Using Controlled Source Electromagnetic Methods for Detecting Submerged Archaeological Resources

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FINAL REPORT
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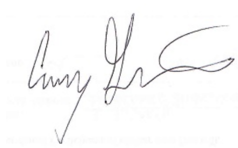

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1. Executive Summary

Sea-level rise following the last glacial maximum (~20 kya) has resulted in the submergence of paleochannels, tar seeps, and archaeological sites on continental shelves. The distribution of these sites is important for archaeological research, offshore infrastructure development, and environmental hazard assessment. Identification of these sites is typically attempted using a combination of side scan and subbottom sonar remote sensing methods, followed by evaluation of hundreds of resulting images to select targets for sampling. Our recent research suggests that the process of narrowing down targets for sampling may be facilitated by incorporating controlled source electromagnetic (CSEM) equipment into the remote sensing surveys. CSEM measures the apparent resistivity of the submerged units (i.e., porosity).

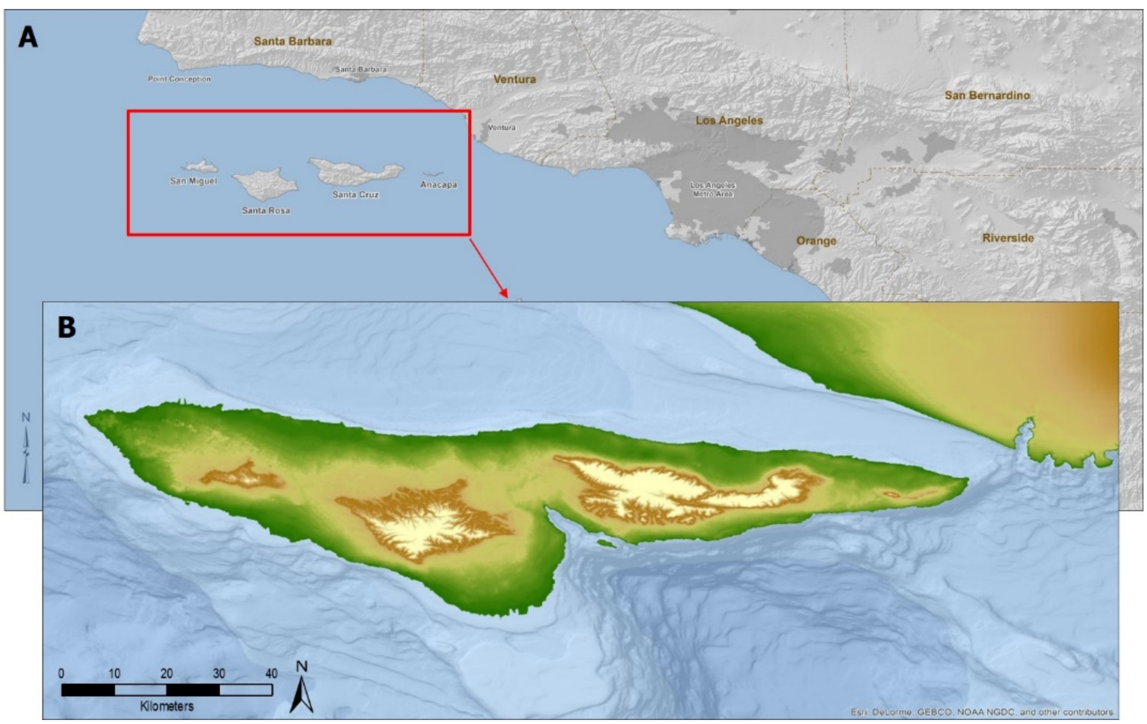
Using MARE2DEM software, we developed a model to test CSEM effectiveness for identifying shell midden deposits, tar seeps, and paleochannels. Results indicated that a modified bottom-towed CSEM system should be able to resolve all three targets. We, therefore, designed and built CUESI, a Compact Undersea Electromagnetic Source Instrument. Initially beginning with Porpoise, a surface-towed CSEM system developed by the Electromagnetic Laboratory at Scripps Institution of Oceanography, we created a modified CSEM system to be deep-towed with frequencies that can detect specific targets of interest for identifying submerged maritime cultural landscapes within the Southern California Bight.

Testing the CUESI system included basic functionality tests (23 & 25 September 2020) as well as field tests (24-25 May 2021). The testing program was designed as a proof of concept using areas of known targets of interest. Previous subbottom data collected offshore from the Northern Channel Islands during a Bureau of Ocean Energy Management project focused on identifying features on the landscapes for core testing. The resulting core data show areas on the submerged landscapes where deposits containing shell and rock are located beneath marine sediment. These core locations were surveyed using the CUESI to test the sensitivity of the system toward characterizing changes in seafloor porosity.

Initial tests of the system acted as guides to better understand CUESI functionality and, importantly, modifications to the system needed for successful use in the field. The initial results of the data collected in May 2021 show that the CUESI system is sensitive to hydrocarbons. However, data collected on 24 May 2021 were found to be chaotic. The lack of a depth sensor on CUESI created uncertainties in correspondence with navigation data. After modifications to the system, CUESI was used to collected data on a subsequent project and these data appear, at least in initial processing, to be effective at identifying a known lag deposit, to model porosity of a core sample with a shell deposit, and identify a known tar seep. These results suggest that CUSEI may be an effective system for consideration in surveys focused on identifying features across paleolandscapes and may narrow target selection for subsequent sampling.

2. Introduction

Sea-level rise following the Last Glacial Maximum (LGM) (~20 kya) submerged millions of square kilometers of coastal landscapes around the world, complicating efforts to understand the paleolandscapes, paleoecology, human dispersals, and the cultural histories of these now drowned regions (Clark et al. 2014). One of these regions surrounding the Northern Channel Islands (NCI) boasts one of the highest densities of terminal Pleistocene (15,000-11,500 yrs BP) and early Holocene (11,500-8,000 yrs BP) archaeological sites in the New World (Figure 1) (Erlandson 1994; Erlandson et al. 2001; Gusick and Erlandson 2019; Rick et al. 2005). Evidence from these terrestrial sites indicates: 1) that the earliest occupants of the NCI were seafaring maritime hunter-gatherers; and 2) that additional Paleocoastal archaeological sites (~15,000-8,000 cal BP) are likely located on the submerged landscapes of the NCI. The search for submerged sites has extended onto the regional continental shelf, but Paleocoastal sites have not yet been identified on this submerged landscape (Gusick et al. 2021). Recent research, however, suggests that with the right technologies features such as paleochannels, shell deposits and offshore tar seeps – all features used and/or created by indigenous communities during the terminal Pleistocene and Holocene along the Pacific Coast – can be identified and used to model paleolandscape and paleoecology on archaeologically sensitive submerged landscapes (Gusick et al. 2019).



The identification of these landscapes is important for archaeological research, offshore infrastructure development, and environmental hazard assessment. Identification of culturally important features or culture sites on submerged landscapes is typically attempted using a combination of side scan and subbottom sonar remote sensing methods, followed by evaluation of hundreds of resulting images to select targets for sampling. Yet, the process of narrowing down targets for sampling may be facilitated by incorporating controlled source electromagnetic (CSEM) equipment into the remote sensing surveys. CSEM measures the apparent resistivity of the submerged units (i.e., porosity), a different variable than that detected by sonar methods. While typically used to identify hydrocarbon in offshore geology, initial modelling of a CSEM system modified to be deep-towed and to detect shallow, varying porosities was promising and the project team worked with the Marine Electromagnetic (EM) Laboratory at Scripps Institution of Oceanography (SIO) to build a modified CSEM system. This equipment was then tested for functionality by surveying over known locations with shell and rock deposits buried beneath sediment on the continental shelf of the California mainland and the NCI.

3. Design Methods and Materials

Initially beginning with Porpoise, a surface-towed CSEM system developed by the Marine EM Laboratory in the Institute of Geophysics and Planetary Physics, University of California, San Diego (Sherman et al. 2017), we modelled and then built CUESI, a Compact Undersea Electromagnetic Source Instrument. CUSEI is a CSEM system modified to be deep-towed with frequencies that can detect specific targets of interest for identifying submerged maritime cultural landscapes within the Southern California Bight (SCB).

A. Initial Modeling

Using MARE2DEM software (Key 2012; Key and Ovall 2011) we developed a model to test CSEM effectiveness for identifying shell midden deposits, tar seeps, and paleochannels, three targets of interest in on the paleolandscapes of the SCB. Characteristic porosities of these targets and the surrounding geologic units of modern medium to course sands and underlying shale were used in the model. These data were related to resistivity values using Archie's law (Archie 1942) and then used to develop an initial model to determine if our targets could be detected with CSEM. This methodology should also allow shell middens to be distinguishable from other anomalous targets identified by sonar systems (i.e., buried rock outcrops, corals, etc.).

The model assumed three targets: 1) a 10,000 year old paleochannel that is 200 meters (m) wide, 8 m deep and is overlain with 2 m of Holocene sediments; 2) a shell midden of 10 m in diameter and 1 m in height located on the paleosurface overlain with Holocene sediments; and 3) a tar seep mound that rises 1 m above the sea floor and is 30 m in diameter. Results indicated that the Porpoise surface-towed CSEM system can resolve the tar seep and the paleochannel, but not the shell midden. We reran the model assuming a CSEM system modified to be bottom-towed that emits an electric ternary waveform of frequencies at 3Hz, 9Hz, 15Hz, 21Hz, and 39Hz, and receivers spaced at 5 m, 10 m, 20 m, and 40 m. The model shows that this modified system is capable of resolving all three targets, including the shell midden (Figure 2). This new CSEM system is CUESI.

