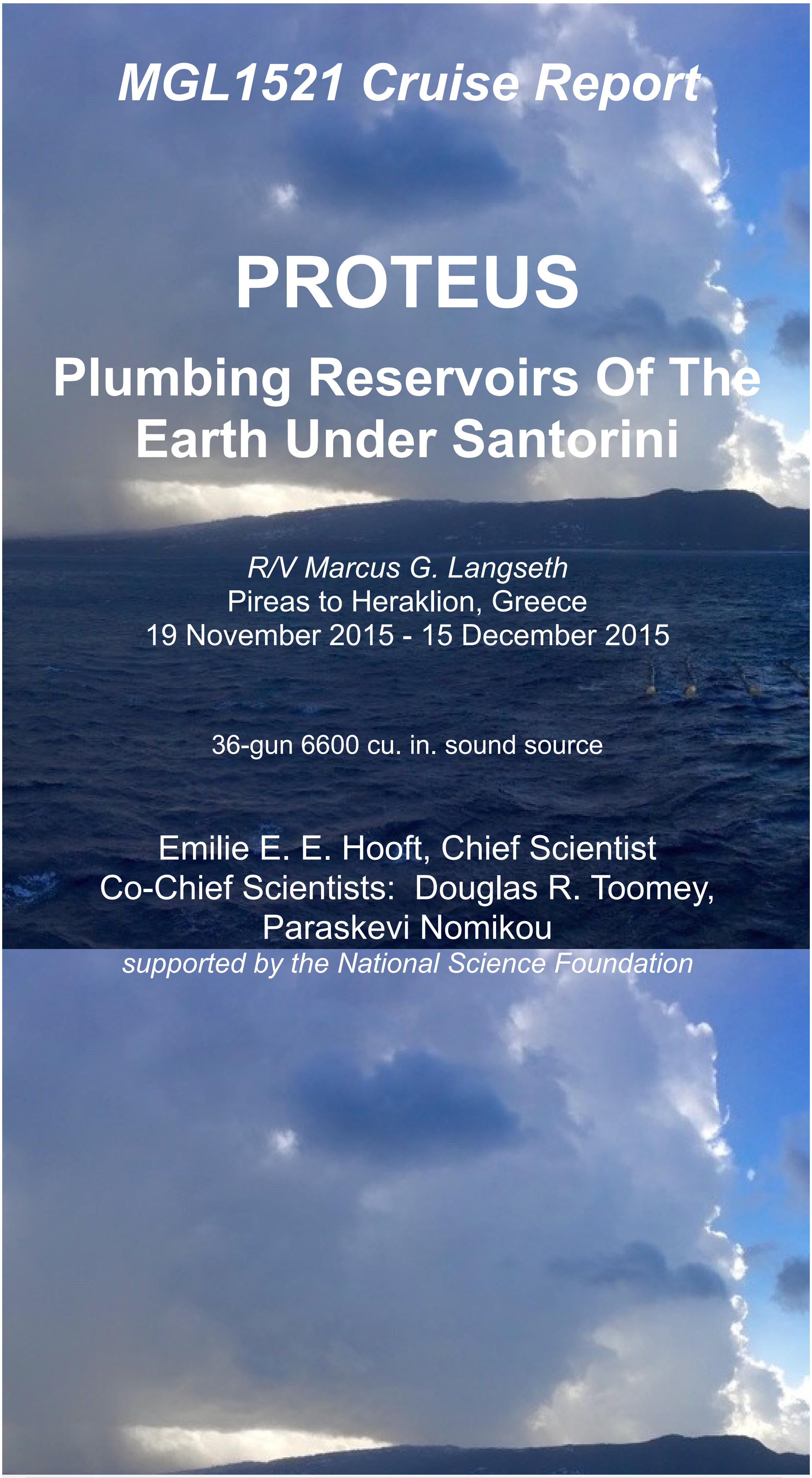


MGL1521 Cruise Report

PROTEUS

Plumbing Reservoirs Of The Earth Under Santorini

R/V Marcus G. Langseth
Pireas to Heraklion, Greece
19 November 2015 - 15 December 2015

36-gun 6600 cu. in. sound source

Emilie E. E. Hooft, Chief Scientist
Co-Chief Scientists: Douglas R. Toomey, Paraskevi Nomikou

supported by the National Science Foundation

Summary

PROTEUS
Plumbing Reservoirs Of The Earth Under Santorini

"One must wait until the evening, to see how splendid the day has been." Sophocles

On this research expedition the *R/V Marcus G. Langseth* leg MGL1521 collected dense seismic data at Santorini volcano in the eastern Mediterranean, Aegean Sea. The study was supported by the National Science Foundation Grant number (1548026)*. During the 26-day expedition, 91 four-component, ocean bottom seismometers (OBSs) were throughout the area to record seismic energy from the 36-element, 6600 cu. in. airgun array of the *R/V Marcus G. Langseth*. The data will be used for 3D, anisotropic seismic tomography and full seismic waveform inversion.

The goal of the research project is to examine the entire crustal magma plumbing system beneath an arc volcano. The magma geometry and connections throughout the crust are physical parameters that control magma migration, storage, and eruption and are thus important to understand geohazards. More broadly, this study will help answer questions about how the processing of magma at arc volcanoes forms the rock compositions that dominate the lower continental crust.

The ocean bottom receivers were from the NSF-supported Ocean Bottom Seismograph Instrument Pool (OBSIP); 61 and 30 OBSs were provided by the Scripps Institution of Oceanography (SIO) and the Woods Hole Oceanographic Institution (WHOI) OBSIP groups, respectively. Of the 91 OBS 90 were successfully recovered. By site, the data return rate appears to be somewhat lower than is typical for active source short-period deployments. The seismic source throughout the experiment was the *Langseth's* 36-gun array, with a total volume 6600 cu. in. Airgun data were collected along 2500 km of track line an average shot spacing of 144 to 165 m. In addition to the seismic data, swath bathymetry, gravity and magnetics data were collected throughout the region.

The structure of this report is as follows: The sections prior to the appendices briefly summarize the scientific and operational objectives, the events that transpired during the cruise, and the overall quality and characteristics of the seismic data. The remainder of the report contained in the appendices is primarily of a technical nature and useful to someone working with the PROTEUS data.

*Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

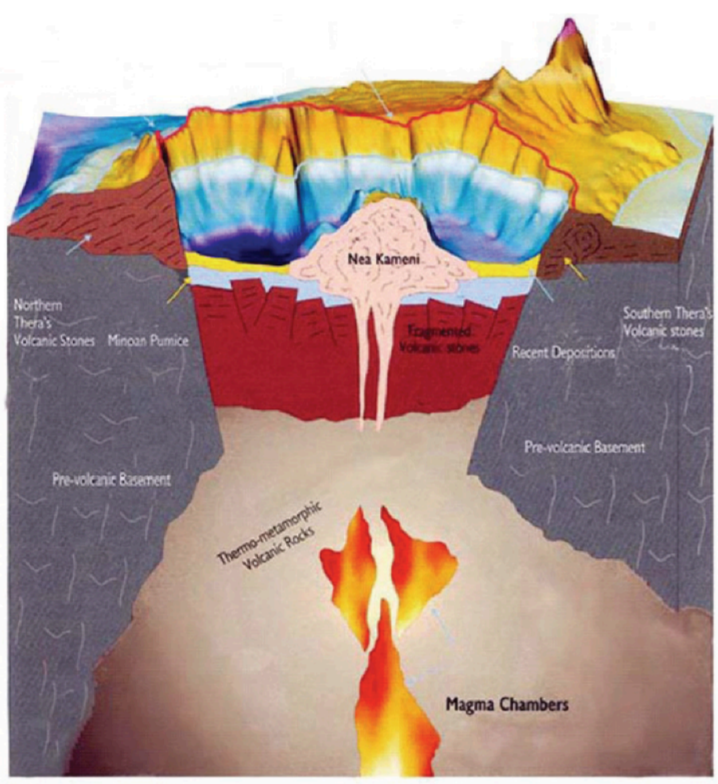
- 1. Cover
- 2. Summary
- 3. Scientific Objectives
- 4. Operational Objectives
- 5. Cruise Narrative
- 6. Preliminary Cruise Assessment
- 7. Appendices A: Science
- 8. Appendices B: Personnel & Multimedia
- 9. Appendices C: Environmental Assessment, Protected Species, and Permitting

Scientific Objectives

- The goal of the Santorini Active Source Seismic Experiment is to examine the entire crustal magma plumbing system beneath Santorini volcano. Santorini is unique for this study because it recently experienced significant unrest; inflation of the ground and intense earthquake swarms during 2011-2013. It is also geologically well-studied. It is an ideal location because is a semi-submerged volcanic system which makes it possible to collect dense 3D marine-land seismic data. We will record sound sources from the US R/V Langseth on 93 short period ocean bottom seismometers and 26 land seismometers.

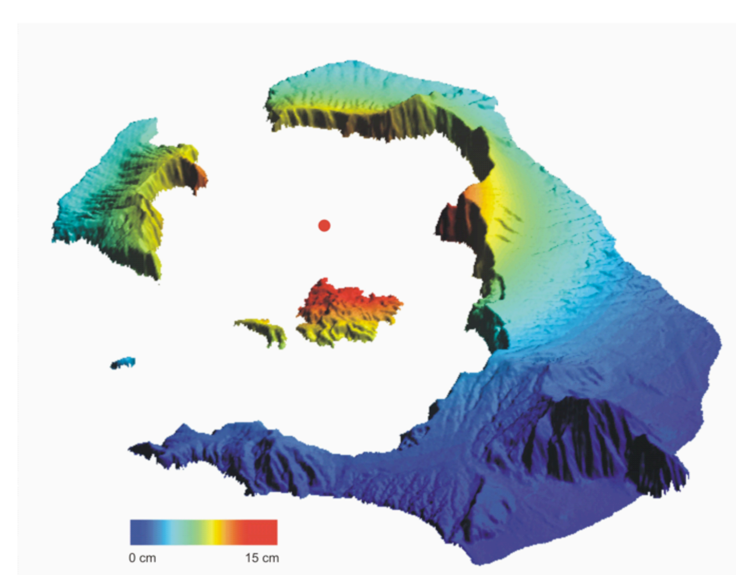
  Santorini provides millions of dollars to the Greek economy annually, and any renewed volcanism and/or seismicity would not only impact the communities on Santorini and the neighboring islands but also have a substantial economic impact. This research will inform the Greek public and civil authorities about volcanic, earthquake, and tsunami hazards and would help inform disaster management planning.

  The proposed high-density spatial sampling of the seismic wavefield and state-of-the-art travel time and waveform inversion methods will provide new insights into the structure of the whole crustal magmatic system and its surroundings. This will allow the scientists to determine the magma geometry and connections throughout the crust – physical parameters that control magma migration, storage, and eruption and are thus important to understand geohazards. More broadly, this study will also help scientists answer questions about how the processing of magma at arc volcanoes forms the rock compositions that dominate the continental crust.

- 

  Hypothetical cross section of Santorini magmatic system (Source: VolcanoCafe.wordpress.com).

- Vertical deformation of Santorini during the period of unrest in 2011 – 2012, determined by Michelle Parks (University of Oxford) from measurements of the deformation field across the islands. The deformation is best explained by the intrusion of magma about 4 km below the red dot.



Operational Objectives

Overview

The primary operational objectives of the marine component of the PROTEUS Project were to deploy 91, four-component ocean bottom seismometers (OBSs) in and around Santorini volcano in order to record active source data from the airgun array of the *R/V Marcus Langseth*, which is owned by the *National Science foundation* and operated by the Lamont-Doherty Earth Observatory.

