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Mapping Porosity Structure Offshore Torrey Pines State Natural Reserve and Del Mar, California Using a Surface Towed EM System

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Mapping Porosity Structure Offshore Torrey Pines State Natural Reserve and Del Mar, California Using a Surface Towed EM System

A Thesis submitted in partial satisfaction of the
Requirements for the degree Master of Science

in

Earth Sciences

by

Thomas Patrick Martin

Committee in Charge:

Professor Kerry Key, Chair
Professor Steven Constable
Professor Leonard Srnka

2015

The Thesis of Thomas Patrick Martin is approved, and it is acceptable in quality and form for publication on microfilm and electronically:

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University of California, San Diego

2015

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Vita

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ABSTRACT OF THE THESIS

Mapping Porosity Structure Offshore Torrey Pines State Natural Reserve and Del Mar, California Using a Surface Towed EM System

by

Thomas Patrick Martin

Master of Science in Earth Sciences

University of California, San Diego, 2015

Professor Kerry Key, Chair

Controlled source electromagnetic methods have been used in exploration of the offshore environment for over 50 years to map the resistivity structure of the earth. Developments in both instrumentation and computational power have lead to many advancements that have led to discoveries and insights about the subsurface. One of these advancements has been the development of towed EM acquisition systems. One system the Marine EM Lab at Scripps Institution of Oceanography has developed is a shallow water system, named Porpoise, can be used in water depths as shallow as 5m. In May of 2014, a one day field test of this new shallow water acquisition system took place offshore of Del Mar and Torrey Pines State Natural Reserve, California.

The data from this field test corresponds with previous interpretations of paleochannels directly offshore modern day San Dieguito and Soledad Valley river outflows. With resistivity data, it is possible to indirectly map porosity in the near surface and to map geological features.

The data dense and economical operation of the Porpoise acquisition system can be used to map resistivity and indirectly porosity in a variety of shallow water marine environments. This field test proves the viability and limitations of the Porpoise system.

Chapter 1

Introduction to Marine Electromagnetic Geophysical Concepts and Practice

1.1 Introduction

Marine electromagnetic geophysical methods have been used for over fifty years to determine the electrical resistivity structure of the the ocean floor. The first uses were deep soundings for lithosphere studies. One of the main tools available is the controlled source electromagnetic (CSEM) method. CSEM uses an alternating current source to transmit frequencies between 0.1 and 10Hz using a horizontal electric dipole (HED). These frequencies and thus CSEM produce crucial sensitivity to shallow structure that is not possible to acquire passively by the magnetotelluric (MT) method in the offshore environment. Research within the past two decades from both academia and industry has led to many developments in instrumentation, computational power and processing methods to make electromagnetic methods accurate enough to be of commercial significance, and make important research discoveries possible. (MacGregor and Tomlinson 2014, Key 2012, Constable 2010)

1.2 History of Marine Electromagnetic Exploration

There are more than a few full length reviews of where marine electromagnetics (EM) and specifically CSEM have come from and their future for exploration, mainly MacGregor and Tomlinson (2014), Key (2012), Constable (2010) and additional references within. A short review is provided here.

Offshore electromagnetic research and technology commenced with Office of Navel Research funding at Scripps Institution of Oceanography (SIO), led by Charles (Chip) Cox and Jean Filloux in the 1960's. The first theoretical examination of a horizontal electric dipole (HED) frequency domain method to map the conductivity structure of the sea floor was by Peter Bannister (1968).

Improvements in instrumentation and electromagnetic research in the marine setting have led to better understanding of magma chambers and mid ocean ridge processes (Key et al. 2013), faulting and fluids in subduction zones (Naif et al. 2013), hydrocarbon resources (Constable 2010, Constable and Srnka 2007), and ground water interactions (Evans et al. 1999, Evans et al. 2000) on the continental shelf.

Sea floor receivers today record both the electric and magnetic fields in two directions at orthogonal angles. Modern systems have an electric dipole of ~10m and can be deployed in 20 minutes with a trained and efficient crew. With a compass that records final heading on the ocean floor, the data can be rotated to a more useful heading for data analysis. Constable (2013) provides a review on modern instrumentation specifically for conventional nodal seafloor CSEM data acquisition that is shown in figure (1).