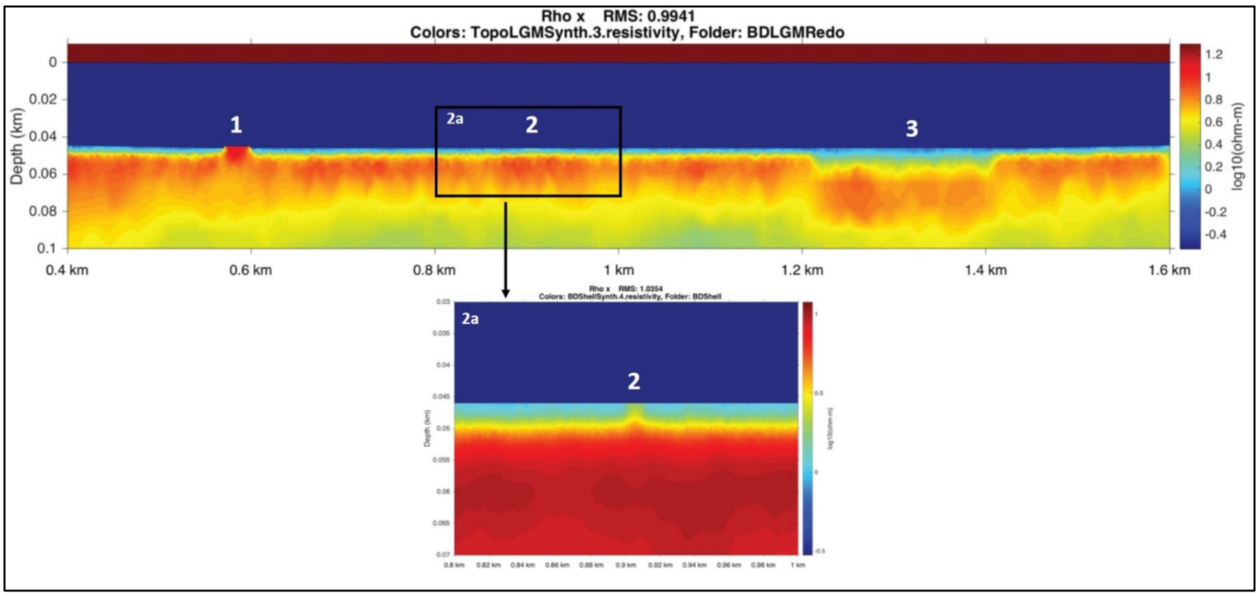


Figure 2. MARE2DEM model output showing resolution of three targets using a bottom towed CSEM system. Targets are, 1) Tarseep/mound; 2) Shell midden; 3) Paleochannel. Image 2a is magnification of target 2 results showing resolution of shell midden. Image modified from King et al. 2018.

B. CUESI Design

The CUESI was designed as a horizontal electric dipole electromagnetic transmitter for CSEM sounding within 5 m of the seafloor. The instrument uses external power to output a current up to 5 amps to a towfish 10 m behind the transmitter (noted as Transmitter Electrode Dipole in Figure 3). Here, 5 amps is transmitted into the seawater with two 10 cm long, 1.5 cm diameter soft copper tubing held 2 m horizontally apart on a rigid frame for a source dipole moment up to 10 Am. Behind the dipole are two three-axis electric field receivers (noted as 3-axis Vulcan receivers in Figure 3) spaced 10 and 25 meters from the dipole respectively. All three towfish are positively buoyant (0.57 to 0.63 lbs) so that when a wire touches the seafloor, the towfish become neutrally buoyant at an altitude between 90 to 100 cm. CUESI is designed to double as a drop weight in continuous towing operations so that wave energy is not transferred to the array allowing towing altitude to remain consistent.

All towfish are equipped with internal and external instruments to record navigational data. The towfish loggers record pressure, compass data, acceleration on 3-axis on 1 to 2 second intervals and an externally mounted compass allows for redundancy. The receiver towfish record the electric field in three directions on a 500 Hz logger and, in order to achieve consistent timing along the array, a timing pulse from CUESI. CUESI is equipped with a camera, lights, clock, altimeter, conductivity and temperature sensor, and a pressure gauge. The entire array sends packages of data to the surface systems on 2 to 10 second intervals to aid in navigation and survey troubleshooting.

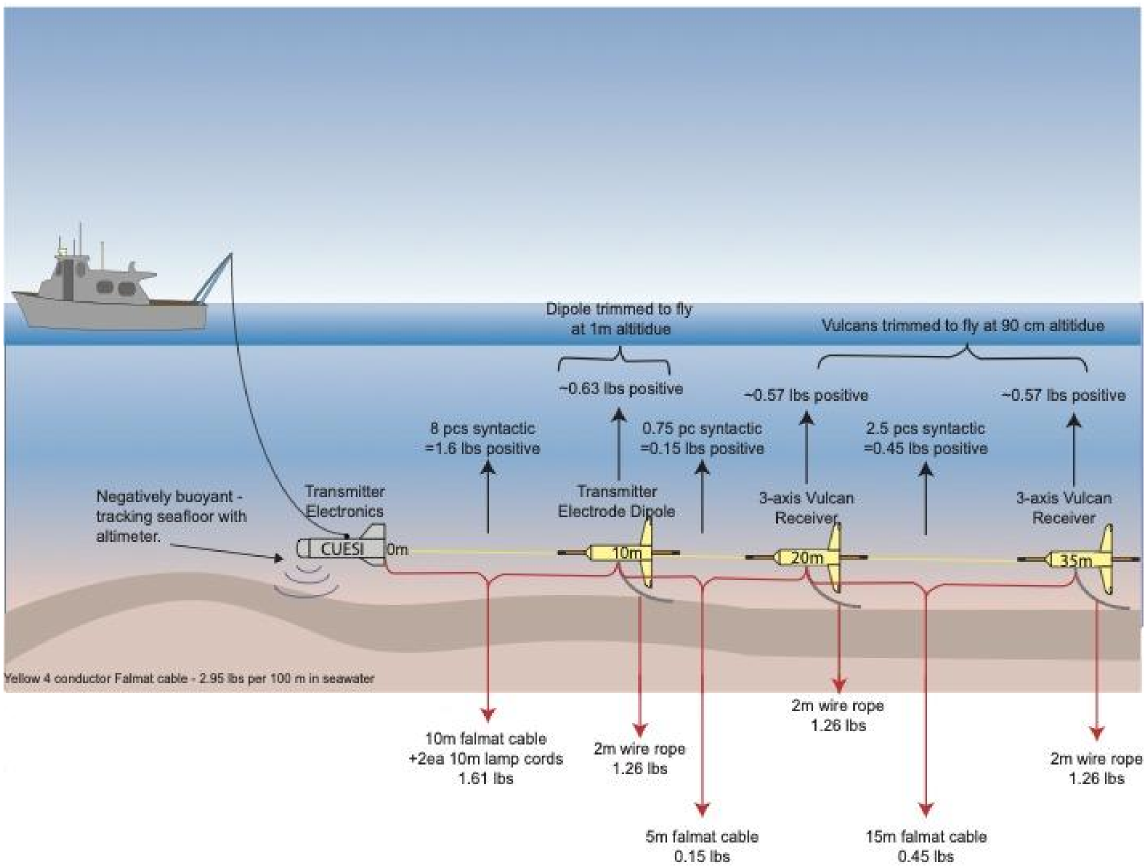


Figure 3. Schematic of CUESI array illustrating instrument spacing and buoyancy of the array.

C. CUESI Build

The CUESI system includes four pressure cases in tow frames housing the equipment: one transmitter and three receivers.

Transmitter Tow Frame:
Dimensions: ~18 inches x 36 inches, Weight: ~200 lbs max
Houses: transmitter, altimeter, and camera

Input: 120v AC power from tow-vessel
Output to receivers: 1-10 Amp current-controlled Waveform and timing pulse
Output to tow vessel: altimeter readings
Build: The electronics designed and built by the EM lab are housed in a MkII pressure case. Figure 4 shows the tow frame design. There is real time communication and commands to and from the transmitter.

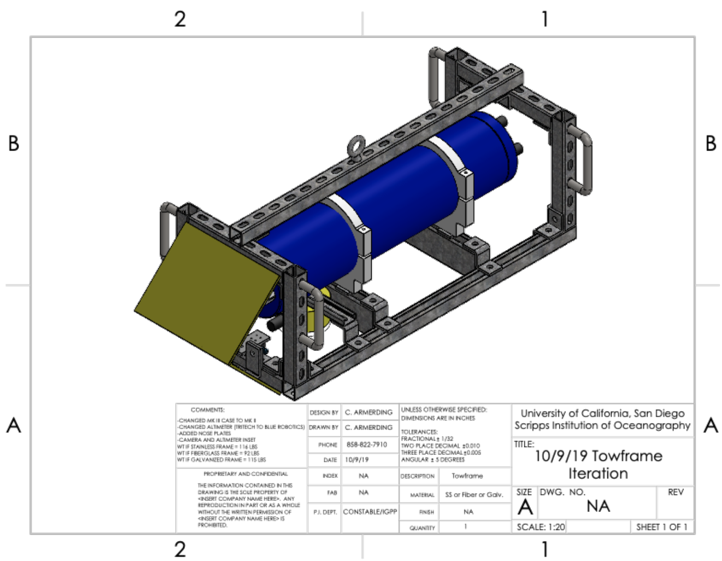


Figure 4. Transmitter tow frame schematic.