The PROTEUS Project also includes an onshore deployment of over 70, three-component seismometers; these are located on the islands of Thira, Anafi, Anhydros, and Christiana.

Data from the offshore-onshore seismic arrays will be used to image the 3-D seismic structure of the crust and topmost mantle beneath Santorini and nearby volcanic lineaments and tectonic features. The experiment will image the magmatic system throughout the crust as well as the regional tectonic structures.

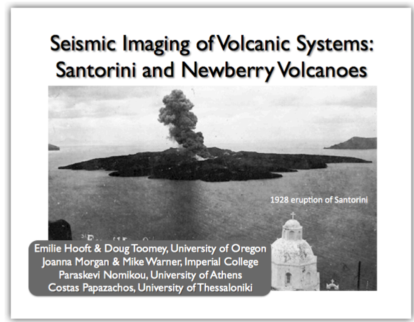
Summary of Operations

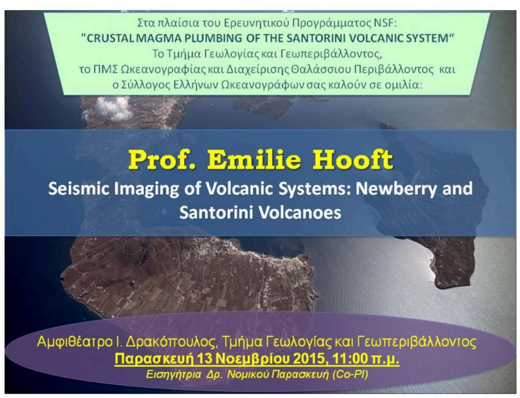
The primary operational goals of the PROTEUS Project were as follows:

- **a.** Deploy 91 ocean bottom seismometers at 91 sites.
- **b.** Record seismic energy from the Langseth's 36-gun, 6600 cu. in. airgun array.
- **c.** Recover 91 ocean bottom seismometers.
- **d.** Produce SEGY files of all OBS data.
- **e.** Complete post-acquisition editing of all Simrad EM122 multibeam data.
- **f.** Collect underway geophysical data, including magnetics and gravity.
- **g.** Archive all cruise-related data and finalize report.

Cruise Narrative

- **Santorini Island: Nov 3 - Nov 10, 2015**
- **Athens-Pireas: Nov 11 - Nov 18, 2015**
  - *Wednesday Nov 11th*
  - *Thursday Nov 12th*
  - *Friday Nov 13th*
    - Early in the morning the R/V Langseth docks in Pireas, terminal E11.
    - The 5 grad students flying in from Oregon have their flights rescheduled because of strikes with Lufthansa and they were all flying together through Paris. They are now arriving at 3 separate times; two today and one tomorrow. Taxi rides to the AirBnB are rearranged by Doug.
    - 9 am Prof. Paraskevi Nomikou (Evi) picks up Doug and Emilie to go to the University. Doug talks to Prof. Papanikolaou while Emilie calls Mrs Touratzof at the Greek Foreign Ministry. She confirms that the desired Note has now been received. She also informs Emilie and Evi that now the EXATH science committee will reconsider the matter on Monday morning!
    - Doug has a lengthy discussion with Prof. Papanikolaos
    - 11 am Emilie's talk is well attended and well received. Many questions afterwards that are followed by individual discussions and emails.
      - Santorini_UnivAthens2015_Talk_reduced.pdf





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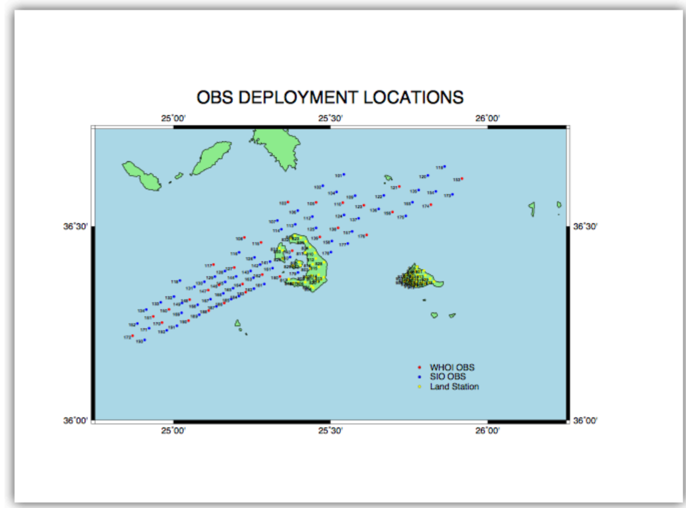
OBS Operations and Data Quality