With the success of the Vulcan (figure 2), a triaxial electric field deep-towed EM acquisition system (Weitemeyer, and Constable 2010, Constable et al. 2012, Kannberg et al. 2013) a surface-towed system has been developed by the Marine EM lab at SIO.

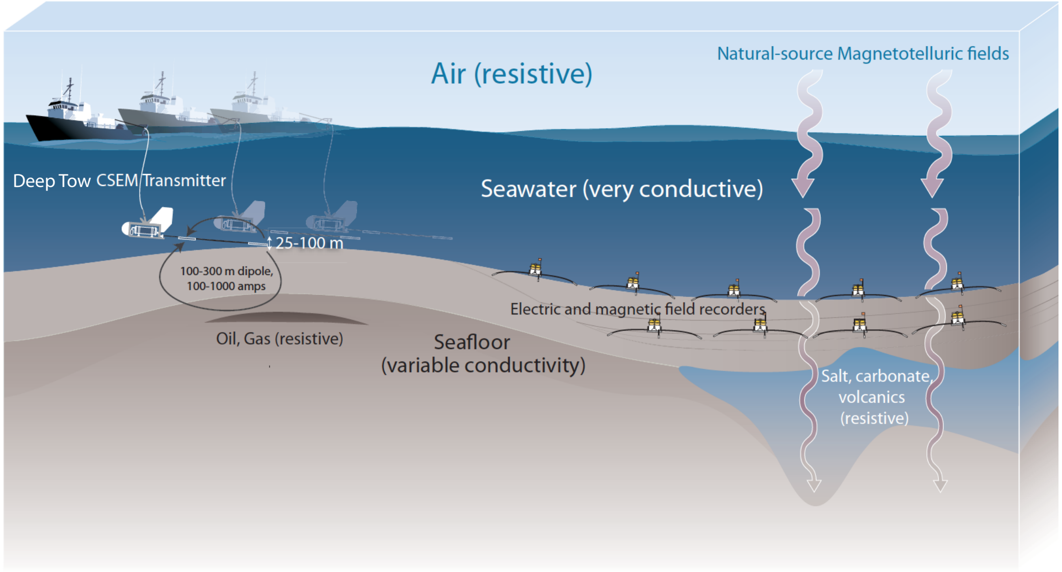


Figure 1. Modified figure 3 from Constable et al. 2010. Diagram of nodal CSEM and MT acquisition using a towed transmitter. Compared to the SIO porpoise system, the nodal system can be used at deeper water depths (400m+) and can acquire passive MT data concurrently.