Receiver Tow Frames (3):
Dimensions: 10 inches x 48 inches, Weight: 70 lbs each
Build: First Receiver Tow Frame supports a 2-meter horizontal electric dipole with 10 cm long electrodes and a vertical 1-meter dipole. The horizontal electric dipole transmits the electric current generated from the transmitter housed in the MkII pressure case of the transmitter tow frame. The vertical 1-meter dipole records the vertical electric field to the logger housed within a receiver pressure case. Second and Third Receiver Tow Frames support a 2-meter horizontal stinger with two standard electrodes and a 1-meter vertical fin with two small electrodes at each tip (Figure 5). The dipoles record the inline and vertical components of the electric field respectively and record the responses within the data logger housed in receiver pressure case. Additionally, the receivers record the timing pulse generated from the transmitter on a serial data logger.

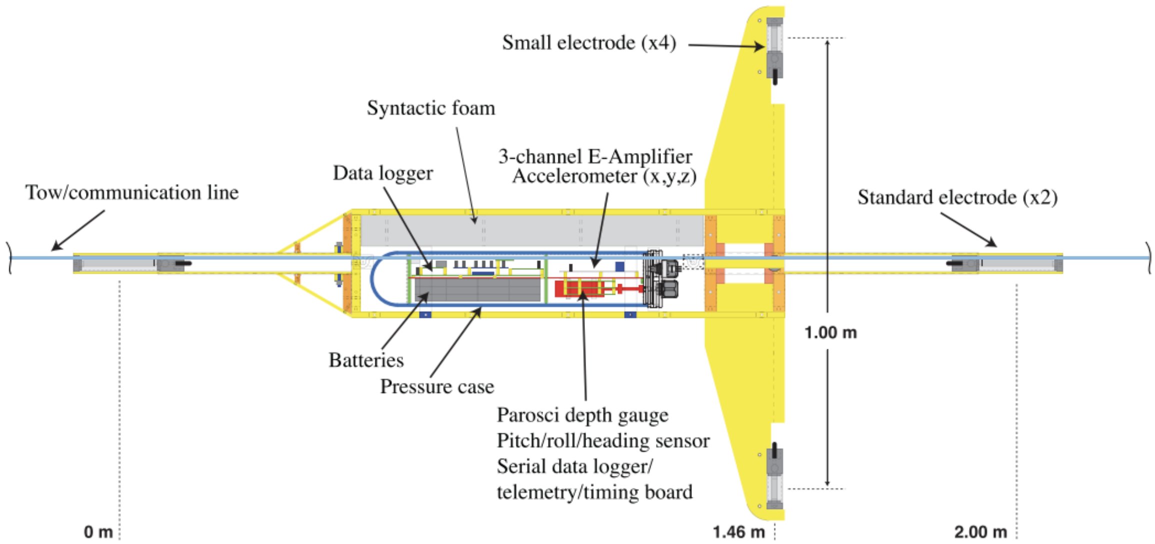


Figure 5. Cut-away schematic of the receiver tow package (Constable et al. 2016)

4. CUESI System Tests

Testing the CUESI system included basic functionality tests as well as field tests. The testing program was designed as a proof of concept using areas of known targets of interest. Previous subbottom data collected offshore from the NCI during a Bureau of Ocean Energy Management (BOEM) project focused on identifying features on the landscapes for core testing. These core data show areas on the submerged landscapes where deposits containing shell and rock are located beneath marine sediment. These core locations were surveyed using CUESI to test system sensitivity toward characterizing changes in seafloor porosity. This is critical to the CUESI success as targets of interests, especially shell middens sites, are predicted to have a higher pore volume than typical marine sediment and in theory could be identified with the CUESI system.

A. Study Areas

The CUESI study areas included the channel between Santa Cruz and Santa Rosa islands and in the area of the La Goleta tar seep off Isla Vista (Figure 6).

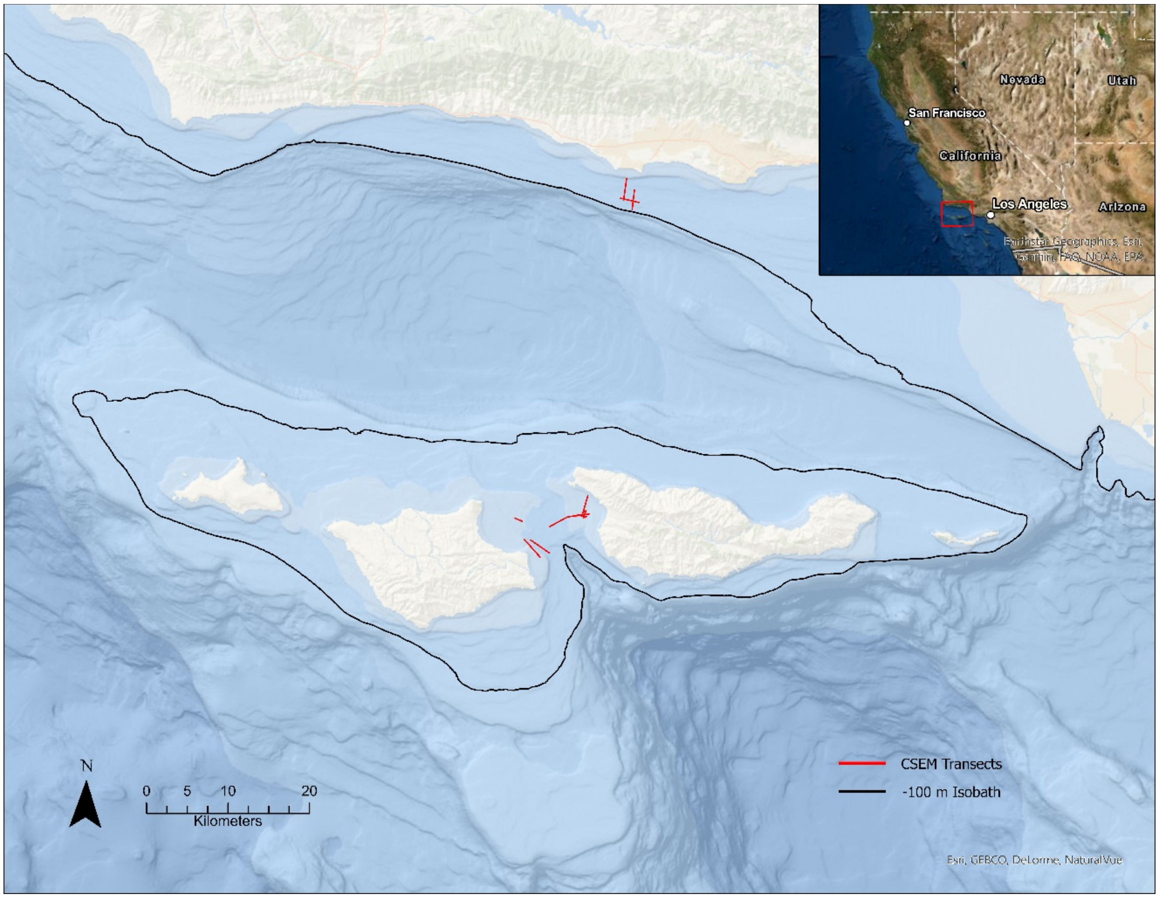


Figure 6. Regional project location showing areas surveyed during the current testing. Red lines indicate CUESI survey lines. Black lines indicate the -100 m isobath.

B. Deployment/Recovery Operations

As part of the testing, receiver preparation, deployment and retrieval operations for the CUESI were developed.

Receiver Preparation

At the start of every survey day, 25 cm silver-silver chloride electrodes must be fixed and cabled to the receiver loggers and rigid frames. External compasses for the receivers must also be set and fixed to the receiver frames. Receivers are then cabled together to create the intended array geometries on four conductor Falmat cables using detachable/reusable pins.

Deployment

1. CUESI pressure sensor must be plugged into an external pressure case that logs output and provides power to the pressure sensor. Pressure sensor will start recording immediately upon charge.
2. Set CUESI camera to intended sampling interval, plug into CUESI power, and secure camera in pressure case. Fasten the pressure case using hex bolts and

then attach the pressure case to CUESI facing downward at an angle between 10 to 30 degrees.

3. Start CUESI by plugging in ‘start box’ to the CUESI pressure case and then sync CUESI internal clock using the external GPS clock within the start box. Record time tag, time, and scrutinize direction and severity of time drift on GPS clock. If satisfied, unplug GPS clock and seal the CUESI pressure case with seal screws.

4. On the deck computer and on the CUESI winch, switch power to CUESI from internal batteries to external (boat) AC power. Review data stream on CUESI graphical user interface (GUI) from CUESI to ensure CUESI and all three towfish are sending data packages up the cable at the intended intervals.

5. Hand-deploy the third towfish in the array off the stern of the vessel. Depending on currents, the water speed for deployments should be between 0.5 to 2 knots for safe deployment. Use boat power to achieve these conditions.

6. Once the towfish pulls the Falmat cable out behind the vessel, hand deploy the second towfish in the array in a similar fashion to the third towfish taking care to not catch the wire rope on the deck. Allow array to straighten before hand-deploying the Transmitter Electrode Dipole towfish.

7. Allow the array to straighten behind the vessel before using an A-frame, two taglines, and the CUESI winch to deploy CUESI. When CUESI is at the water line, remove tag lines and drop CUESI 1 m below the water line. Check that altimeter readings are expected considering the water depth and start transmitting. Check that the voltage and amperage are within expected (programmed) ranges and that all instruments are still sending data packages up the cable.