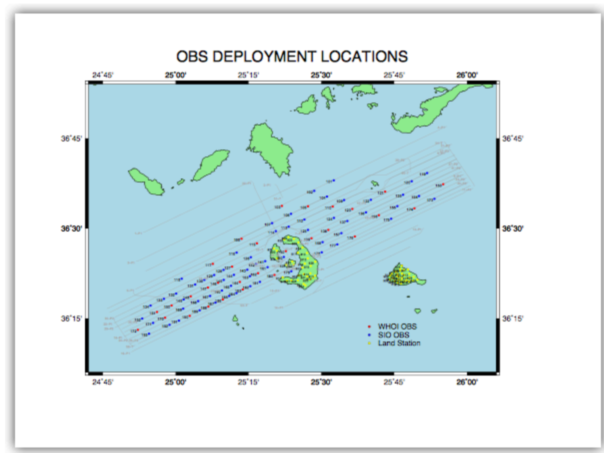
- **OBS Summary Table.xlsx**

Land Sites
- LandSites.dat
- final-sites.kml

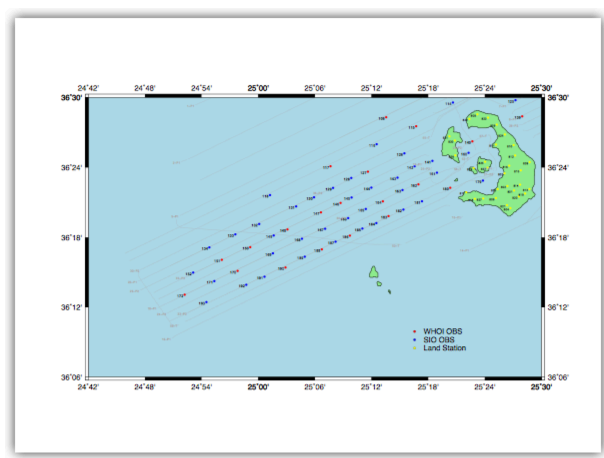
- AllStation_OBSLand



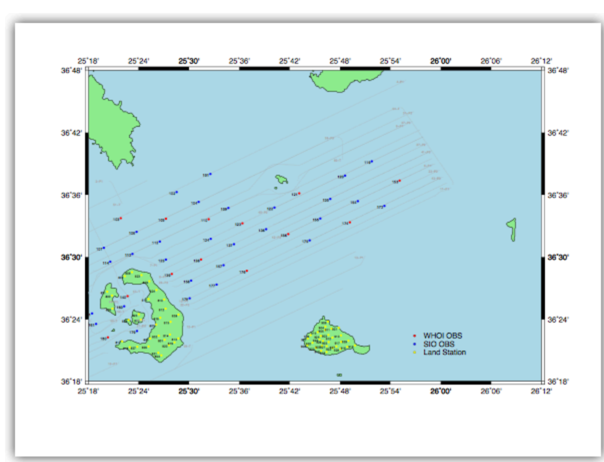
- FullMap AllStations AllShots



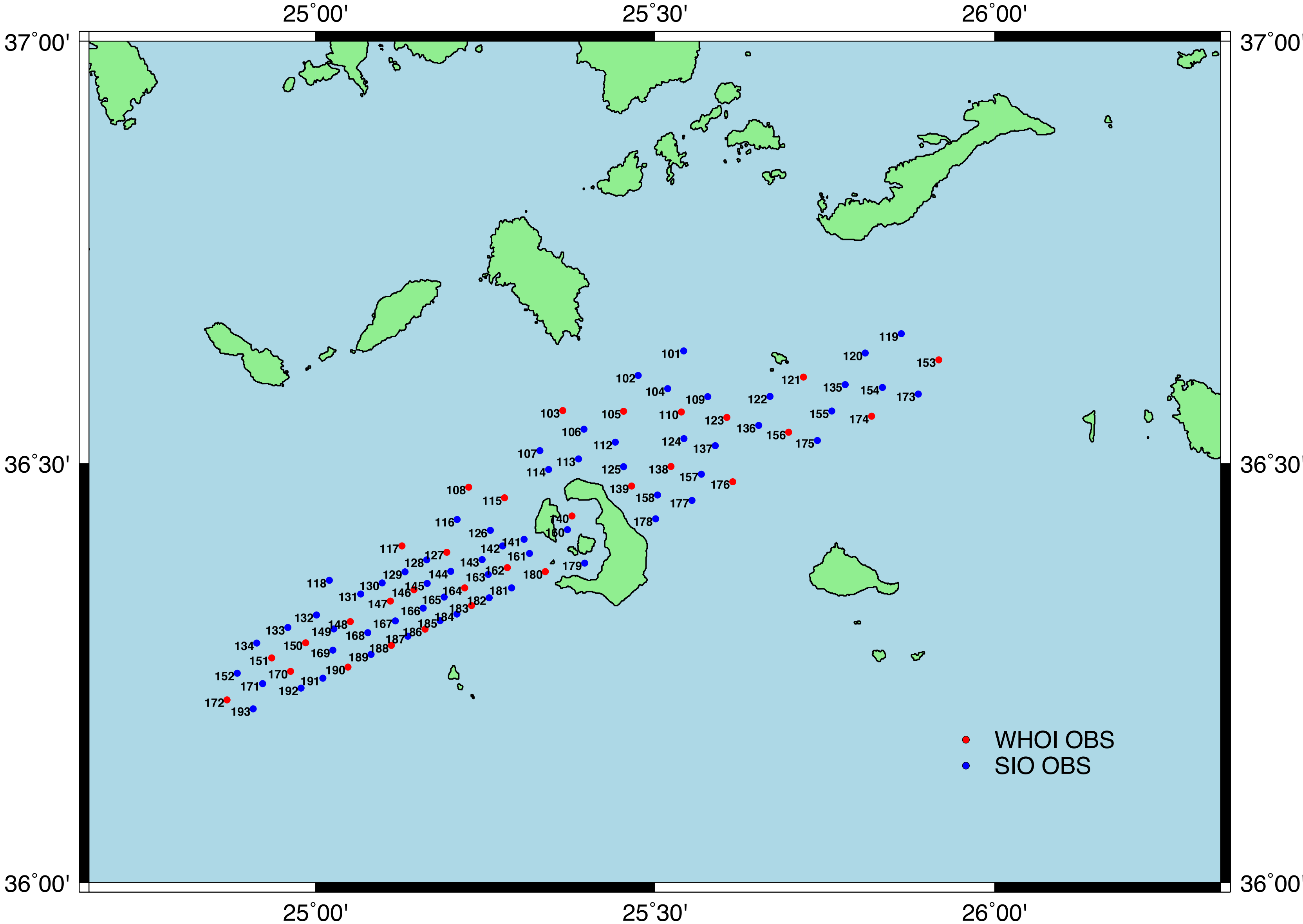
- SWCorner



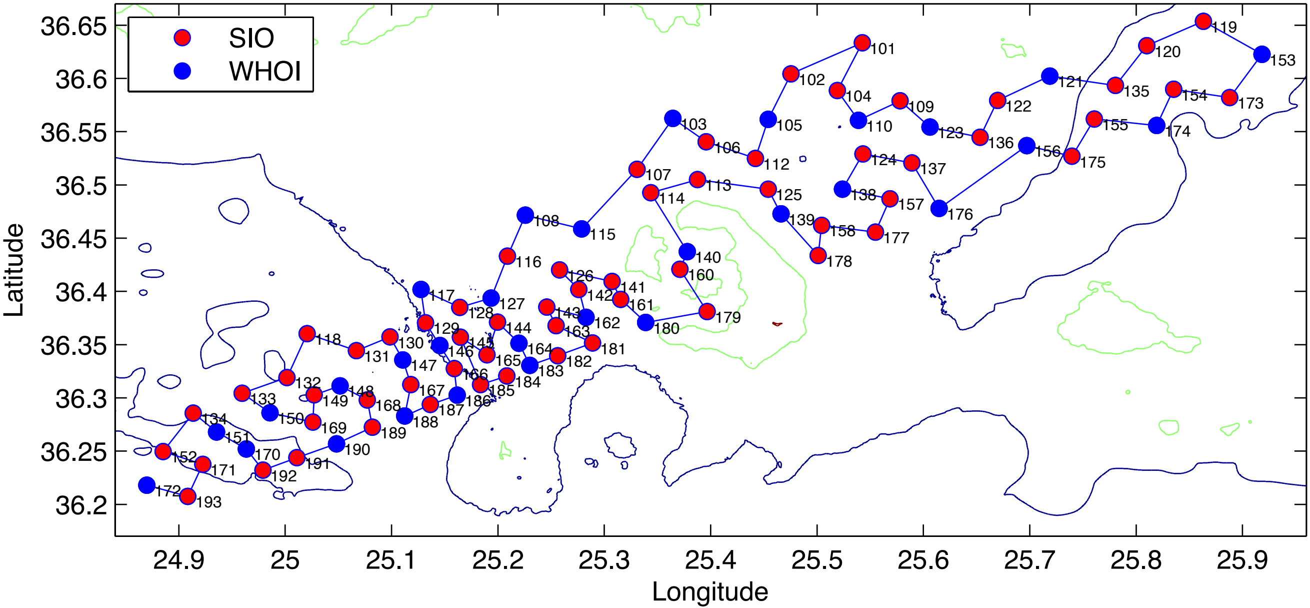
- NECorner



OBS DEPLOYMENT LOCATIONS



WHOI and SIO stations along recovery path (version 10)



A2: Seismic Survey Summary

- **Santorini_ShotLineTable**

Included in Appendix A2 are the following:

- **1.** Description of the survey
- **2.** Seismic Line naming convetion
- **3.** Shot log file description
- **4.** Maps of the seismic survey
- **5.** Interweaving between shot lines comparison between East and West side.
- **6.** The airgun data quality is described in the section "Airgun Operations and Source Reliability".
- **7.** The SEGY file formats are described in Appendix A5 and A6 for the SIO and WHOI instruments, respectively.
- **8.** Reading of the OBSIP log files and SEGY files is described in Appendix A13

1. Description of Survey

The Santorini Seismic Experiment provides multi-tiered imaging of the Santorini Volcano magmatic system and associated terranes. Shot lines are divided into 3 categories (P1,P2,P3)

- *P1*: P1Shot lines are the primary shot lines and compose lines deemed most important for understanding the deep magmatic system. Ship speed for P1 lines was 3.5 knots (ship turns will be at 5.5 knots). Shot interval was ~90 seconds yielding a shot spacing of 165 meters
- *P2*: P2 shot lines are lines in between primary shot lines, which increase shot density and hopefully seismic resolution. Ship speed for P2 lines was 4 knots (ship turns will be at 5.5 knots). Shot interval was ~70 seconds. This yields a shot spacing of 144 meters.
- *P3*: P3 shot lines are reshoots of the ends of some of the P1 shot lines. Reshooting lines allows for stacking of traces and better picking of arrivals. This will allow for the creation of a better travel time tomographic model. Ship speed for P3 lines was 4 knots (ship turns will be at 5.5 knots). Shot interval was ~70 seconds. This yields a shot spacing of ~165 meters. Shots were interleaved with the shots from the original shooting of these lines.

- Airguns were towed at ~12 m water depth throughout the experiment for enhanced low frequency content

2. Seismic Line Naming Convention

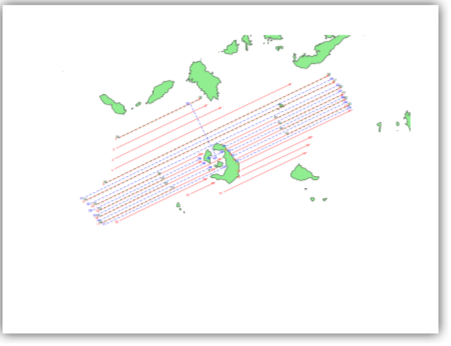
- Shot lines are named in the order they were shot. All shot log names begin with the heading OBS. For example OBS06 was the sixth shot line. Transit shotline (shot lines shot while in transit between main lines) were labeled with a T followed by a number (e.g OBST01 was transit 01). For our srEvent files, the id is the shot line number. Transits are labeled as the transit number + 50 (e.g. transit 01 has id 51). This is to have unique ids for all events that still retain relative shot line info.

3. Shot log file description

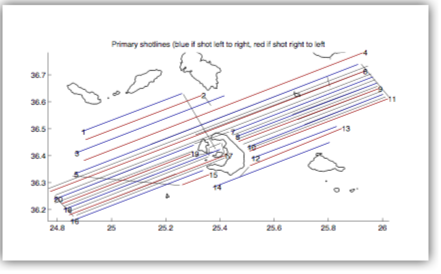
- Each shotlog file is named after the line shot (eg. MGL1521OBS02.shotlog for line 02). Each file contains: shotnumber, date, time, sourceLat, sourceLon, shipLat, shipLon, waterDepth, sciTag. Further description is provided in A13

4. Maps for seismic survey:

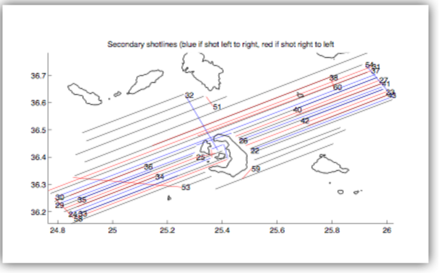
- Shot Lines: This shows the proposed lines and does not reflect the order that they were shot.



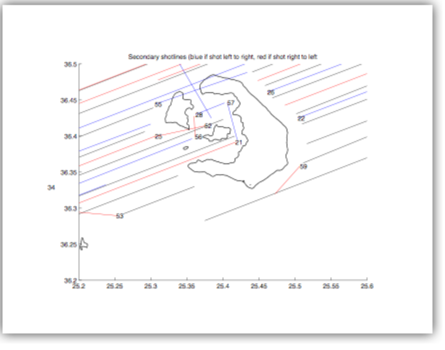
- Primary shotlines colored by shooting direction: Note all lines are drawn as straight lines from first to last shots. Lines are colored depending on whether the first shot is to the left of the last (blue) or if the first shot is to the right of the last shot (red)



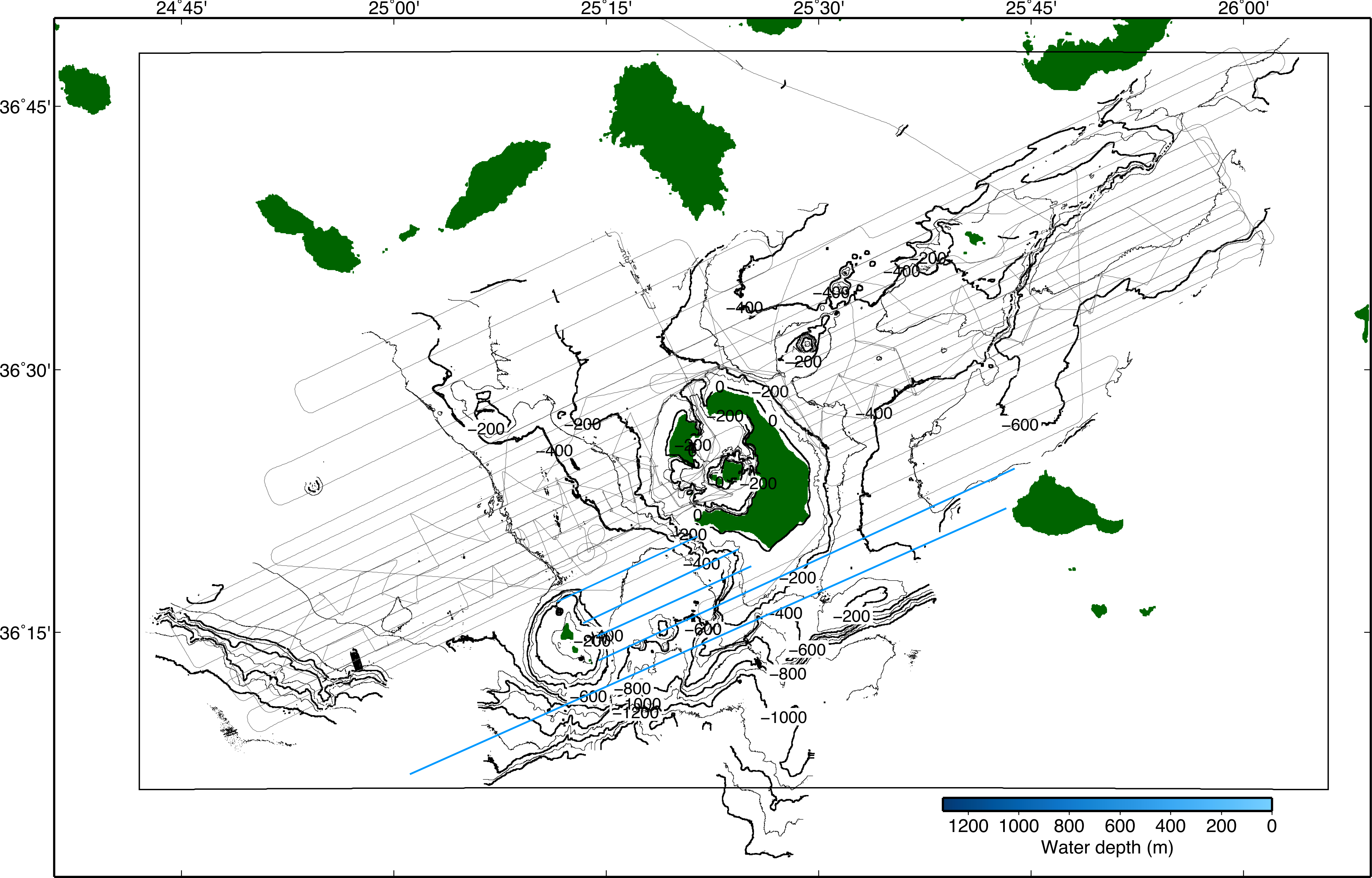
- Secondary and tertiary shotlines colored by shooting direction



- Secondary and tertiary caldera centered lines colored by shooting direction.



5. Interweaving between shot lines comparison between East and West side.



24°45'
25°00'
25°15'
25°30'
25°45'
26°00'
36°45'
36°30'
36°15'
-200
-400
-600
-800
-1000
-1200
0
1200 1000 800 600 400 200 0
Water depth (m)

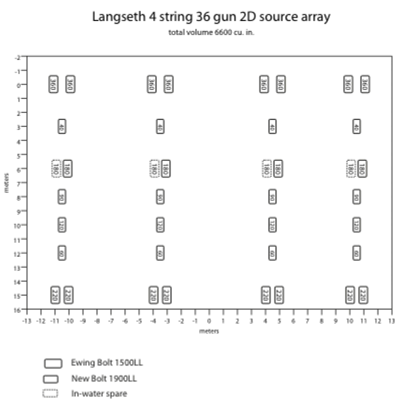
A4: R/V Marcus G. Langseth Sound Source

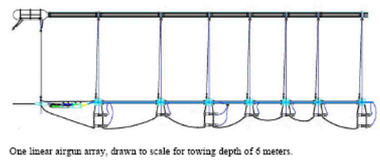
MGL1521 Airgun Operations

The R/V Langseth airgun array consists of 36 air guns with a total volume of 6600 in3 at 2000 psi. To enhance power and low frequencies the airguns were run at depths of 12 m for the duration of the experiment. During airgun operations the towing speed of the Langseth was 3.5 or 4 kt.