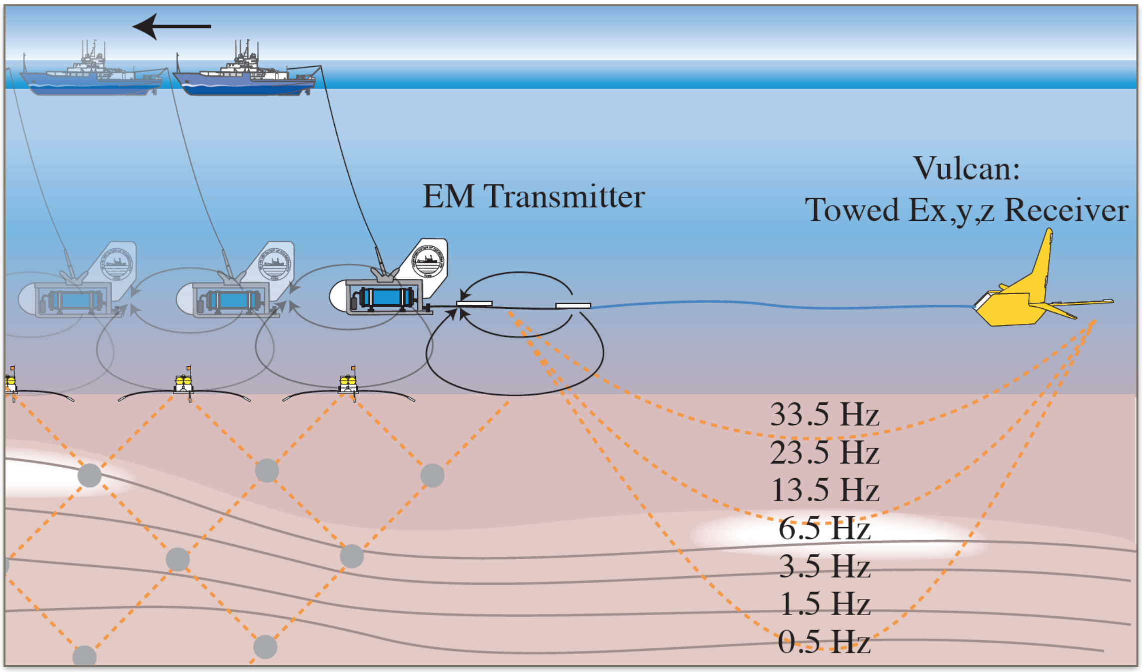


Figure 2. Modified figure 3 from Weitemeyer and Constable 2010. Diagram of the Vulcan triaxial electric field receiver, a constant offset deep tow system. Can be used with seafloor receivers. Compared to the SIO porpoise system, the Vulcan system can be used at full ocean depth (6000m).

The advantages of a surface towed system include efficient data acquisition, continuous data coverage, shallow operations and safer deck operations. Initially shallow water acquisition of this type was thought to be impossible due to the dominance of the airwave signal and high noise attributed wave noise at the ocean surface. These problems have been overcome through careful modeling and consideration of the airwave and careful instrumentation design. (Andréis and MacGregor 2008, Mittet and Morten 2013, Weiss 2007)

Electromagnetics (EM) has been useful for mapping porosity and geologic features that are difficult to image with typical seismic methods, as seismic and CSEM methods are sensitive to different physical properties. Specifically CSEM data can provide information necessary for interpreting complex features such as gas blowouts, sub-salt and sub-basalt regions (Schwalenberg et al. 2005, MacGregor and Sinha 2010). Today EM surveys are being used to image the subsurface in all water depths for exploration and research purposes (MacGregor and Sinha, 2000; Greenwood et al. 2006; Hansen and Mittet, 2009; Lovatini et al., 2009; Barker et al. 2012).

1.3 EM Concepts

The physics behind passive and active source EM exploration is based on electromagnetic induction as described by Maxwell's equations. At the frequencies used for EM geophysics, 0.001 to 1000Hz (excluding ground penetrating radar), induction is governed by the diffusion equation, in contrast to the wave equation that governs seismic methods. Keeping this in mind, the resolution, especially in the vertical axis is considerably less than reflection seismic methods, but better than potential field

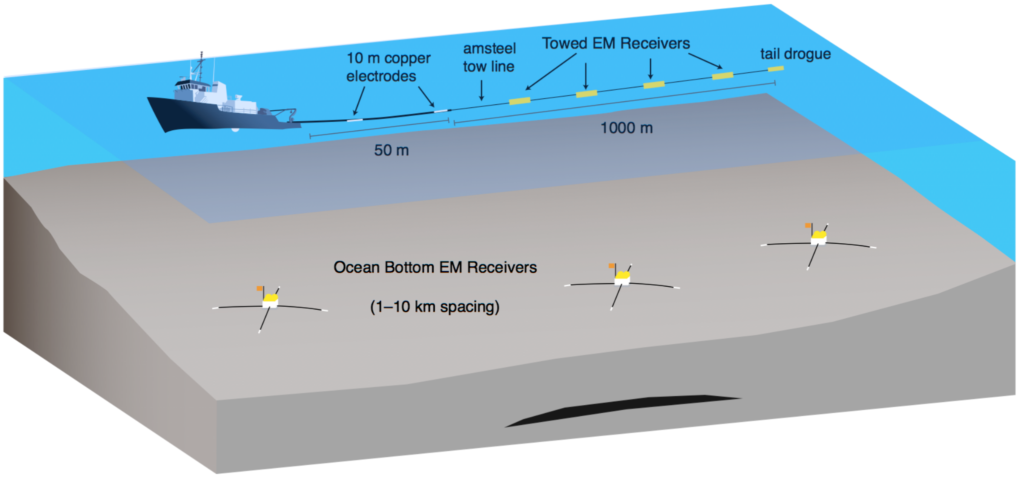


Figure 3. Diagram of the Porpoise surface towed system developed by the Marine EM Lab at Scripps institution of Oceanography. Can either be used with or without seafloor instruments. Typical tow speed for data acquisition ranges from 1-4 knots.