8. Lower the array using the winch until the altimeter reads between 2 and 5 m (depending on sea-state). Tow the array at 2 knots (speed through water) adjusting CUESI height above seafloor using the winch controls.

Recovery

1. Stop CUESI transmission using the deck computer.

2. Notify the crew of intent to recover the array. Station two people at stern with hook and pole (for later taglines) to watch for the array and tend the winch line.

3. Use winch to haul in CUESI and towfish array, noting altimeter reading. Slow haul in when altimeter readings approach water depth. When CUESI is first sighted at the water line, stop the winch, and hook the CUESI frame with two taglines.

4. Recover using the taglines, A-frame, and winch and secure CUESI to the deck.

5. Hand pull in each towfish while tending Falmat cable and secure to deck.

6. Once all gear is secured on deck, remove CUESI seal screw, plug in start box, and record time tag.

7. Power down CUESI using the start box and then switch off power to the winch.
8. If no surveying is planned for the next twelve hours, remove silver-silver chloride electrodes from receivers and unplug CUESI pressure sensor from the external pressure case.

C. Functionality and Field Tests

The tests of the system included two functionality tests that occurred near to SIO, and two field tests.

23 September 2020 – Functionality Test

Initial tests of the system occurred on 23 September 2020 aboard the SIO R/V *Beyster* (Figure 7). This was the first test of the CUESI system aboard a vessel and the test was designed to gain an understanding on how the system tows through the water, outputs current, responds to winch and computer operations, and if the receivers collect data on all three channels. The altimeter malfunctioned on this first test and the ship time was cut short in order to bring the equipment back to the EM lab for modification.

Test Results:

- Altimeter is not functioning.
- The cables that connect CUESI to the two 10 cm long 1.5 cm diameter soft copper tubing on the transmitter electrode dipole towfish has too much resistance and is inadequately shielded from seawater to output current on the horizontal electric dipole.
- CUESI was not hydrodynamic and required more weight and less drag. CUESI needs only one stabilizer wing and needs a stronger connection to the tow cable.
- The connection between the CUESI cables and the two 10 cm long 1.5 cm diameter soft copper tubing on the transmitter electrode dipole towfish need to be improved.
- CUESI needs a conductivity and temperature sensor to remove variables during data processing.

25 September 2020 – Functionality Test

Another test of the system occurred on 25 September 2020 after modifications to the CUESI tow frame including, removal of side panels, 24 lbs of weight added to the frame, and a single vertical wing was attached to the frame for stability. The connection between CUESI and the tow cable was reinforced to reduce roll on CUESI during towing and a new altimeter was installed on the CUESI frame. This test was successful.

Test Results:

- The 0.5-inch diameter shielded aluminum wire resulted in consistent output current.

- Modifications to the weight, panels, and wings of CUESI reduced pitch and roll of CUESI.
- The new altimeter functioned without issue.
- The CUESI frame should be modified to have permanent weight and a more robust frame considering the drag on the system.
- A conductivity sensor will need to be added to the CUESI system.
- In order to use phase data, we will need accurate timing. This can be achieved if the CUESI internal clock can be synced to a GPS clock. We need to alter CUESI for these capabilities.
- The buoyancy of the receiver towfish is too high and need to be trimmed to decrease buoyancy.

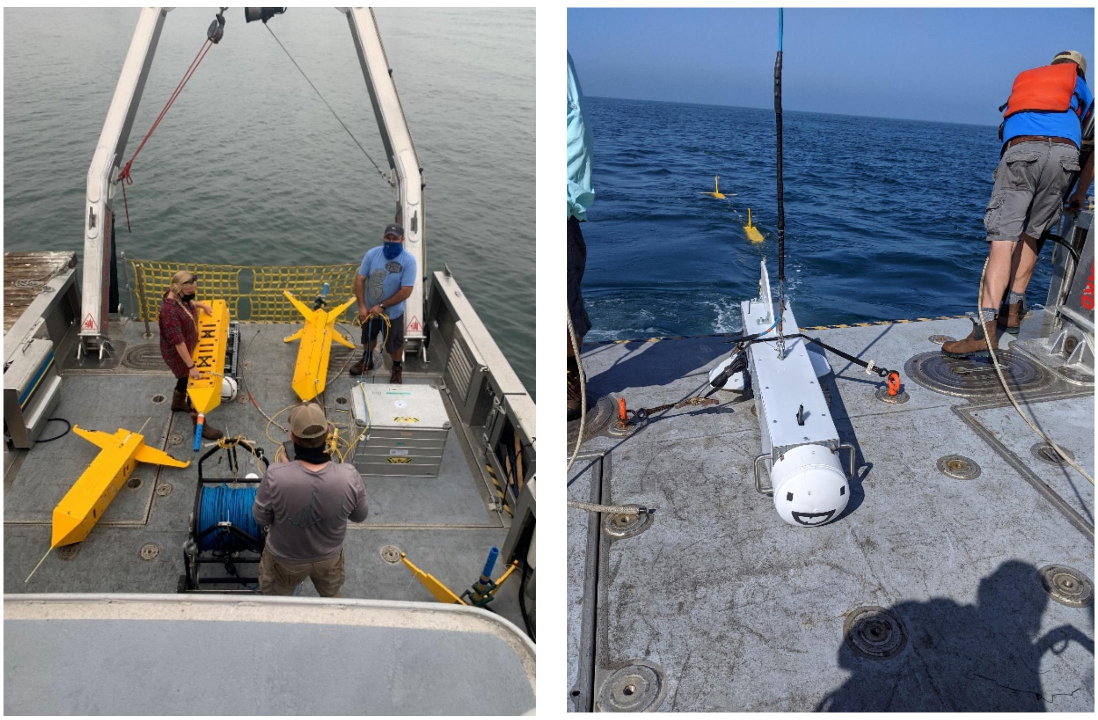


Figure 7. Left: The EM crew getting ready to deploy the system. Yellow objects are the three receiver tow frames that house the receivers. Right: Deploying the EM system. The white object is the transmitter tow frame that houses the transmitter.

24 May 2021 – Field Test

The initial field test for the CUESI system focused on areas with known targets buried beneath marine sediment off the western coast of Santa Cruz Island (Figure 8). This was to test CUESI frequencies over core locations with known varying sediment types from a prior BOEM survey. These cores exhibit changes in lithology that offer a unique test of the sensitivity of the CUESI system to thin (>50 cm) lenses of material of varying character. Additional tests of the CUESI system focused on the La Goleta tar seep offshore Isla Vista (Figure 9). This tested the sensitivity of the CUESI system to hydrocarbons and to compare the data collected with the CUESI system to that collected with the surface-towed CSEM Porpoise system.

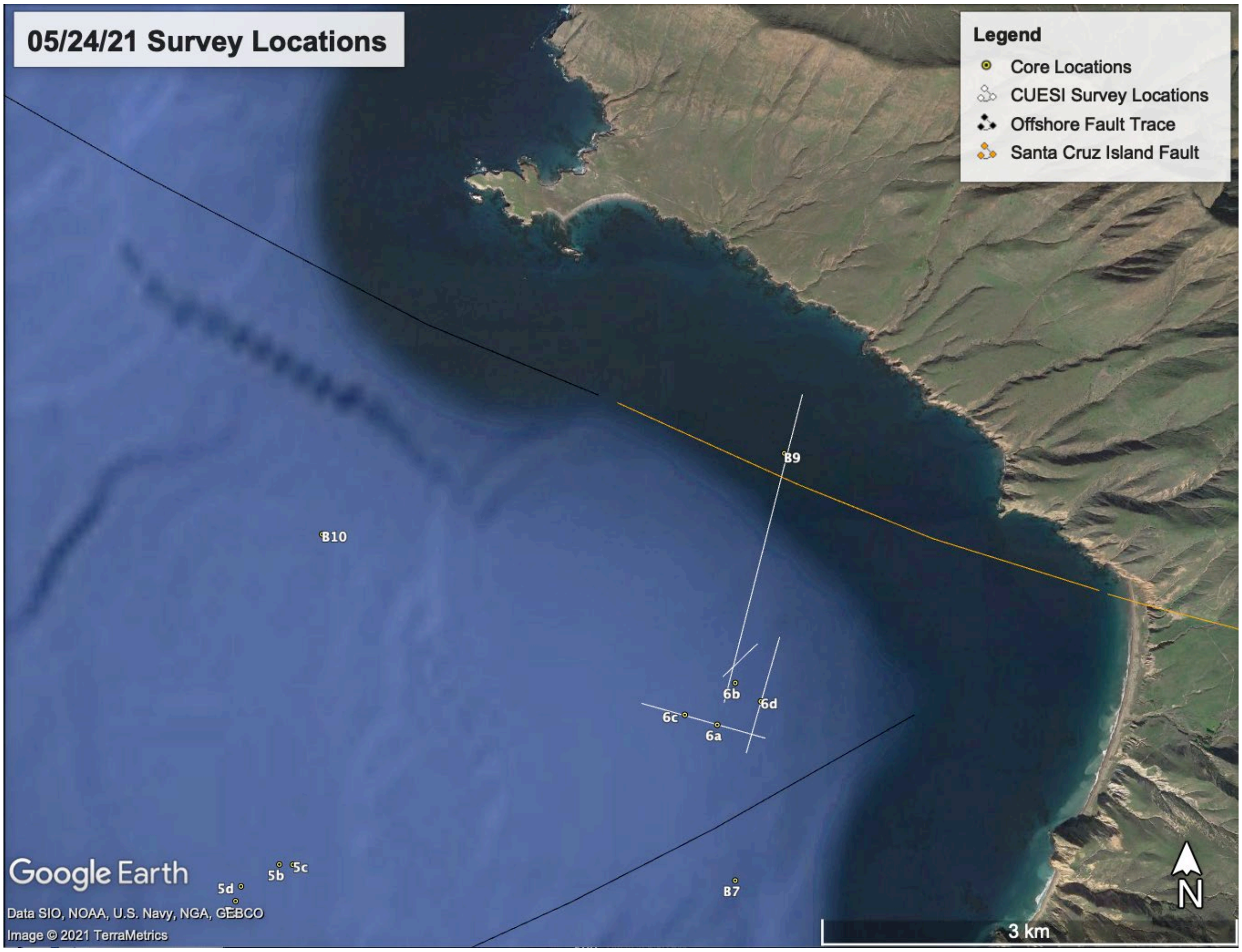


Figure 8: Survey location for CUESI survey off the western coast of Santa Cruz Island. Targeted cores locations from BOEM survey are shown.