The R/V Langseth seismic source consists of four identical linear arrays, or strings each of which has ten air guns. Nine air guns per string were fired on all four strings simultaneously, while the tenth was kept in reserve as a spare to be turned on in case of the failure of another air gun. Shots were fired at predetermined coordinates while on the shot lines and a 60 s intervals during transects between lines. Typically, on each string gun 5 is kept as a spare, but if there were issues with one of the other guns, gun 5 on the string in question was put in service and the other gun was shut off.

Seven different volumes of Bolt Models 1500LL & 1900LLXT Long Life Air Guns are used. Guns 1 & 2 are 360 in3 and are used in parallel. Gun 3 is 40 in3. Guns 4 & 5 are 180 in3 and are used in parallel. Gun 6 is 90 in3. Gun 7 is 120 in3. Gun 8 is 60 in3. Guns 9 & 10 are 220 in3 and are used in parallel.





One linear airgun array, drawn to scale for towing depth of 6 meters.

GUN	TYPE	X(m)	Y(m)	Z(m)	VOL(cu)	PR(psi)
1	1500LL	0	0	5.4	360	2000
2	1500LL	0	0	6.6	360	2000
3	1900LLX	3.23	0	6	40	2000
4	1500LL	5.59	0	5.6	180	Spare
5	1500LL	5.59	0	6.4	180	2000
6	1900LLX	8.23	0	6	90	2000
7	1900LLX	10.69	0	6	120	2000
8	1900LLX	13	0	6	60	2000
9	1500LL	16	0	5.53	220	2000
10	1500LL	16	0	6.47	220	2000

Figure 1: Schematic R/V Langseth gun array layout. The array comprises four identical but separately towed strings, each with ten air guns. (a) Each string is made up of three two-gun clusters and four individual guns. The purpose of the clusters is to provide a larger, more slowly reverberating residual air bubble (which improves overall array tuning) while at the same time reducing the amplitude of that bubble's reverberation, which further improves tuning. One of the 180 in3 air guns within the central cluster is normally turned off and held in reserve as a spare. (b) Detailed side view of the towing arrangement for one of the four identical source strings on the R/V Langseth, drawn to scale for a towing depth of 6 meters.

The airgun array signature depends on the towing depth (Fig. 2). We used a towing depth of 12 m.

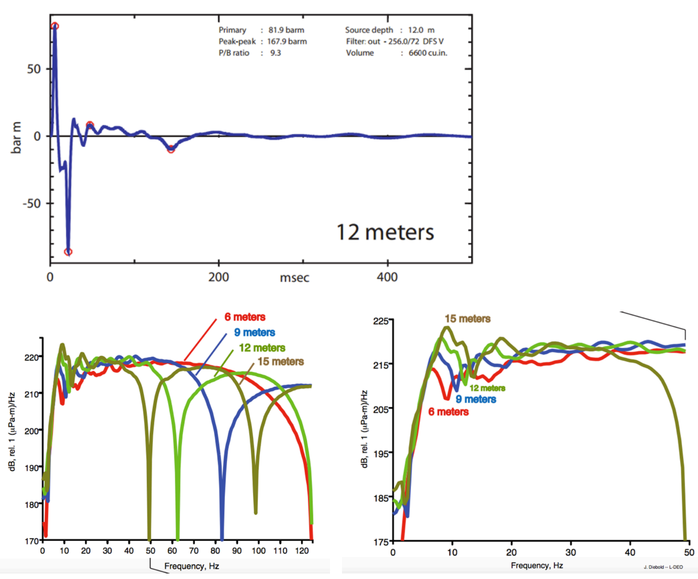
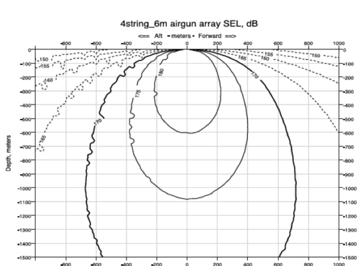


Figure 2: Airgun signature modeled for 12-m tow depth and the frequency response at 4 different tow depths by John Diebold –LDEO using gunsig.

The rate at which sound levels decay around the airgun source depends on the towing depths. Acoustic received levels were quantified using sound exposure level (SEL) calculations. In the U.S.A. the current standard for mitigation is root-mean-square (RMS). The RMS amplitude, typically expressed as dB referenced to 1 mPa, is a measure of the average pressure over the duration of the pulse. It is calculated as the square root of the sum of the squared pressures within a given time window and therefore depends on the selection of this window and its duration. SEL is a measure of the energy flux density of an arrival, defined as the product of signal intensity and duration. Its decibel value (dB referenced to 1 Pa2s) will equal the RMS decibel amplitude if calculated for a 1 s duration window: SEL(dB) = RMS(dB) + 10 log10 (T), where T is the RMS integration time in seconds. For signals with durations <1 s, as expected for an air gun pulse, the SEL value will be less than the RMS. Current practice is to use 170 dB SEL as a proxy for 180 dB for the RMS sound exposure level used in permitting.

Models predicting acoustic levels for the full array were tested using a 6 m towing depth for deep water (~1600 m), intermediate water depth on the slope (~600–1100 m), and shallow water (~50 m) in the Gulf of Mexico (GoM) in 2007–2008 (Tolstoy et al. 2009; Diebold et al. 2010). Simple scaling factors were calculated using the deep water model in order to calculate acoustic levels for a 12 m tow depth (FIG. 3). During power downs a single 1900LL 40-in(_^3) airgun will be used which falls into the low energy source category (Table 1).



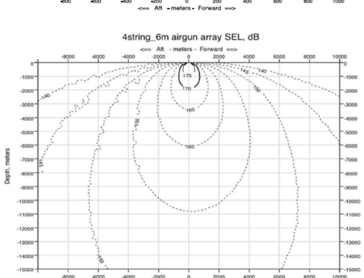


Figure 3: Decibel sound level for the airgun source towed at 9 and 15 m. The contours are SEL (sound exposure level), which is similar to EFD (energy flux density) and RMS sound exposure level with a fixed 1-second integration window.

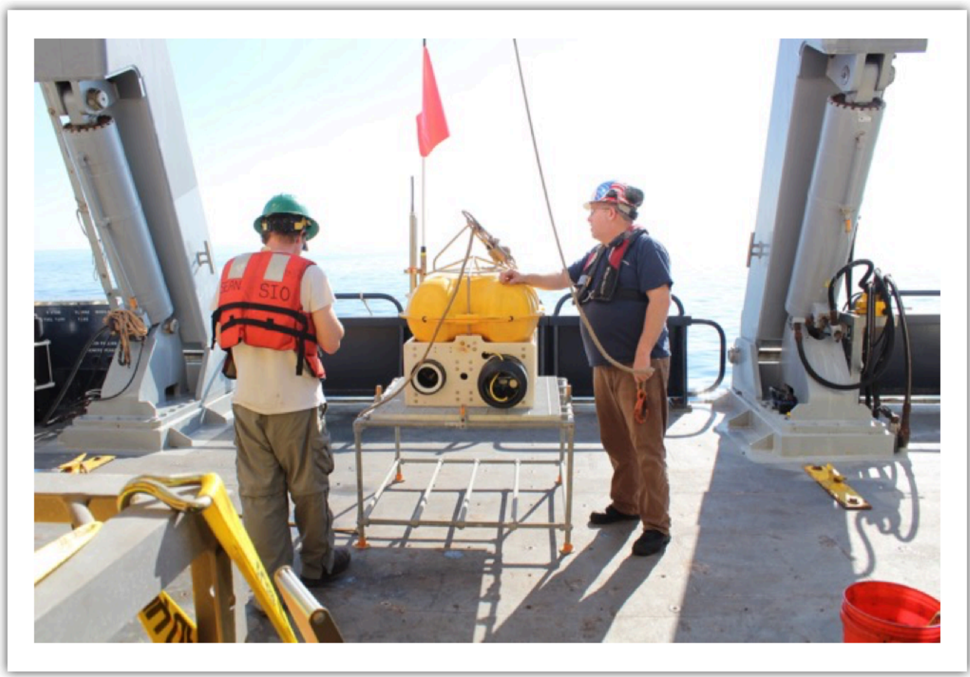
Table 1: Predicted distances to which sound levels ≥ 190-, 180-, and 160-dB re 1 µ Parms are expected to be received during the proposed survey in the eastern Mediterranean Sea. From the IHA and EA

Source and Volume	Tow Depth (m)	Water Depth (m)	Predicted rms Radii (m) 190 dB	180 dB	160 dB
Single Bolt airgun, 40 in^3	9 or 12	>1000 m	100	100	431[1]
		100–1000 m	100	100	647[2]
		<100 m	27[3]	96[3]	1041[3]
4 strings, 36 airguns, 6600 in^3	9	>1000 m	286[1]	927[1]	5780[1]
		100–1000 m	429[2]	1391[2]	8670[2]
		<100 m	591[3]	2060[3]	22,580[3]
4 strings, 36 airguns, 6600 in^3	12	>1000 m	348[1]	1116[1]	6908[1]
		100–1000 m	522[2]	1674[2]	10,362[2]
		<100 m	710[3]	2480[3]	27,130[3]

[1] Distance is based on L-DEO model results.
[2] Distance is based on L-DEO model results with a 1.5 x correction factor between deep and intermediate water depths.
[3] Distance is based on empirically derived measurements in the GoM with scaling applied to account for differences in tow depth.

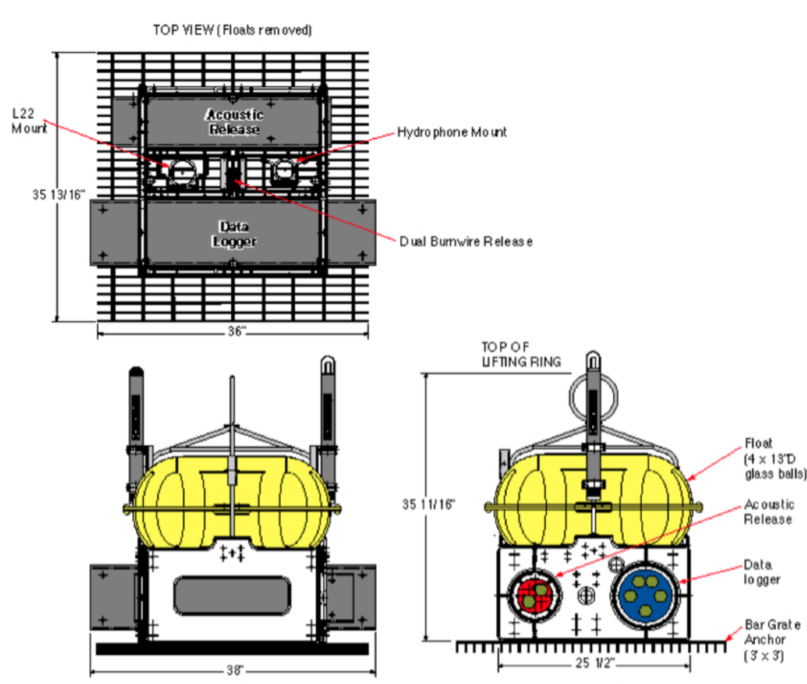
A5: SIO OBS Configurations & Performance Summary

- For the ETOMO experiment, the Scripps Institution of Oceanography (SIO) OBSIP IIC provided 61 short-period ocean-bottom seismometers (OBSs). The SIO team at sea included Ernie Aaron, Mark Gibaud and Sean McPeak.