data from gravity and magnetic surveys. EM methods can constrain depth through the skin depth dependence (eq 1.) where with every skin depth the fields decay by 1/e (roughly 37%) and phase lags by one radian. Where T is period in seconds and ρ is resistivity in ohm(m) labeled as Ω.

$$Zs \approx 500(\rho T)^{(0.5)}(m) \qquad (1)$$

It is important to note that skin depth is a not bounds on resolution, but gives an idea of the maximum distance EM energy can propagate in conductive earth materials. Another factor in depth sensitivity is offset between transmitters and receivers, where a very general rule is EM surveys are sensitive to half the offset in depth. Even with the lack of depth resolution compared to reflection seismic methods, CSEM soundings are more sensitive to bulk rock properties. EM methods have a higher sensitivity to fluid saturation in the rock and depending on survey parameters and depending on background geology it can distinguish between conductive salt water to resistive hydrocarbons. (Wright et al. 2002)

When interpreting 2D resistivity profiles, one needs to keep in mind where a thin resistor in a conductor is difficult to accurately constrain the size with the same resistivity-thickness product at depth. An example of this is a 100Ω resistor that is 2m thick and a 50Ω resistor that is 4m thick have the same resistivity thickness product and the size of the body is hard to distinguish at depth. (Constable and Weiss 2006, Key 2012 review)

1.4 Archie's Law

Archie's Law (Archie 1942) relates porosity and pore fluid resistivity to bulk rock resistivity. As electromagnetic methods map bulk resistivity, is it important to put this measurement into physical context to the geology of the Del Mar region. Seawater is conductive (.2 -.4Ω) depending on temperature, and the resistivity of the fluid (P_f) drives the whole rock resistivity (ρ).

$$\rho = (P_f)\beta^{-m} \qquad (2)$$

The equation for Archie's Law (eq. 2) has two variables that can be changed if one has knowledge of the conductivity of the seawater. The cementation exponent, (m) and porosity (β) are calculated by sampling the geology directly or through calibrating downhole tools. For this survey, we do not have access to this type of data. Typically the value for the cementation exponent is around 2 but can be as high as 3 or as low as 1.4 (Evans et al. 1999, Evans et al 2000).

1.5 Shallow Water Electromagnetic Exploration Technologies

The first theoretical paper describing controlled source electromagnetic exploration in shallow water was by Peter Bannister in the sixties (Bannister 1968). More recently there has been interest in improving shallow water exploration technologies for geotechnical, energy and research purposes (Evans et al. 2009, Andreis and MacGregor 2007). Shallow water compared to deep water it has its own set of logistical and survey challenges from surf, near shore currents, increased fishing activity, as well as piloting ships into areas with shallow draft. Besides logistical challenges, correctly modeling the airwave in shallow waters cannot be overlooked.

Mapping the porosity of near shore sediments is important for understanding continental shelf processes and hydrogeology. Some previous experiments have floated commercially available terrestrial equipment (Greenwood et al. 2006) in shallow lagoonal environments. The Geologic Survey of Canada has a towed system that is dragged on the sea floor as described in Evans et al. (1999) where up to 40m offsets were recorded, having sensitivity to the upper 20m. A short offset bottom towed system has been used to study groundwater interactions and geology offshore of Wrightsville Beach, NC (Evans and Lizarralde 2011). Many of these studies have used a Geonics EM31 or EM34 (http://www.geonics.com/) transmitter with offsets up to 40m limiting these studies to shallow depths of investigation. A bottom dragged magnetic source system developed at Woods Hole Oceanographic Institution, based on the Canadian system, has some logistical and data collection advantages compared to previous studies with Geonics equipment, but still can only image the top 20-30m (Evans 2007).

The Scripps Porpoise system is a towed electromagnetic source and receiver that can be used with or without seafloor instruments. The towed system consists of one horizontal electric dipole (HED) transmitter and 4 receivers spaced every 250m for offsets up to 1km. The transmitter can output 60 amps on a 50m dipole, and the receivers with a 2m dipole sample at 250hz. This frequency domain system is packable in a pickup truck and can be used with smaller ships of opportunity, compared to a typical large-scale industry CSEM survey equipment. An advantage of this system over previously described shallow water EM acquisition systems is longer offsets and multi-frequency data. With offsets approaching 1km, it is possible to image ~400m down while still having high resolution at shorter offsets due to the multiple receiver setup.