Table 1. CUESI survey lines off Santa Cruz Island – 05/24/2021.

Site	Survey Line Name	Start Lat. (DD)	Start Lon. (DD)	End Lat. (DD)	End Lon. (DD)	Length (km)
NCI	C_052421_NCI_L1	34.024434°	-119.915818°	34.022035°	-119.905759°	0.98
NCI	C_052421_NCI_L2	34.021103°	-119.907179°	34.028807°	-119.904493°	0.92
NCI	C_052421_NCI_L3	34.028380°	-119.906299°	34.026150°	-119.909210°	0.37
NCI	C_052421_NCI_L4	34.024487°	-119.909014°	34.045192°	-119.902707°	2.41

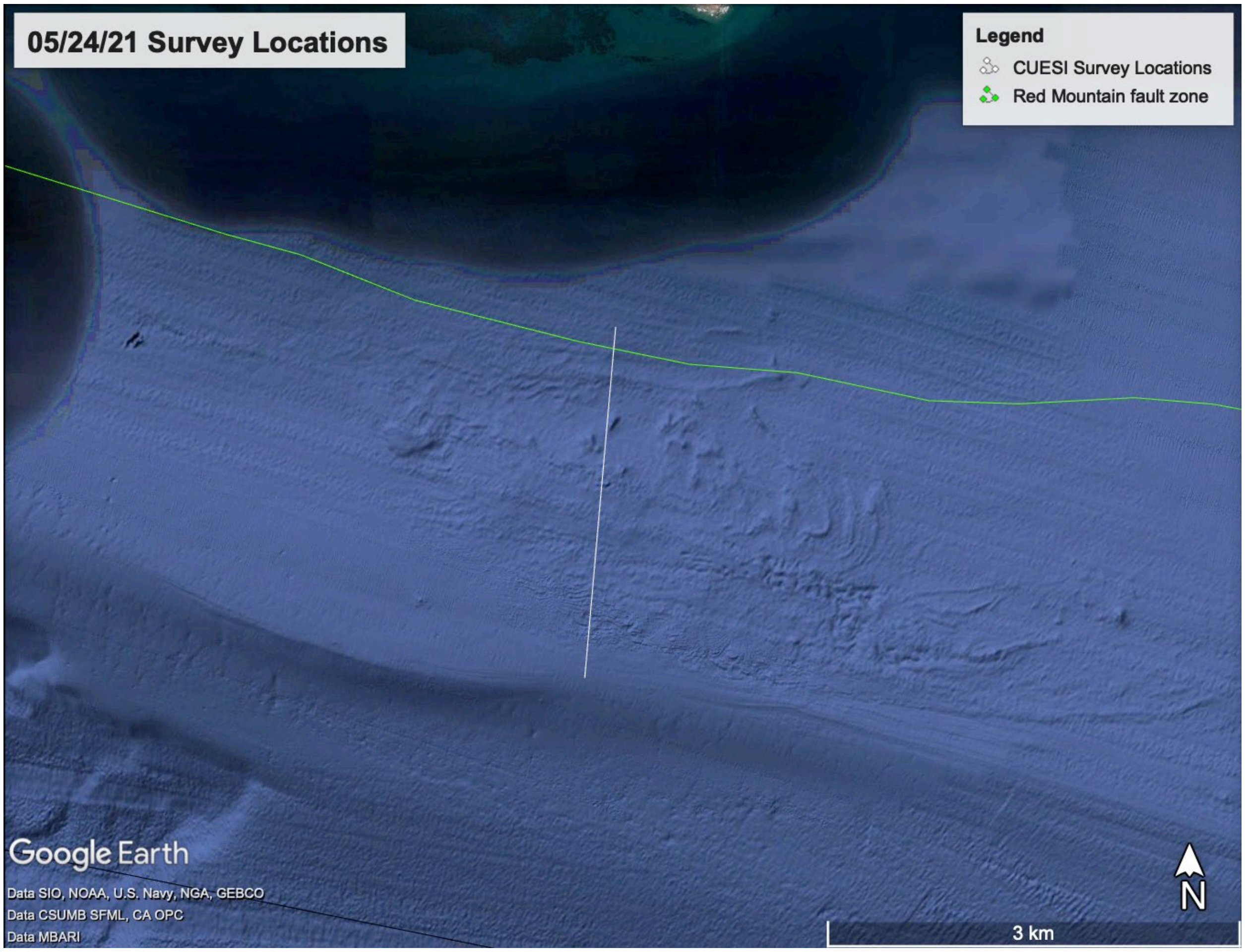


Figure 9: Survey location for CUESI survey offshore Isla Vista targeting La Goleta Seep Field.

Table 2. CUESI survey lines off Isla Vista – 05/24/2021

Site	Survey Line Name	Start Lat. (DD)	Start Lon. (DD)	End Lat. (DD)	End Lon. (DD)	Length (km)
IV	C_052421_IV_L1	34.384871°	-119.851949°	34.362481°	-119.854339°	2.54

Test Results:

- The relationship between internal CUESI clock drift and commands sent along the tow cable must be better understood.
- The communication box electronics should be investigated to avoid further cruise disruptions.
- The current control within CUESI needs to be calibrated and refined for more control over output current.

<u>25 May 2021 – Field Test</u>

This survey extends the area surveyed the previous day with CUESI as well as allowing for comparison between CUESI and Porpoise datasets (Figure 10). Additionally, several tie-lines were collected to directly compare the data collected by CUESI in different directions to gain a better understanding as to the influence of navigational noise or currents on data collection and quality.

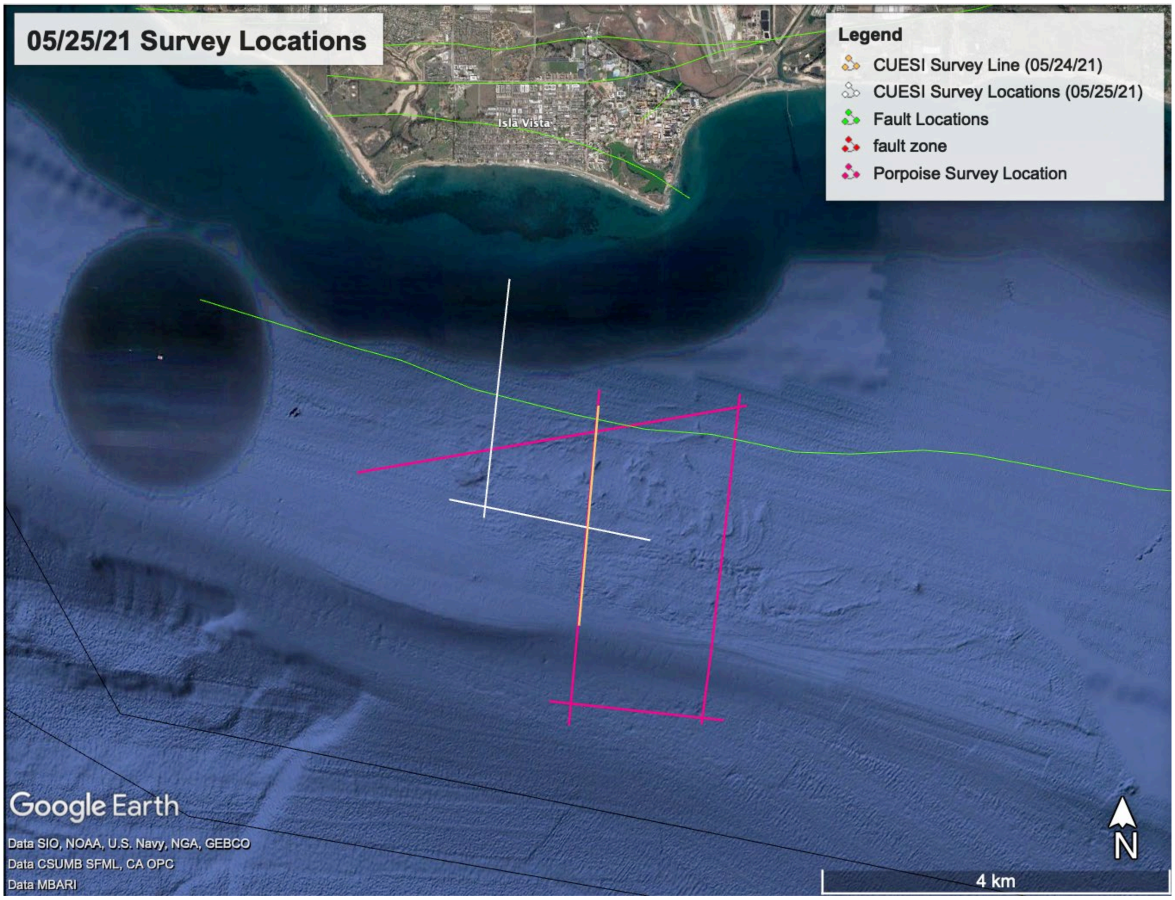


Figure 10. Survey location for CUESI survey and Porpoise survey offshore Isla Vista targeting La Goleta Seep Field. This survey extends the area surveyed the previous day with CUESI (noted in orange) and provides a direct comparison with Porpoise datasets.