OBS Configuration

- The Institute of Geophysics and Planetary Physics at Scripps Institution of Oceanography (IGPP/SIO) in conjunction with the Ocean Bottom Seismology Instrument Pool (OBSIP) provided 61 of the 91 total instruments for the Santorini study. The sensors used on the SP-OBS are an Sercel L28 gimbaled 3-component geophone, and a hydrophone. Each instrument is comprised of a 100-pound anchor, a four-ball McLane glass float assembly on which the lifting bail is attached, two syntactic foam blocks are added for additional floatation to aid positive buoyancy, a polyethylene frame holding the sensors, an acoustic release transponder, and two types of mechanical release systems. Two types of data loggers are used. Of the 91 OBSs deployed 26 contain a LC4x4 data logger (data logger labelled *13###*) and 35 contain “new electronics” (data logger labelled *SP###*). According to the SIO OBS team, there is no operational difference between the two loggers.
- The SP-OBS float and frame components are stored separately in a custom rack system and are assembled and tested prior to deployment on a raised preparation platform, which is secured to the deck. The complete instrument weighs approximately 400 pounds in air (with anchor). The anchor is a 100-pound iron grate held to the base of the poly frame by a single 2“ oval quick-link when the release mechanism is cocked and secured. When the anchor is released for recovery, the four 12” glass spherical floats, as well as the syntactic foam blocks provide sufficient buoyancy to lift the instrument at about 45 m/min to the sea surface. To increase visibility at the surface, an orange flag on a 48” fiberglass-resin staff is attached to the floats. The recovery aids also include a Novatech low-pressure activated strobe beacon and radio, which operates at 160.725 MHz.
- The acoustic release transponder developed in conjunction with ORE/EdgeTech is comprised of a main circuit board, a SIO developed alkaline battery pack, and an ITC-3013 transducer manufactured by International Transducer Corp. These are all installed in and on a 4-5/8” aluminum pressure case. All SIO transponders interrogate at 11 kHz and respond at 13 kHz. The alkaline batteries provide 18 volts power for the burn cycle, 12 volts power for the transponder, and 9 volts power for the circuit board logic. The release mechanisms include a single ORE burnwire and a MELT release system (designed for use in multiple environment types—not salt water specific). The ORE burnwire is the default release mechanism and the MELT release system is included as a backup. The acoustic battery pack provides up to 18 volts to one of two release wires. Release of the anchor typically occurs within 6-7 minutes.
- SIO OBS Schematic



SIO SEGY Files

- ***Check Format Post-Processing***
- SIO SEGY files contain one channel per file. For each OBS there are four SEGY files. The naming of the SEGY files and numbering of the data channels is as follows (where ### is the OBS number):
  - OS###_sanshots_L28X.segy; Channels 0 & 1 = horizontals
  - OS###_sanshots_L28Y.segy; Channels 0 & 1 = horizontals
  - OS###_sanshots_L28Z.segy; Channel 2 = vertical
  - OS###_sanshots_HYD.segy; Channel 3 = hydrophone

Hardware-specific FIR Filters

Performance Summary

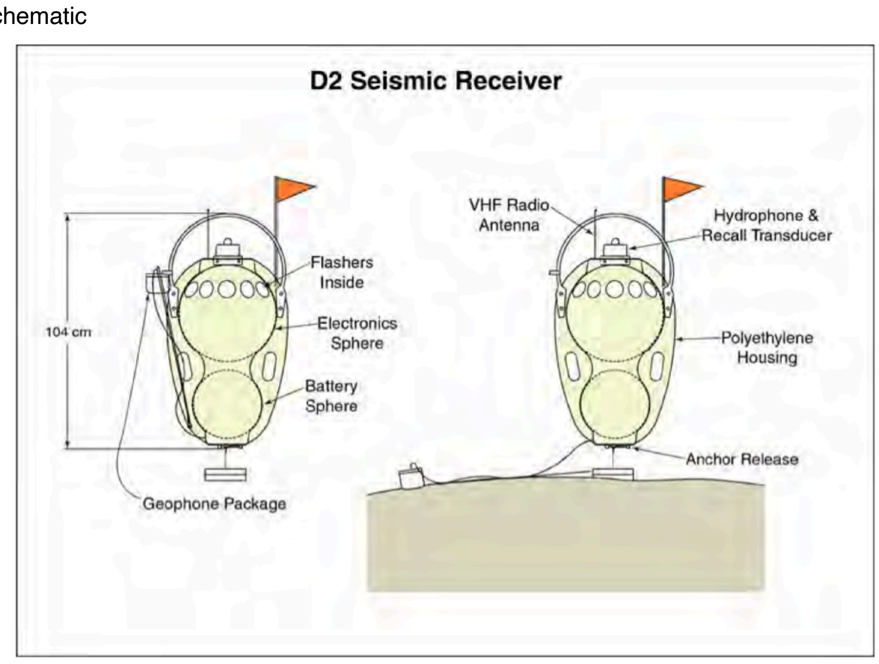
- OBS 116 not recovered since it would not release
- OBS 107 all data bad
- OBS 152 CF card write error
- OBS 182 no good data - signal issue
- OBS 187 time break errors - perhaps recoverable at SIO
- OBS 129 time break errors - perhaps recoverable at SIO
- OBS 149 hydrophone bad

A6: WHOI OBS Configurations & Performance Summary

- For the Santorini study, the Woods Hole Oceanographic Institute (WHOI) OBSIP IIC provided 30 short-period ocean-bottom seismometers (OBSs). The WHOI team at sea included Alan Gardner, Tim Kane, Jimmie Elsenbeck.

OBS Configuration

- The WHOI short-period OBS, "D2", is a compact, relatively lightweight system, which allows recording of three components of ground motion and one of pressure at sampling rates of up to 200 Hz. Physically, D2 is comprised of two glass balls containing electronics and batteries enclosed within a rigid plastic housing. The system stands 39" high and weighs approximately 115 lb in air (with anchor).
- The upper glass ball (17" diameter) contains a Quanterra Q330 data engine, a Quanterra Packet Baler storage device with 20 GB hard disk and Ethernet hub, an EdgeTech acoustic release board, recovery aids, and custom electronics. A Seascan clock is located on a system control board and is accessible via a serial ASCII current loop. Recovery aids include four flashers and a programmable VHF radio with a minimum range at sealevel of ~2 nm. The VHF antennae is attached to the inside surface of the glass ball. The Q330 includes operating software, a low-power analog-to-digital converter with 140 dB dynamic range, digital filters, clock, and 8-16 Mbytes of buffer memory. Engineering data and four channels of signal are continuously recorded and intermittently logged via an Ethernet connection onto the disk drive in miniSEED format. For this experiment, we used a sample rate on all data channels of 200 Hz. In the lower glass ball (10" diameter) are battery packs comprised of both alkaline and lithium cells that supply power separately to the Q330 and hard drive, the recovery electronics board and aids, and to the EdgeTech release board (separate cells for acoustic ranging and releasing). Ethernet connections can be used to program the operating software and to recover data from the hard drive.
- The external plastic case or "hard hat" provides protection for the glass balls and structural rigidity. An ITC 12 kHz acoustic transponder is attached to the upper cover of the case. Next to the transponder is a HighTech model HTI 1-90-U hydrophone. Three orthogonally mounted 4.5 Hz geophones are mounted in a 5" diameter (5.5" high) titanium case, which is attached by a weighted cable through the plastic case to the upper electronics ball. The case is filled with high viscosity silicone oil. Internal gimbals allow the geophones to passively orient themselves with respect to gravity through 180 degrees of motion. Prior to deployment, a bail is screwed to the seismometer case, and the bail is hooked to the tip of a 23" long fiberglass wand. The bottom of the wand is attached to the base of the plastic housing by a rotatable joint. The tip of the wand and the seismometer are raised and attached to the side of the plastic housing by a galvanic link that dissolves in seawater after ~4 hours. When the link dissolves, gravity carries the sensor can out and away from the D2. The sensor can slips from the tip of the wand, which is then pulled up and away from the can by a bungee cord.
- The D2 has ~25 lb of buoyancy and is weighted by a 55 lb steel plate anchor (6"x15"x2"). A 9" length of stainless steel wire rope to a 2" diameter ring connects the anchor plate. The ring is held to the D2 by a lever arm. One end of the lever arm is attached to the D2 base plate by a burn-wire that can be severed by an electric current triggered by a coded acoustic signal to the EdgeTech transponder. A battery that is separate from the battery supplying power to the Q330 and the hard drive powers the burn-wire and the release electronics.
- WHOI OBS Schematic



WHOI SEGY Files

- *****Check Format Post-Processing*****
- WHOI SEGY files contain all four channels in one file. For each OBS there is one SEGY files. The naming of the SEGY file and the numbering of the data channels is as follows (where ### is the OBS number):
  - 1E_OS###_ELZ_EL1_EL2_EDH.segy (E1 is the IRIS DMC network code)
  - Channel 1 = vertical
  - Channels 2 & 3 = horizontals
  - Channel 4 = hydrophone
  - ***This is different from the numbering system used in the SIO SEGY headers**

Hardware-specific FIR Filters

OBS Performance Summary

- OBS 180 was noisey due to shallow water depth at deployment site.
- OBS 172 had a flooded can and the vertical did not record good data. The hydrophone did.

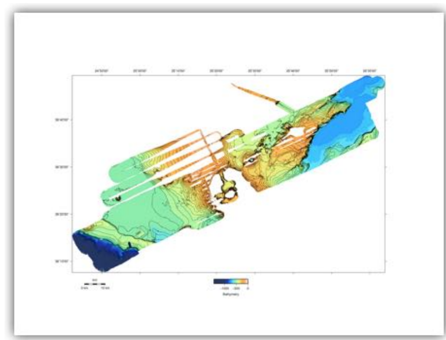
A7: EM122 Multibeam Collecting & Processing

- **A. Figures**
- **B. Data Collection**
  - The bathymetric data was collected using R/V Marcus Langseth's Simrad EM122 12kHz multibeam echo sounder. The vessel entered the survey boundary at 11/20/2015 04:34:34.394 JD 324, 36°.7947N 25°3953E, where the data acquisition commenced.

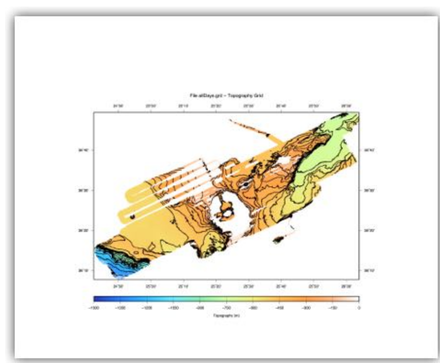
    During the deployment and the recovery of the OBSs the EM 122 was disabled at each site to avoid interference with the acoustic release and ranging of the OBSs. Moreover, after the deployment of W140 and S160 OBSs additional survey lines were conducted on south west side of caldera to determine the appropriate path to enter in order to avoid shallow water area and ensure that the string of guns towed at 12m below the sea surface did not hit the sea bottom.