Another surface-towed system has been developed for hydrocarbon exploration by Petroleum Geo-Services. This system can operate alongside and with typical seismic operations and has been tested over oil fields in the North Sea with success in water depths of <400m. This is a much larger system with a 1000A+ source dipole and up to eight kilometers of offset. (Key et al. 2014, Anderson and Mattsson 2010)

1.6 Modeling with MARE2DEM and the Occam Method

The nature of field-collected electromagnetic geophysical data is its inherent non-uniqueness. That is, for one finite set of noisy data, there are an infinite number of models that can fit the data within its uncertainty. This is not to say that all of the models make sense on a geologic basis. Solutions to this constrain the model with either *a priori* knowledge of the geology or by restricting model bounds or complexity. These user-defined limitations might produce stable models, but care must be taken. Great modification and previous input will have a considerable effect on the final output of the algorithm. To overcome the shortfalls of non-unique data and an infinite number of possible models, the Occam method (Constable et al. 1987) is used to find the smoothest model that fits the data. One reason why a smooth model is sensible for electromagnetic data is EM data cannot constrain sharp boundaries or thin boundaries/layers due to its diffusive nature. One must be cautious though, as the Occam method wants to smooth the model space and minimize complexity. There is no reason that a more complex model cannot be more realistic to the geology and both types of models can fit the data to the same misfit. Having a basic understanding of the geology and what are reasonable structures in the area adds a lot of value to final interpretations. Integrating other geophysical methods with electromagnetic data assists with the interpretation and constraining the non-uniqueness of the data. Specifically with reflection seismic data that has difficulty imaging sub-salt and sub-basalt geologic regions, CSEM can add understanding to these geologies.

MARE2DEM is a 2D algorithm that does forward and inverse modeling for both controlled source or passive source frequency domain EM problems (Key and Ovall 2011, Key 2012). MARE2DEM uses triangular finite elements that can handle various EM problems such as steep topography, towed and nodal survey design, marine and terrestrial surveys. MARE2DEM was developed with funding from the Seafloor Electromagnetic Methods Consortium and now is available online under the GNU general public license. (http://mare2dem.ucsd.edu/)

Chapter 2

Synthetic Modeling Studies

2.1 Introduction

Before modeling survey data, it is important to understand the capabilities of the Porpoise towed system. Looking at a few synthetic models is a quick way to get an understanding of sensitivity, resolution and depth of investigation. The forward and inverse modeling described herein was completed using the open source MARE2DEM (http://mare2dem.ucsd.edu/) set of tools and algorithms (Key and Ovall 2011, Key 2012). First a geology/resistivity section was constructed, then an array of transmitters and receivers were created to simulate a realistic survey. For the synthetic tests, two arrays are used. The first one has the same survey design as the porpoise system using one transmitter with four receivers with Rx-Tx spacing's of 250m, 500m, 750m and 1000m. The receiver and transmitter locations are visible on the inversion profiles as white dots. The other array used has all of the same Rx-Tx spacing's as above but with additional seafloor receivers spaced every 2km. It is important to note that they are all modeled as point receivers and transmitters (Streich and Becken 2011) instead of finite length bipoles due to the additional computational cost. However at the offsets of the receivers the point dipole approximation is justified. After successfully completing a forward model, random Gaussian noise is added to the data to get closer to field data quality prior to inverting it.

For the next four models, three percent random noise was used. The next step is to invert the data to see how close the inversion approaches the original structure. The four synthetic models use log10 amplitude and phase of the inline electric field with four frequencies .25, .75, 2.25 and 8.25Hz. All of the models are in 10m water depth with no bathymetric relief. A discrete transmitter and towed receiver is located every 125m. All of the inversion meshes had no prior structure in them or penalty cuts. All of the models stopped on normal convergence at RMS of ~1.

2.2 Dual Resistor

The dual resistor model (figures 3-5) is a 2km wide, 10Ω shallow structure that is above a 1km wide 100Ω reservoir at 200m depth located in a 1Ω half space (figure 8-10). The shallow resistor could represent sub basalt, carbonate, gas hydrates and other geologic conditions. The amplitude data shows a ~30% anomaly over the resistive feature compared to the 1Ω half space. The Occam method of finding the simplest model typically will “bleed” resistive features together. Having separation between both features in the towed data was a great result, along with modeling the reservoir better than the deeper model described in section 2.2.