Table 3. CUESI survey lines off Isla Vista – 05/25/2021

Site	Survey Line Name	Start Lat. (DD)	Start Lon. (DD)	End Lat. (DD)	End Lon. (DD)	Length (km)
IV	C_052521_IV_L1	34.371202°	-119.845562°	34.375373°	-119.870117°	2.36
IV	C_052521_IV_L2	34.373666°	-119.866080°	34.397609°	-119.862828°	2.71

Table 4. Porpoise survey lines off Isla Vista – 05/25/2021

Site	Survey Line Name	Start Lat. (DD)	Start Lon. (DD)	End Lat. (DD)	End Lon. (DD)	Length (km)
IV	PS_052421_IV_L1	34.386521°	-119.852128°	34.353107°	-119.856133°	3.9
IV	PS_052421_IV_L2	34.355452°	-119.858445°	34.353427°	-119.837322°	2.03
IV	PS_052421_IV_L3	34.353165°	-119.839996°	34.386027°	-119.835083°	3.82
IV	PS_052421_IV_L4	34.384896°	-119.834129°	34.378229°	-119.881618°	4.51

Test Results:

- The CUESI frame needs to be rebuilt out of heavier and stronger materials, possibly welding a frame for maximum strength.
- Deployment of both the CUESI system and the Porpoise system should be avoided if possible as transitioning between these two systems takes a significant amount of time.
- To reduce uncertainties in navigation, CUESI should be outfitted with a depth sensor.

5. Results and Discussion

Initial tests of the system acted as guides to better understand CUESI functionality and, importantly, modifications to the system needed for successful use in the field. While some needed modifications are apparent in the field, others are identified during data processing, which in some instances can take months. The CSEM data in real time does not produce images akin to those from sonar data. The processing of CSEM data involves extracting amplitude and phases of the CSEM response functions from the collected raw time-series data. To increase the signal-to-noise ratio, the resulting transfer function estimates are stacked using an arithmetic mean to obtain the transfer function estimates for every stacking window along with an error estimate. This method yields high quality amplitude and phase response data for the receivers as a function of position and frequency. The signal to noise ratios for these data are scrutinized to ensure the CSEM data associated with the harmonics are well above the noise floor, making them suitable for inversion.

These data are then modelled with a modeling software that uses the publicly available, goal-oriented, adaptive, finite-element two-dimensional (2D) MARE2DEM inversion and modeling code of Key (2016). This code uses Occam's Inversion, a method that regularizes the inversion to obtain the smoothest resistivity model that fits the data (Constable et al. 1987). CSEM data are scrutinized manually for obvious outliers and subjected to an error floor, dependent on data quality, before being included in the model as finite-length dipoles.

The starting models include the seawater as a fixed parameter, using conductivity data collected by the dorsal and available bathymetric data. Thus, the free inversion regions are reduced to the area below the seafloor and set to a uniform starting resistivity of 1 Ωm. Inversion parameter grids are constructed using quadrilateral cells that increase in height with depth to mimic the loss of resolution of the EM method with distance. Due to the adaptive nature of the MARE2DEM code, this computation grid is allowed to refine where necessary to fit the data. The resistivity inversions are allowed to run until a minimum root mean square is achieved; this value is then increased by ten percent to avoid overfitting. The final resistivity inversions are then ready for analysis and discussion (Figure 11).

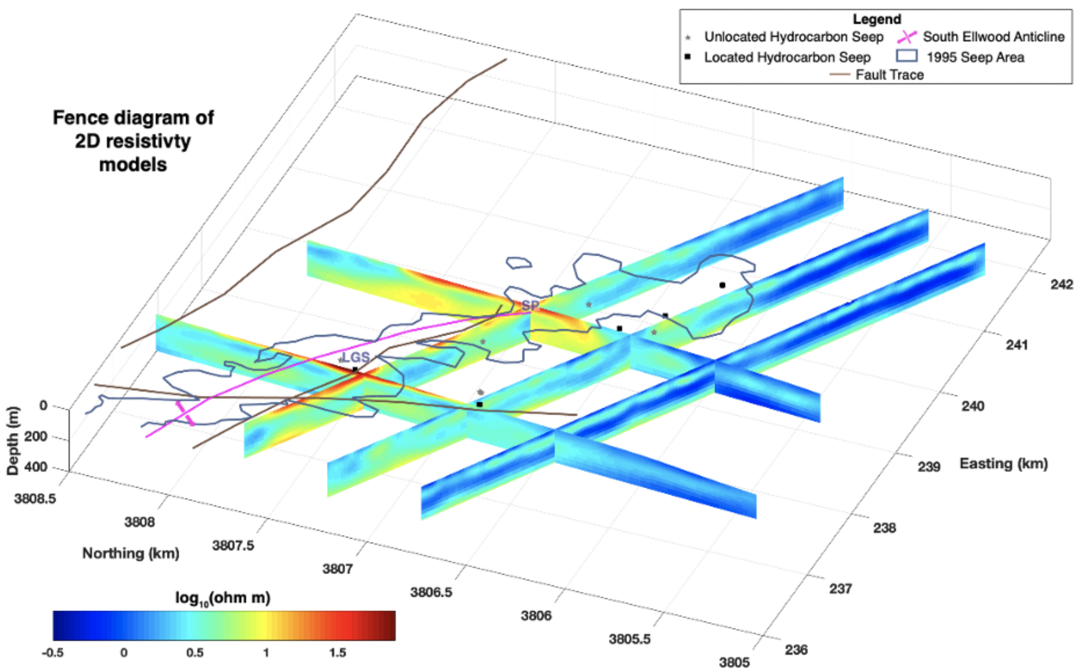


Figure 11. Example of a fence diagram created using processed CSEM data showing locations of tar seeps in red. This is not from the current project. Image by Roslynn King.

The initial results of the data collected with the current project show that the CUESI system is sensitive to hydrocarbons. As seen in Figure 12, the amplitude response data from the CEUSI system shows sensitivity to the hydrocarbon that has been identified by the Porpoise system. The model and amplitude responses are collocated as seen in Figure 10 and target La Goleta Seep Field. The amplitude response is in agreement with the final resistivity model of the surface-towed Porpoise system and demonstrate that both systems are sensitive to hydrocarbon accumulation associated with La Goleta Seep field. This was an important test of the CUESI system to ensure overlapping identification from a system that has already been established. Future tests of the CUESI sensitivity to hydrocarbons will include variations in final models as CUESI is likely to better model the shape and type of seep.

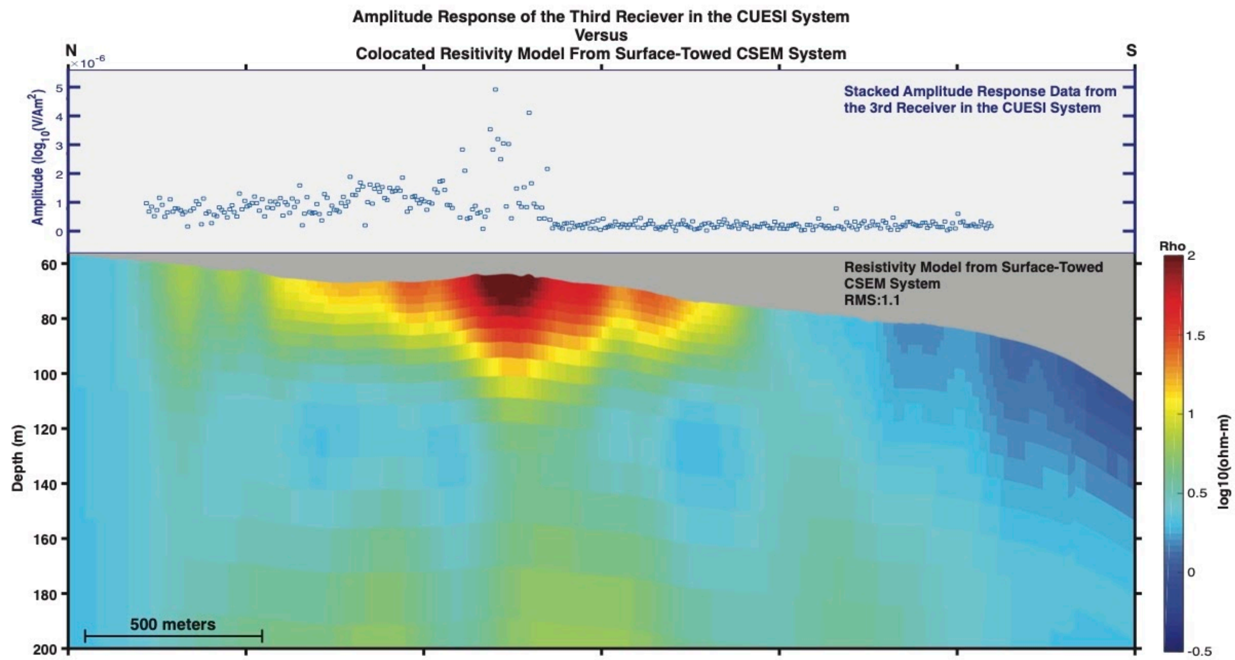


Figure 12: Figure illustrating the final resistivity model generated from Porpoise data versus the 10-second stacked amplitude response recorded by the third receiver in the CUESI system/array. Warm colors in the lower figure (resistivity model) indicate areas of higher resistivity typical of hydrocarbon occurrence. In the upper amplitude response figure, higher amplitude generally corresponds to regions of higher resistivity. Image by Roslynn King.