    The EM 122 has a maximum swath width up to 6 times the water depth depending on the sea state. During the first days of the survey, especially when shooting the outer lines (1-4) the data was of very good quality, the center and outermost beams didn't have significant scatter. The data was of poorest quality when heading into rough seas and the outermost beams had significantly more scatter than the inner ones. The ping mode was set to SHALLOW and the swath angle to 75° (depths < 450m) and then narrowed down to 68° (depths > 450m) to achieve highest possible resolution. During the cruise 28 XBT's were launched but only the first 19 imported in the SVP editor (except the 15th and 16th that were launched into the Kolumbo and the 17th that malfunctioned). Moreover, on 12/03/2015 at 1:48am the EM 122 crashed for one minute, worthwhile taking into account while processing. After the recovery of the OBSs and multiple attempts to recover OBS 116, additional survey lines were conducted at the southern part of Santorini.

    Data was acquired by the EM 122 system into half hour Simrad ".all" files with the filenames ####_YYYYMMDD_HHMMSS_Langseth, where "####" is a sequential file starting with "0000" and ending with "0968".The files were processed with MB-SYSTEM.
- allDays_preprocessed-reduced.jpg



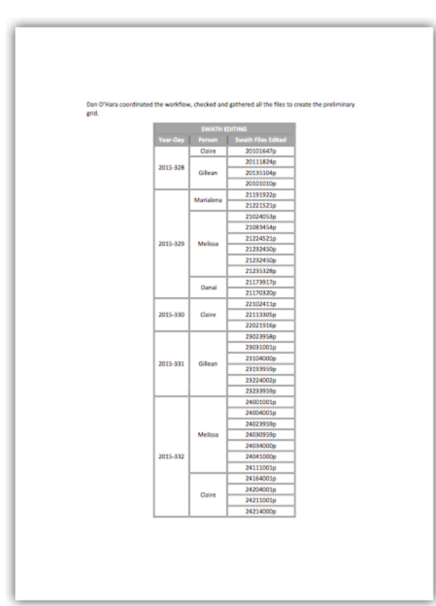
- allDays_manualProcessed.grd



- **A. Processing Performed at Sea**
  - Processing of the raw multibeam data was performed using the open source software package MB-System (http://www.ldeo.columbia.edu/res/pi/MB-System/). Gilles Guerin (Marine Tech.—ACQ) provided the well-commented document 'multibeam_processing' (under **D. Routines**) that provides descriptions and examples of the MB-System commands used to covert raw files, clean the data, and generate .grd files for GMT.

    The first step in processing was the definition of a vessel configuration file "langseth.hvf". Because the EM122 system includes corrections for the relative positions of sensors on the boat, the Heave, Pitch, Roll, Gyro and Navigation sensors were assigned coordinates in meters [X(positive to Forward), Y(positive to Standboard), Z(positive Downward)] of [0,0,0] and in degrees [Roll, Pitch , Heading]. The correct values for the Transducer were set to [20.925, 0.570, 8.459] and [0.1603, -0.0772, 359.99]. The correct values for the Receiving transceiver were set to [16.068, 0.050, 8.535] and [0.1603,-0.0772, 0.00] and the Waterline was set to Z=+1.94.

    The MB-SYSTEM processing steps applied during the cruise comprised:
- **B. Generation of a Preliminary ".grd" Grid and GMT Maps**
- **C. MB-System Processing not Performed at Sea**
- **D. Outstanding Questions/Tasks**
- **E. Routines**
- Appendix A6-V3
- EdittingTasksTable.pdf



Dan O'Hara coordinated the workflow, checked and gathered all the files to create the preliminary grid.

SWATH EDITING		
Year-Day	Person	Swath Files Edited
2015-328	Claire	20101647p
	Gillean	20111824p
		20135104p
		20101010p
2015-329	Marialena	21191922p
		21221521p
	Melissa	21024053p
		21083454p
		21224521p
		21232450p
		21232450p
		21235328p
	Danai	21173917p
		21170320p
2015-330	Claire	22102411p
		22113305p
		22021916p
2015-331	Gillean	23023958p
		23031001p
		23104000p
		23193959p
		23224002p
		23233959p
2015-332	Melissa	24001001p
		24004001p
		24023959p
		24030959p
		24034000p
		24041000p
		24111001p
	Claire	24164001p
		24204001p
		24211001p
		24214000p

A8: Knudsen 3.5 kHz Processing

- KNUDSEN PROCESSING.docx

This Appendix contains the following sections:
- **1.** Where to find things
- **2.** Issues with the Knudsen data
- **3.** Initial processing of the Knudsen data
- **4.** Useful pieces of code

1. Where to find things:
- Knudsen raw files are found in MGL1521/raw/knudsen/.
- Processed files are in MGL1521/processed/knudsen
- The processing flow and fortran files described below are in MGL1521/public/knudsen_processing
- The Windows software by Knudsen for processing and converting the files is locations in MGL1521/public/knudsen_processing/Knudsen_software

2. The were several issues with the Knudsen data:
- **1.** the time headers are not stored at a constant offset, but vary depending on the seafloor topography.
- **2.** Shallow sea also means the Knudsen subbottom profiler pings at a higher frequency.
- **3.** All Knudsen files were logged one day ahead of the actual date (the computer date-time was ahead one day), this holds for both the month-day and yearday format.

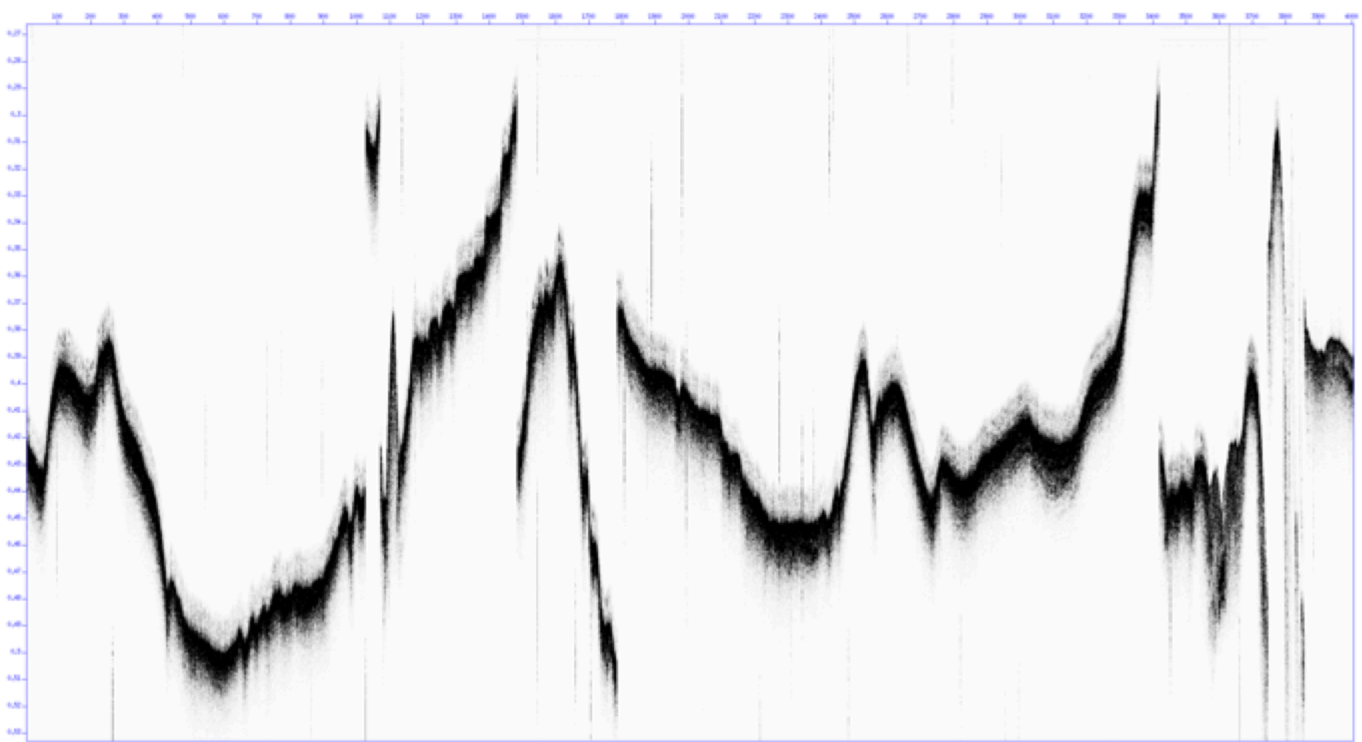


Figure 1: segy image of Knudsen 3.5kHz data for 1 half-day data file

In an attempt to work around this problem, we have processed the data using a Fortran code rather than in traditional seismic processing software.

3. Initial processing of the Knudsen data was carried out using the following steps:

4. Useful pieces of code:

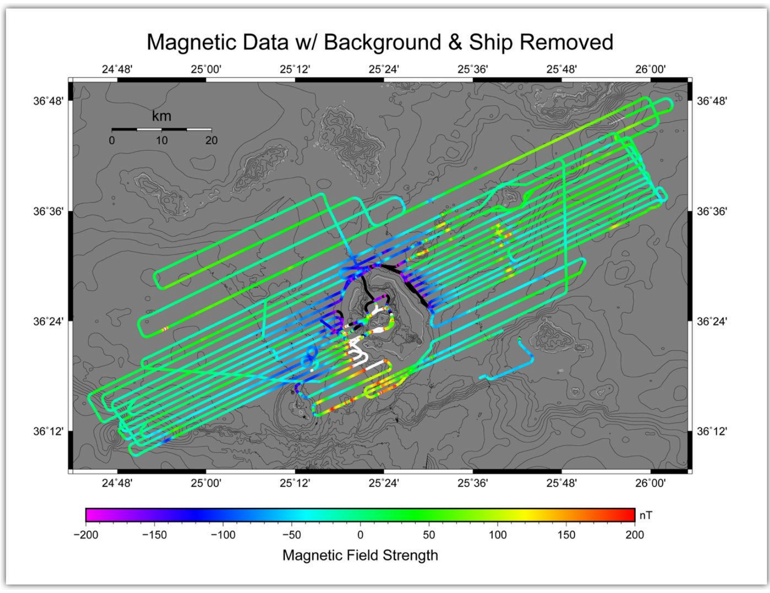
A9: Magnetics Processing

MAGNETICS

This appendix contains the following sections:

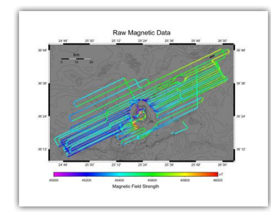
- **1.** Plots
- **2.** Instrument detail
- **3.** Processing Methodology
  - Collection
  - Merging
  - Filtering and quality control
  - Background magnetic field removal
  - Ship magnetic field removal
  - Final data and output
- **4.** Useful codes

1. Plots

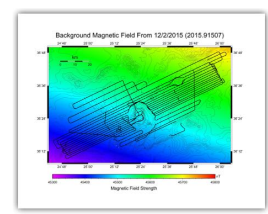


Magnetic_corrected.jpg

- Magnetic_raw.jpg



- Magnetic_background.jpg



2. Instrument Detail:

3. Processing Methodology:

Data processing was completed using a series of Matlab functions and script files (see schematic, fig. 1). All processing was completed through the header function UpdateAll (Attachment 1). Each step of processing is outlined below.

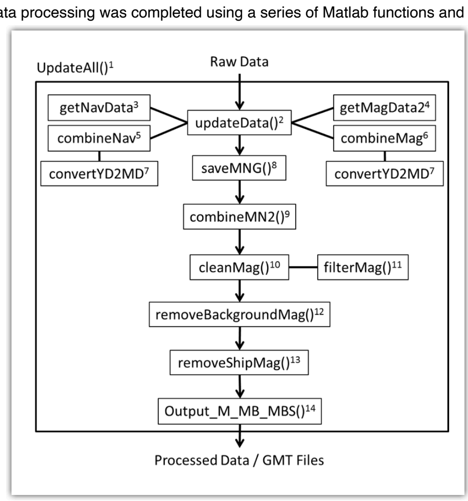


Figure 1. Schematic of Matlab files used during magnetic data processing steps.