2.3 Deep Buried Reservoir

The buried reservoir (figures 6-8) is a 100Ω body in a 1Ω half space that is located 400m below the sea surface, and is 50m thick and 2km wide. This is representative of a shallow simple hydrocarbon system. The towed system had

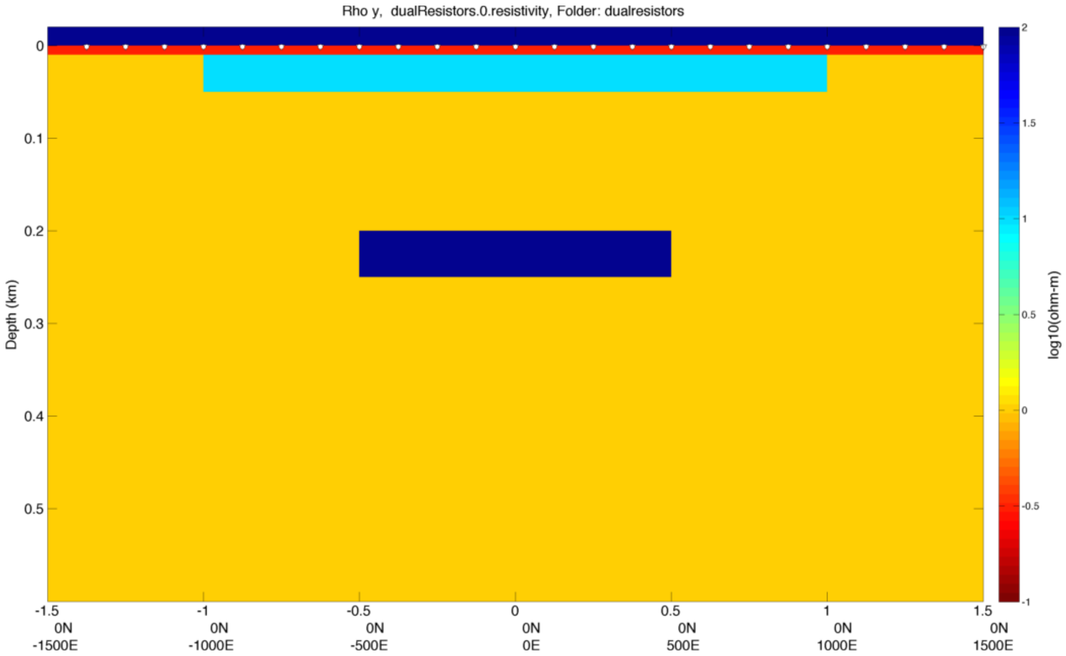


Figure 4. Model of dual resistor geology. 10Ω upper resistor above a 100Ω reservoir in a 1Ω half space. logarithmic resistivity scale used.