Data collected on the 24 May 2021 field test were processed and found to be chaotic. The lack of a depth sensor on CUESI created uncertainties in correspondence with navigation data. Additionally, the error in output current was 10% of the signal. This is too large to reach the sensitivity needed to identify targeted features in on the sea floor. Due to the nature of CSEM data processing, these issues were identified during post-processing. Once identified, this allowed us to modify the system to include depth sensor for accurate navigational data.

After completion of the needed CUESI system modifications identified from the NCPPT cruises, we were able use the CUESI system on a subsequent project funded by the National Oceanic and Atmospheric Administration Office of Ocean Exploration (OER). With the inclusion of a depth sensor, in addition to the altimeter, and an adjustment in frequencies, the CUESI system appears to have functioned as intended.

On 09 September 2021, we surveyed coring locations offshore western Santa Cruz Island using CUESI array (Figure 13). This repeated some of the transect lines run during our field tests for the NCPTT project, and added new areas that were consistent with our goals for the OER project (Figure 14).

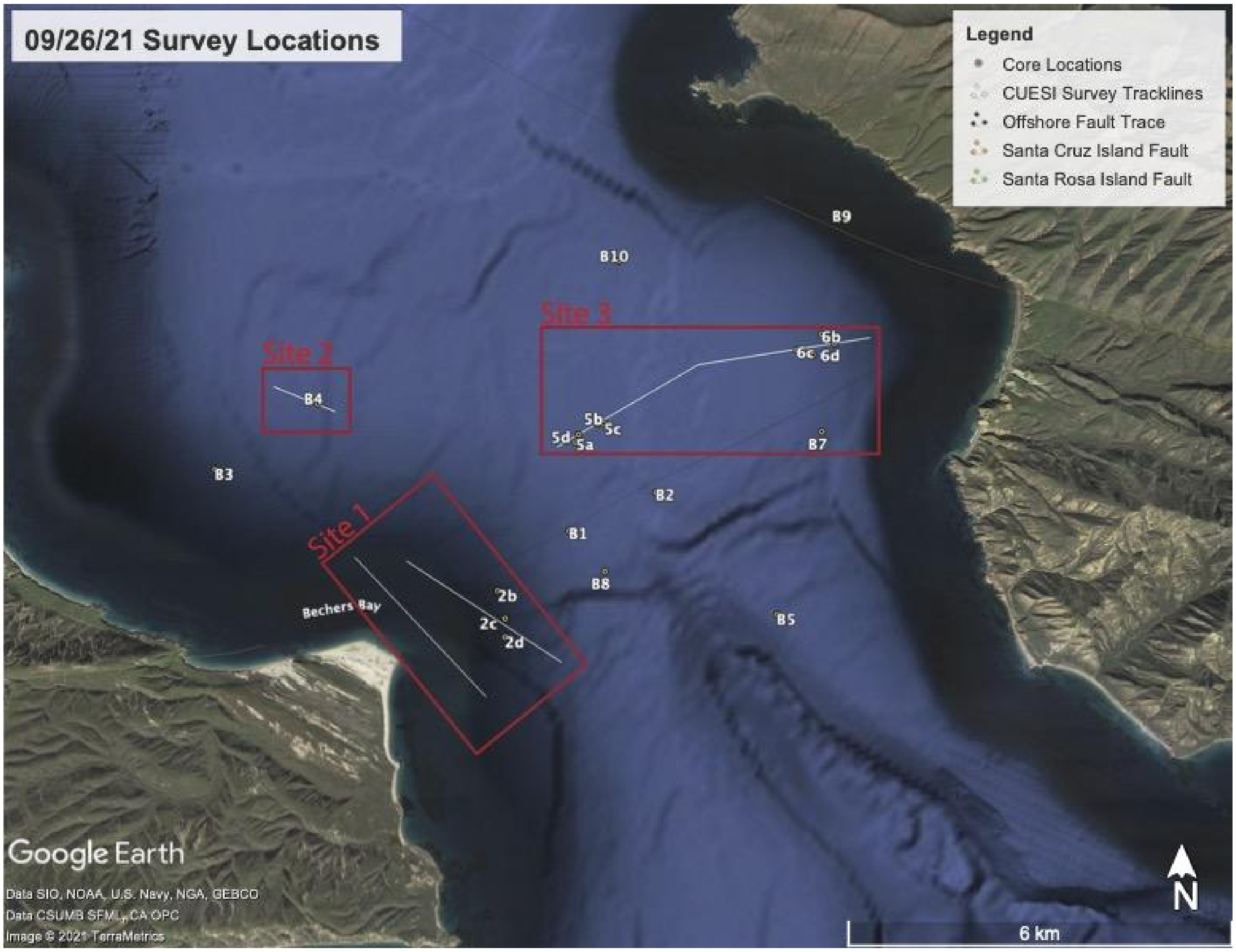


Figure 13: Survey location for CUESI survey on 09/26/21. This CUESI survey targeted possible seepage along a fault trace and several core locations.

Table 5. CUESI survey lines in Santa Cruz Island Channel – 09/26/2021

Site	Survey Line Name	Start Lat. (DD)	Start Lon. (DD)	End Lat. (DD)	End Lon. (DD)	Length (km)
1	CUESI_092621_L1	33.976089°	-119.963633°	33.995084°	-119.985243°	2.92
1	CUESI_092621_L2	33.994707°	-119.976740°	33.980817°	-119.951200°	2.81
2	CUESI_092621_L3	34.018664°	-119.998754°	34.015043°	-119.988362°	1.0
3	CUESI_092621_L4	34.010419°	-119.951853°	34.021606°	-119.928425°	2.51
3	CUESI_092621_L5	34.021606°	-119.928425°	34.025226°	-119.900086°	2.64

One of the modifications to the CUESI system was to correct the auto-shot camera that was installed inside a pressure case on the CUESI frame. This camera was set to take photos every four seconds. This resulted in over 2000 images. These images can be location-related to the CSEM data to provide images of the sea floor. This was a test of this concept and the results were blurry, but helpful in collecting images of various types of sea floor and marine animals (Figure 14). Plans for this improving imaging capability on the CUESI include a more advanced camera, and the possibility of adding a data cable that can transmit images topside during survey.

Figure 14. Examples of images of images from the CUESI camera. These are blurry, but the type of sea floor can be inferred from the photos. These also show that the concept was successful.

Although full processing of CUESI data is forthcoming, preliminary results are promising. Two of the core locations surveyed with the CUESI appeared in the processed data as areas with high resistivity and/or porosity values set in our starting models.

<u>Core 6c</u>

This core location showed a lag deposit starting at approximately 100 cm depth beneath the sea floor. The ability of the CUESI to identify these types of deposits is important for identification of buried lithic material, as well as changes in the sediment that can indicate a paleoenvironmental shifts, or ancient habitats covered with marine deposits during marine transgression (Figure 15).