- **Collection**: Raw magnetic (date, time, field strength) and CNav navigation (date, time, latitude, longitude, heading) data was collected from each separate day of the cruise (Attachments 2, 3, 4). Afterwards, data from the separate days were formatted and combined to a single magnetic and navigation table (Attachments 5, 6, 7 8). Main formatting at this stage involved converting the date and time format of the raw data (Year, Yearday, Hour, Minute, Second) to a serial date format.
- **Merging**: Raw magnetic data was merged with the CNav navigation data using the serial date data field (Attachment 9). Since the magnetic and navigation data were collected at separate frequencies (0.1 and 1 Hz, respectively), data was matched to the closest second.
- **Filtering and Quality Control**: Data was automatically checked for missing or erroneous values which fell outside 0.4 standard deviation away from the mean (Attachment 10). Afterwards, high-frequency features were filtered out of the data using a 10m moving- window average (Attachment 11).
- **Background Magnetic Field Removal**: We estimated the background magnetic field during the cruise using the International Geomagnetic Reference Field 2012 (IGRF 2012) model and a predictive model of the secular variation for adjusted dates between 2015 and 2020. We created a 10m grid of background magnetic variation using the midway cruise date (12/2/15, 2015.91507) and subtracted it from the raw data (Attachment 12). Values in the grid ranged [45310, 45734] nT (fig. 2). Across the cruise dates (11/22/15 – 12/15/15), the magnetic field at the grid boundaries (latitude: [24.7353, 26. 0488], longitude: [24.7353, 26.7353]) varied <3 nT.
- **Ship Magnetic Field Removal**: Using the method of Buchanan et al. (1996), we further corrected the data by removing the ship's magnetic field (Attachment 13). The magnetic field of the ship (f_s) at a given heading (in azimuth) is given by the equation:

  $$f_s = a_1 + a_2 \cos(h+\theta) + a_3 \cos(2(h+\theta)) \quad (1)$$

  Where h is the ship heading, θ is the angle of the magnetometer relative to the ship, and a_1, a_2, and a_3 are constant coefficients. From the raw magnetic field with the background signal removed, we collected the mean and standard deviation of field values over 2 degrees of heading from measurements located away from the Santorini caldera to remove bias from extreme maxima and minima (fig. 3, black dots). Using the mean and standard deviation values (fig. 3, white diamonds, purple lines, respectively), we used a least squares approach to calculate the coefficients a_1, a_2, and a_3. Afterwards, we fit different values of θ to the equation to find the value that best shifted the curve to match the data. The least squares method found coefficient values of -55.9669, -116.7476, and 42.7715, respectively, after three iterations with a relative residual of 6.3 x10-15. Furthermore, we found a θ value of -8° best matches the observed data (fig. 3, green line). Thus, our corrections for ship magnetic field are defined by the equation:

  $$f_s = -55.9669 - 116.7476 \cos(h-8) + 42.7715 \cos(2(h-8)) \quad (2)$$

  For each data measurement, the ship's magnetic field was calculated from the measurements heading and was subsequently removed.

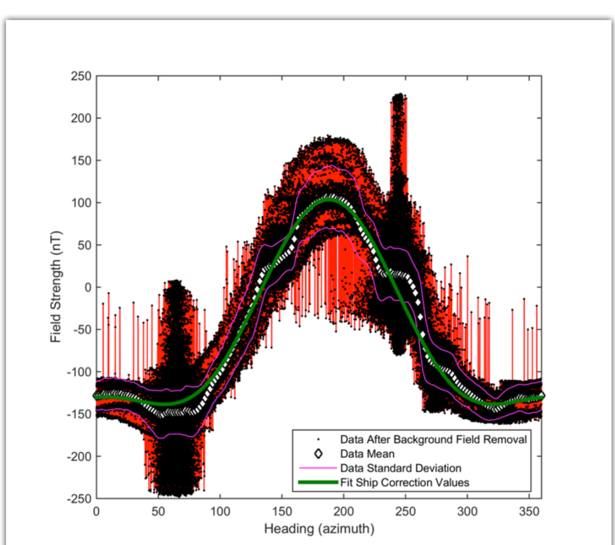


Figure 2. Ship magnetic field correction. Black dots with red lines are raw data with background field removed. White diamonds are mean field strength taken at 2° intervals with standard deviation above and below the mean given by purple lines. Green line is the fit to the data using equation (2).

- **Final data and output**: The final data contains the navigation position and the corrected total field readings after background and ship magnetic field correction in one second intervals matched to the navigation GPS timestamp at the nearest second. The latitude, longitude, and total field strength is then output to data files to use in map generation (Attachement 14).

4. Useful codes:

A10: Gravity Processing

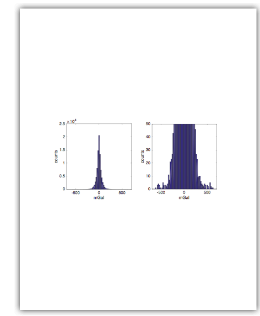
- The gravity field was recorded using a Bell Aerospace BGM-3 marine gravimeter. Gravity data was collected throughout the duration of the experiment with measurements taken every 1-second. Gravity measurements were displayed in real-time on a monitor in the main lab. The gravimeter appeared to be functioning properly and producing good quality data. Only the raw data is available upon completion of the cruise. All data processing is performed by LDEO science support staff following the cruise.
- The raw data can be found in: MGL1521/raw/serial/. All the file names are formated as follows: MGL-vc01.yxxxxdzzz where xxxx is the year and zzz is the Julian day on which the samples were collected.

Instrument Detail

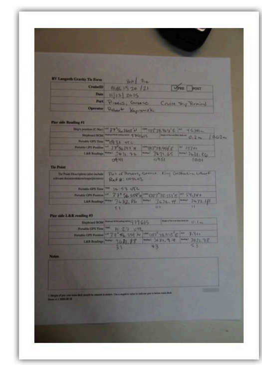
- Bell Aerospace BGM-3 Marine Gravity Meter
- Data is output at 1-second intervals and logged on a LDEO logger system
- The raw gravity measurements are stored as counts. Counts are linearly mapped to mGals using routines kept by LDEO.
- The raw data for each day is stored in a text file. These files have the following format:
  - *vc01   year:Julian_day:hour:min:sec (to 4 decimal place)   XX:counts   YY*
  - The leading "vc01" identifies the document as gravity readings; "XX" is the output frequency (Hz); The "counts" value is the raw gravity reading (unitless); and "YY" is the sensor status (unitless).
- The location of the gravimeter relative to the navigation reference point (NRP) of the *R/V M. G. Langseth* is detailed in the attached document, "MGLSensorConfiguration".
  - MGLSensorConfiguration

Quality Control

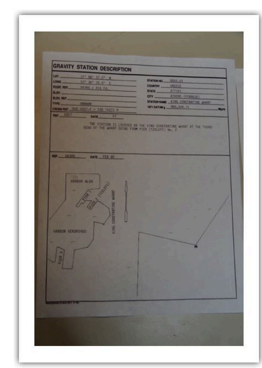
- Calibration: We could not obtain information on the gravitmeter calibration.
- Dropped Scans: All data logged is checked for droped scans using "checktimes_rev", a LDEO program that checks the time difference between each sample.
- Spot-checks: Occasionally, the raw gravity counts for a given day were converted to mGals and plotted as a histogram as a first-order check of the data quality (verifying a reasonable range of gravity values is recorded). The attached pdf shows the raw gravity measurements for Julian day 320 of the cruise. A reasonable range of values is recorded with some outliers.
  - RawGravHist_y2015d320.pd



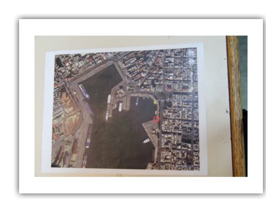
- Gravity Ties: A gravity tie was performed at the cruise ship terminal in Piraeus, Greece on 2015/11/13 at an absolute gravity tie point prior to departure using a LaCoste Romberg G portable gravimeter by LDEO science personnel, Robert Koprowski. A second gravity tie was performed at the conclusion of the experiment in Heraklion on 2015/21/15 (performed in same manner as the first). The gravity tie form and documents describing the station locations are attched below.
  - Start of Missions Docs
    - MGL1521_Start_Mission_Gravity_Tie_Form.jpg



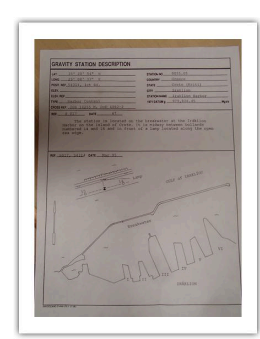
    - MGL1521_Start_Mission_Gravity_Tie_StationDescription.jpg



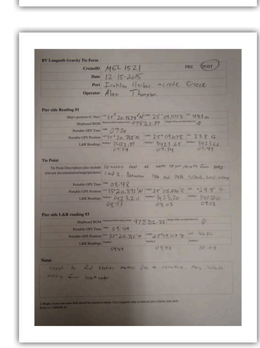
    - MGL1521_Start_Mission_Gravity_Tie_Map.jpg



  - End of Mission Docs
    - MGL1521_End_Mission_Gravity_Tie_PG1.JPG



    - MGL1521_End_Mission_Gravity_Tie_PG2.JPG



    - PC151618.JPG

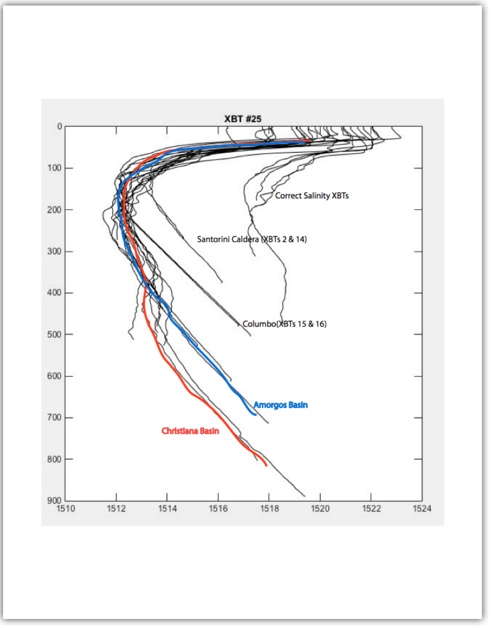
- Drift: Based on the first gravity tie (**date**), the initial DC shift calculated on **YYYY/MM/DD** is **XX** mGals. Based on the second gravity tie (**date**), the final DC shift calculated on **YYYY/MM/DD** is **YY** mGal. From the inital and final DC shifts, the estimated drift of the gravimeter is **ZZ** mGals/day. **Potsdam correction was removed from the absolute gravity tie point as the BGM-3 outputs uncorrected gravity values.**

Processing Methodology

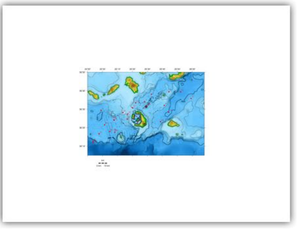
- NOTE! All processing and data reduction is performed by LDEO science support staff following the completion of the cruise. None of the processing routines are available aboard the Langseth. At the time of the cruise completion, only the raw data (see **Instrument Detail** for raw data format) is available.
- The raw 1-second gravity counts are filtered with a 360-second Gaussian filter. Counts are converted to mGal via a linear relationship. The gravity data is merged with the navigation attributes (latitude, longitude, course, and veocity) via the GPS time stamp. Eotvos correction is then applied to the dataset. Data plots are generated and visually checked to determine satisfactory Eotvos corrections. Data spikes caused by turns and other anomalies are deleted from the dataset. The Free-air anomaly (FAA) is then calculated using the 1987 International Gravity Formula (IGF). The final dataset is decimated to one-minute samples.
- EOTVOS Correction: Corrects for artificial gravity effects due to changes in the ship's coarse and speed. The correction is given by:
  - $EOTVOS = [7.5038 * V_E * \cos(phi)] + [0.004154 * V_T]$
  - Where V_T is the ship speed in knots, V_E is the eastward component of the ship's velocity, and phi is latitude in degrees. These velocities are derived from a smoothed GPS navigation using LDEO developed scripts.
- Free-air Anomaly: The FAA reduces the gravity measurements by removing the gravitational effects of the reference ellipsoid. This will be done using an LDEO program. The 1987 IGF is:
  - $g(phi) = 978032.68 * [1 + 0.00193185138639 * \sin^2(phi)]/\mathrm{sqrt}[1 - 0.00669437999013 * \sin^2(phi)]$
  - Where g is absolute gravity and phi is latitude.
  - Historical Note: Earlier cruises have used the 1980, 1967, and 1930 gravity formula in calculating the FAA. Since these all differ by a constant, it is necessary to check the formula used in a particular survey prioir to merging data across multiple experiments.