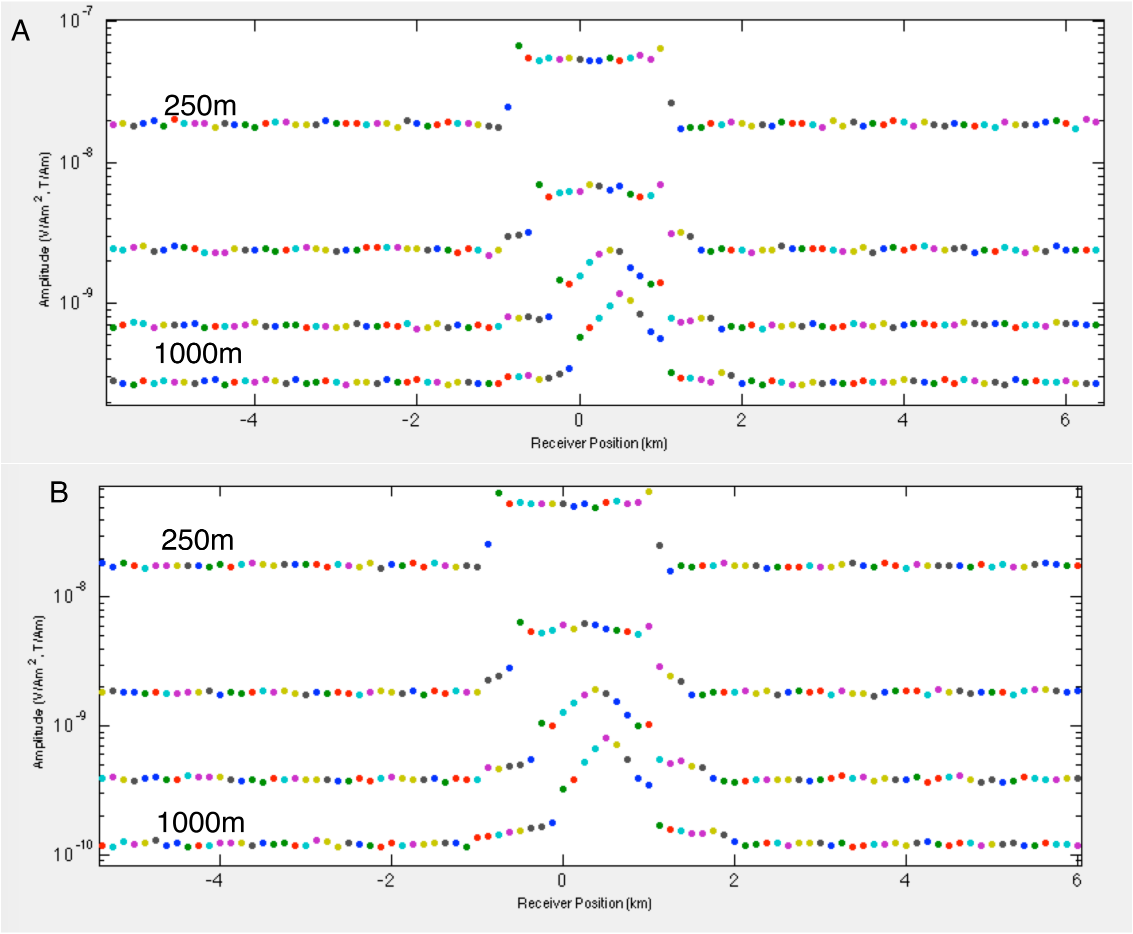


Figure 5. Raw amplitudes for dual resistor model. Section A is for .25Hz and section B is 2.25Hz. The distances are approximate Rx-Tx offsets.