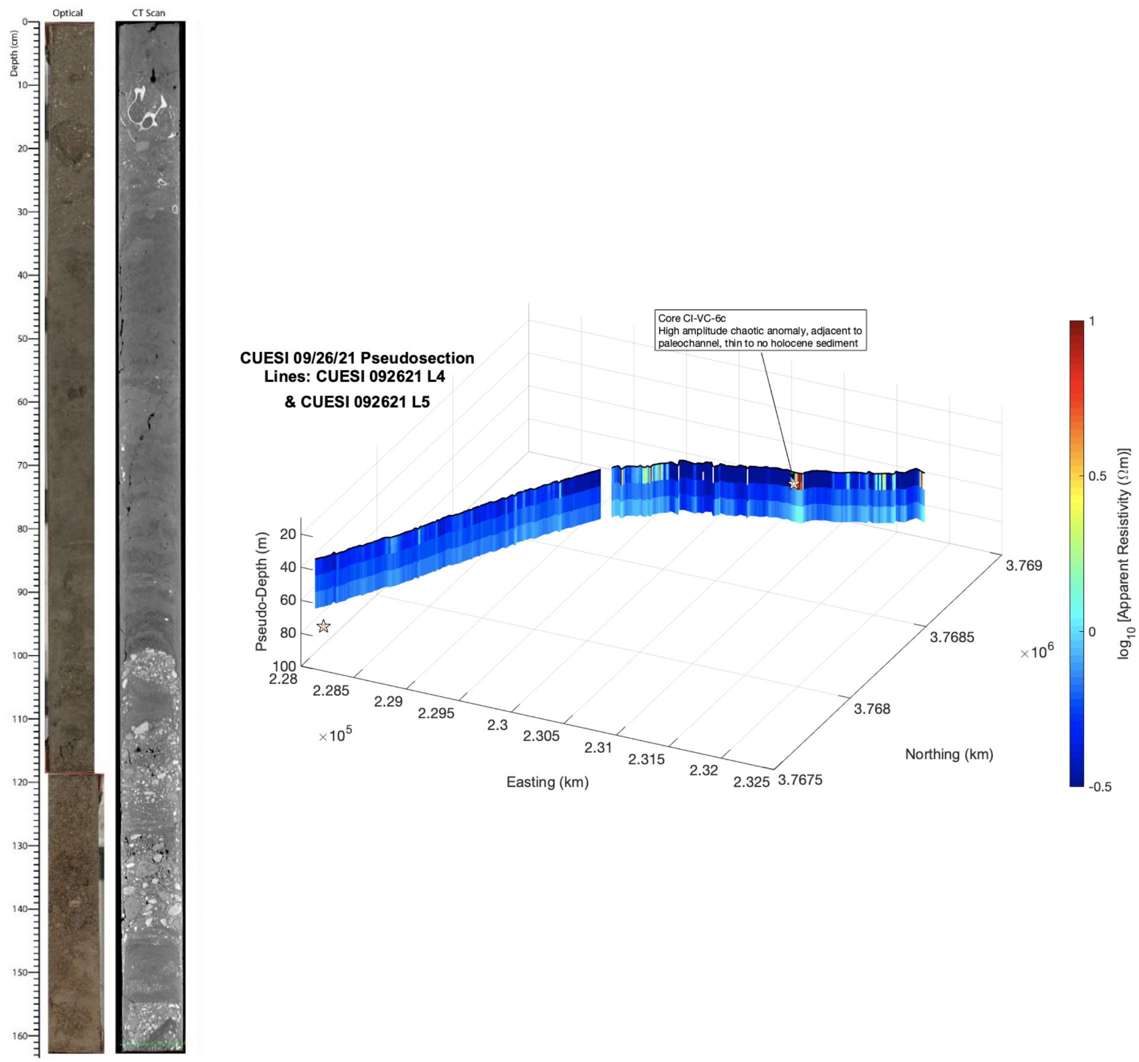


Figure 15. Left: Split core with lag deposit starting at ~100 cm. Right: Pseudosection of survey over this core (starred location) showing high resistivity values, indicated as red colors on the chart. Image by Roslynn King.

Core B4

This core location showed a shell deposit starting at approximately 55 cm depth beneath sea floor. The ability of the CUESI to identify buried shell deposits was one of the main goals of the system design. CUESI ability to identify shell porosity values, which would be unique, can aid in narrowing down areas to target for testing based on remote sensed data. The pseudosection shown in Figure 16 includes only porosity values pulled from the CUESI data. The location over core B4 shows a porosity value of 68.8%, an almost exact match for the modelled porosity volume of the core sample, measured at 69%. Additional processing of these data can help to clarify these finding. In future surveys, the CUESI system could potentially generate porosity maps for further investigation or identify areas with little consolidation, which is valuable to offshore infrastructure projects.

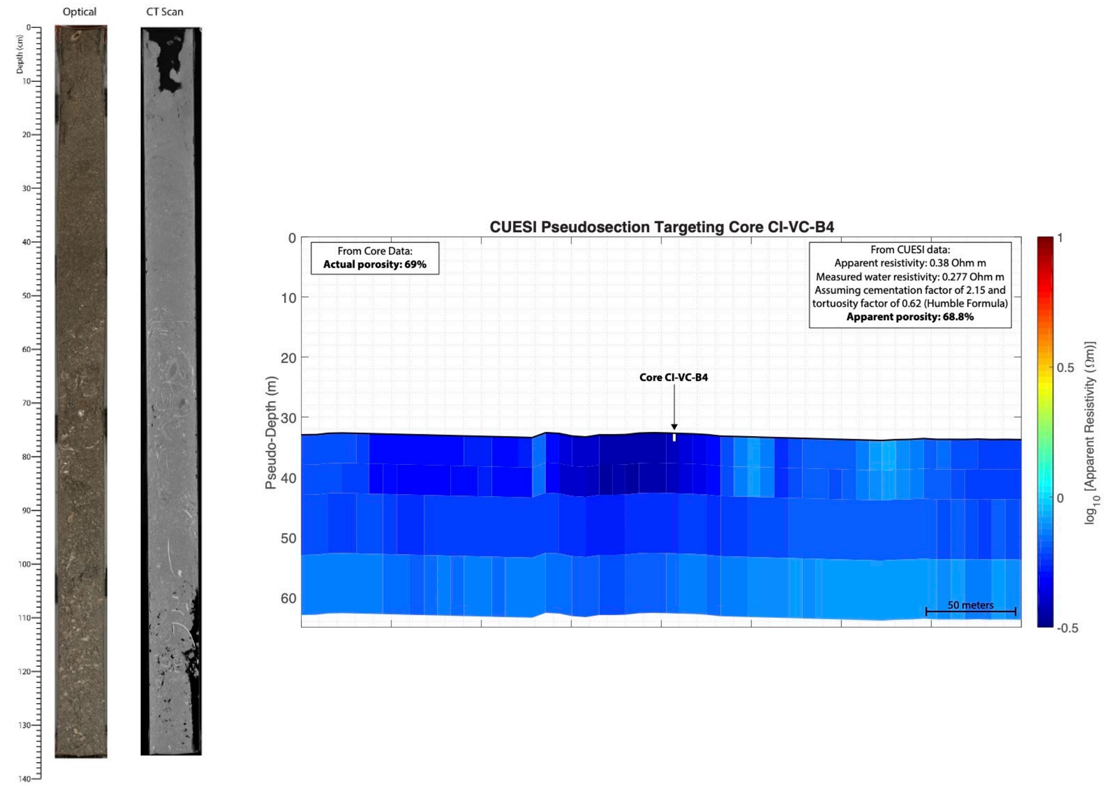


Figure 16: Left: Split core with shell deposit starting at ~55 cm. Right: This pseudosection highlights the sensitivity of the CUESI system toward characterizing changes in seafloor porosity that can aid in identifying shell middens which are predicted to have a higher pore volume than typical marine sediment. Image by Roslynn King.

The results of the field tests as well as the data collection on the subsequent project show that the CUESI system may be a beneficial addition to remote sensing data surveys focused on identifying targets on submerged paleolandscapes. CUESI collects altimeter, pressure, conductivity, and temperature data as designed. These data provide conductivity profiles both vertically and laterally through the water column that can aid in identifying seafloor seepage (either through changes in temperature or conductivity) and stratified water columns. The altimeter and pressure data, when processed and combined, can create high-resolution (.5 meter lateral resolution and 10 cm vertical resolution) bathymetric profiles. These datasets are useful toward building accurate starting models for, thereby reducing error in, later inversions. Additionally, the response data from the receiver towfish can be used to create resistivity pseudosections of the upper 40 m of seafloor material. These data and pseudosections can be used to identify possible changes in porosity in the seafloor (Figure 16), lithics (Figure 15), or hydrocarbons (Figure 12). Resolution and sensitivity to these targets could be improved by collecting more sets of higher resolution navigational data as well as incorporating phase data. Efforts to use this data in 2D inversions are still underway.

Incorporation of the camera on the CUESI system shows promise, though modifications are needed. The camera collected thousands of photos of the seafloor during a dive on 26 September 2021. The camera later malfunctioned due to power interruptions, which will be addressed in future lab tests. The lights associated with the camera provided adequate light when the system was within 5 m of the seafloor. Many of the photos were out of focus due to the adaptive focal settings on the camera; this will be addressed by setting a permanent focal distance for future surveys.

The design of CUSEI to be deep-towed is integral to the success of the system. This design included a drop weight with the transmitter electric dipole and receiver towfish 1 to 2 meters (or within 5 m) above the seafloor with minimal contact with the seafloor. The navigational data collected on 26 September 2021 demonstrates that the transmitter electric dipole and receiver towfish maintained an altitude of 1 to 2 meters above the seafloor. Additionally, the navigational data indicates that CUESI functioned effectively as a drop weight as little wave noise was recorded on the transmitter electric dipole and receiver towfish. These data also show that CUESI is able to generate a consistent current controlled signal between 1 to 5 amps and these signals propagate to the receivers in a predictable manner. Further analysis of receiver data may help better understand the stability of this signal and could help improve modeling efforts.

6. Conclusions

The CUESI system was initially developed as a novel bottom-towed CSEM system to survey the immediate seafloor and shallowly buried features on the continental shelf with minimal impact of the seafloor substrate and benthic community. A major goal of the datasets and models generated by this system were to map changes in porosity that could be indicative of shell middens left from human occupation. To achieve a level of sensitivity to image middens, the system would need to generate small EM signals and the receivers would need to ‘flown’ within 5 m of the seafloor and be highly sensitive to minor perturbations in the electric field. Reducing seafloor impact and maintaining a consistent altitude above the seafloor would require precise control of instrument buoyancy and ship speeds. Additionally, from forward models, the presence of middens generates a small fluctuation, around 5% total change in recorded signal, in the electric field. Therefore, all sources of noise, especially navigational noise need to be below this threshold. The influence of navigational error on the final resistivity models can be minimized by collecting accurate and high-density navigational data.

Through several iterations, test cruises, and pier tests, the functionality and data collected by the CUESI system has significantly improved and sensitivity to changes in porosity is apparent. CUESI was used to collected data on a subsequent project and these data appear, at least in initial processing, to be effective at identifying a known lag deposit. CUESI was also able to effectively locate modelled porosity of a core sample with a shell deposit, and a known tar seep. These results suggest that CUSEI may be an effective system for consideration in surveys focused on identifying features across paleolandscapes that may narrow target selection for subsequent sampling. This selection can create a more efficient process to collect data germane to geological, biological, and paleontological disciplines, and narrow search parameters to identify archaeological “hot spots'' on the continental shelf. These data are crucial in our ability to identify sensitive cultural landscapes and eventually identify, document, and preserve underwater cultural heritage resources.

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