A11: XBT Profiles

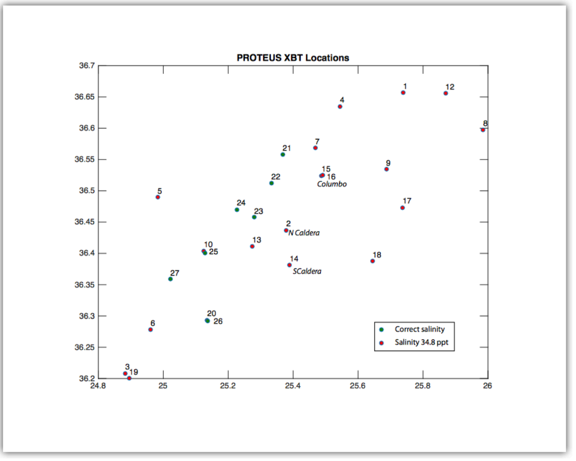
- During the PROTEUS project, the water's temperature versus depth was measured using XBT's (T-7 & T-5), Expendable Bathythermographs. XBT's were dropped at various points in the survey area every single day. Using this information, the sound velocity and temperature was found for the water column.
- **Water velocity and Sounding Velocity**: Figure 1 showing the XBT data collected during the PROTEUS project. The recorded file during the launch is edited and then imported to MultiBeam System. The blue lines show the sound velocity for each XBT launch. The black shows the average sound velocity for Christiana basin while the cyan shows the average sound velocity for Amorgos basin. The green line shows the average sound velocity for salinity value 34.8 ppt (first measurements were conducted with this value) and the magenta line shows the average for salinity value 38.8 (corrected after 20th XBT). Yellow line shows the sounding velocity for 34.8 ppt and the red one shows the sounding velocity for 38.8 ppt. Mean OBSs depth is between 400 m and 600 m. Sounding velocity does not vary over this depth range. Travel time difference between the two different velocities is dt = 0.5/1.514 - 0.5/1.5186 = 1 msec.
  - AllXBTs.pdf



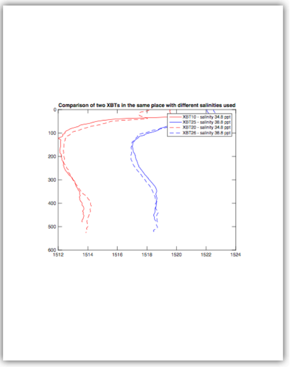
  - xbt_loc.jpg



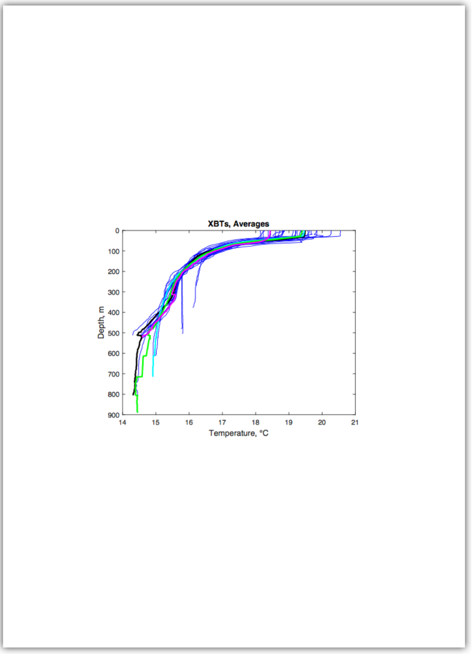
  - XBTLocations-annotated.pdf



  - XBT-salinityComparison.pdf



- **Temperature distribution**: Figure 2 showing the temperature measurements collected from XBTs launches. The blue lines show the temperature distribution for each XBT. The black shows the average temperature for Christiana basin while the cyan shows the average for Amorgos basin. The green line shows the average temperature for salinity value 34.8 ppt and the purple line shows the average temperature for 38.8 ppt.
  - Figure 2.pdf



- **Procedure for collecting XBTs**: The MK-21/ISA Bathythermograph Data Acquisition System, employed during this study, is a portable data acquisition system that measures and outputs ocean temperature, conductivity and sound velocity versus depth using expendable probes that are launched from surface ships. The Sippican expendable probe is a small oceanographic sensor, which measures the water temperature. The probes free-fall in the ocean at a known rate while collecting the data.
- **To launch a probe from a vessel**, the canister containing the probe is first inserted into a Sippican Hand-Held Launcher. Contacts on the canister provide the electrical connections to the launcher which is connected by cable to the MK21 interface board. When the probe is ready to be launched, the operator pulls a release pin out of the canister, and the probe slides out of the canister into the water. The probe's hydrodynamic shape allows it to descend through the water at a stable and known rate, enabling continuous calculation of its depth throughout the entire descent. As the probe descends, its sensors continuously measure the water temperature. The measurements are transmitted by a wire back to the MK21 interface board. The wire de-reels both from a spool in the probe as the probe descends and from a spool in the canister as the vessel from which the probe was launched moves along the surface. This dual spooling technique enables the wire to remain stationary in the water. Soon after the probe reaches its maximum depth, its wire breaks and the probe continues its descent to the ocean floor.

- XBT'S.xlsx
- vel_profile.m

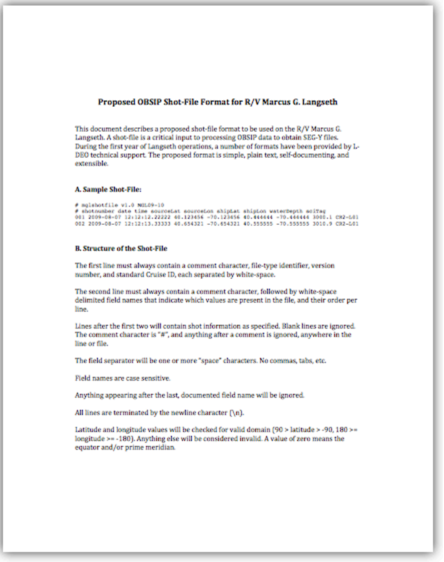
A13: Reading OBSIP log Files and SEGY Files

Included in this appendix are the following:

- **1.** Description of the shot log files and MATLAB function to read this format.
- **2.** Description of the SEGY file naming, channel labeling conventions, and SEGY documentation
- **3.** MATLAB files to read the SEGY files into tlPicker

1. Shot Log Files

- For each line the seismic survey is a shot log. The log files are named according to the convention: MGL1521OBS##.obsip or MGL1521T##.obsip, where ## is the seismic line number. In the former case, the line number goes from 01 to 43, whereas the latter goes from 01 to 10. This naming convention is described in Appendix A2: MGL1521 Seismic Survey Summary.
- WHOI provided the following description of the OBSIP shot logs for the ETOMO experiment. This description is also applicable to the shot logs generated during the PROTEUS experiment.
- OBSIPshotFile



Proposed OBSIP Shot-File Format for R/V Marcus G. Langseth

This document describes a proposed shot-file format to be used on the R/V Marcus G. Langseth. A shot-file is a critical input to processing OBSIP data to obtain SEG-Y files. During the first year of Langseth operations, a number of formats have been provided by L-DEO technical support. The proposed format is simple, plain text, self-documenting, and extensible.

A. Sample Shot-File:

```
# mglshotfile v1.0 MGL09-10
# shotnumber date time sourceLat sourceLon shipLat shipLon waterDepth sciTag
001 2009-08-07 12:12:12.22222 40.123456 -70.123456 40.444444 -70.444444 3000.1 CR2-L01
002 2009-08-07 12:12:13.33333 40.654321 -70.654321 40.555555 -70.555555 3010.9 CR2-L01
```

B. Structure of the Shot-File

The first line must always contain a comment character, file-type identifier, version number, and standard Cruise ID, each separated by white-space.

The second line must always contain a comment character, followed by white-space delimited field names that indicate which values are present in the file, and their order per line.

Lines after the first two will contain shot information as specified. Blank lines are ignored. The comment character is "#", and anything after a comment is ignored, anywhere in the line or file.

The field separator will be one or more "space" characters. No commas, tabs, etc.

Field names are case sensitive.

Anything appearing after the last, documented field name will be ignored.

All lines are terminated by the newline character (\n).

Latitude and longitude values will be checked for valid domain (90 > latitude > -90, 180 >= longitude >= -180). Anything else will be considered invalid. A value of zero means the equator and/or prime meridian.

MATLAB function to read OBSIP shot logs, entitled read_obsip_shotlog_proteus.m

- read_obsip_shotlog_proteus.m

Script to run read_obsip_shotlog.m and save the LAT-LON coordinates of each shot as an .xyz file for use with GMT; the script is entitled shotlog2GMT.m.

- shotlog2GMT.m

2. SEGY Files

SEGY file naming convention

SIO SEGY files contain one channel per file. For each OBS there are four separate SEGY files. The naming of the SEGY files and numbering of the data channels is as follows (where ### is the OBS Number):

- OS###_MGL1521_L28X.segy; Channels 0 & 1 = horizontals
- OS###_MGL1521_L28Y.segy; Channels 0 & 1 = horizontals
- OS###_MGL1521_L28Z.segy; Channel 2 = vertical
- OS###_MGL1521_HYD.segy; Channel 3 = hydrophone

WHOI SEGY files contain all four channels in one file. For each OBS there is one SEGY file. The naming of the SEGY file and the numbering of the data channels is as follows:

1E_OS###_ELZ_EL1_EL2_EDH.segy (1E is the IRIS DMC ID assigned to the experiment and ### is the OBS number).

- Channel 1 = vertical
- Channels 2 & 3 = horizontals
- Channel 4 = hydrophone
- • *This is different from the numbering system used in the SIO SEGY headers*

Documentation on the SEGY format

3. MATLAB functions to read the binary SEGY files into tlPicker:

read_segy.m will load one of four channels of the SEGY (and the shot range specified) data where:

- Channel 1 = vertical
- Channels 2 & 3 = horizontals
- Channel 4 = hydrophone

read_segy.m file to read SEGYs

- read_segy.m

Creating a SEGY catalog for tlPicker

- Santorini_create_segyCatalog.m
- catalogSegy_santorini.m

A default menu for tlPicker menu window

- default_menu_Santorini.m