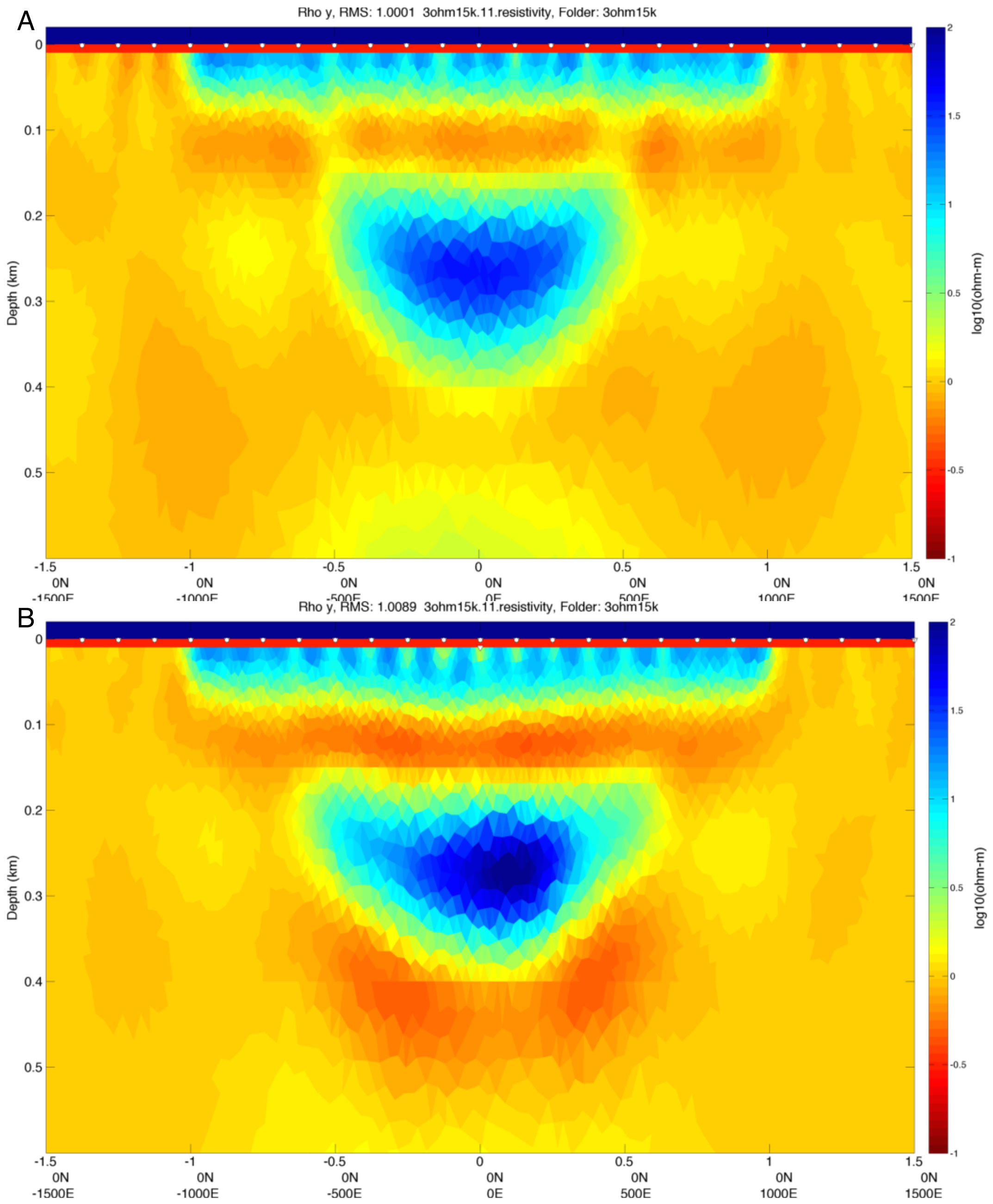


Figure 6. Inversion of towed data (A) and towed plus seafloor data (B). Converged to RMS of 1. The scalloping in the upper 10Ω resistor is an artifact of the transmitters and receivers spacing. Same scale is used for both inversion profiles.

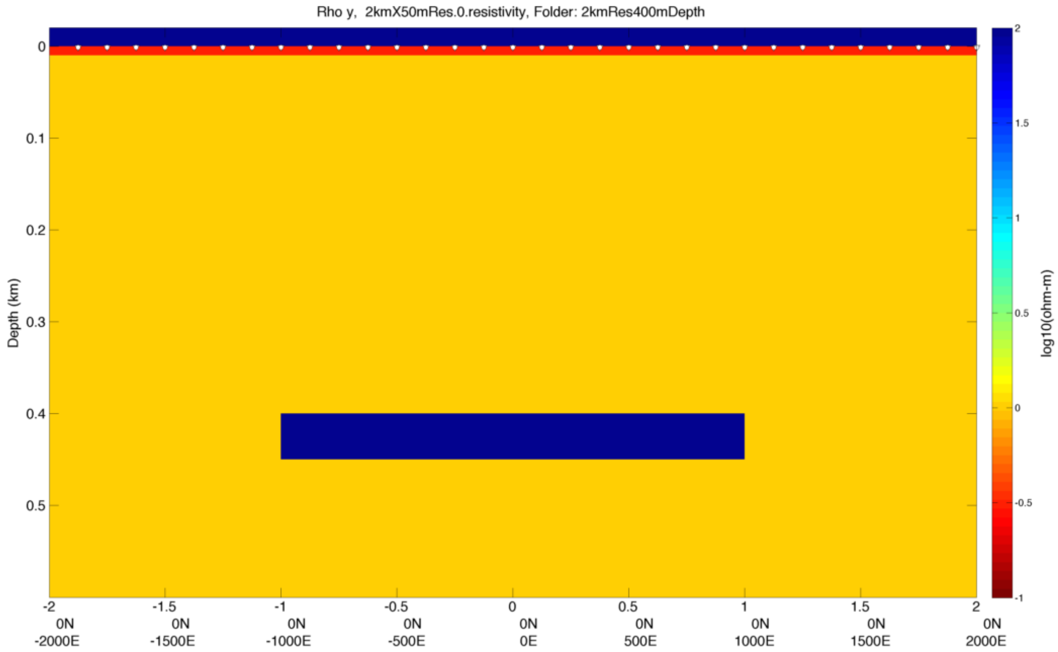


Figure 7. Model of the 400m deep reservoir in 10m of water. Created using the Mamba set of tools. The model reservoir is 50m thick. Log resistivity scale.

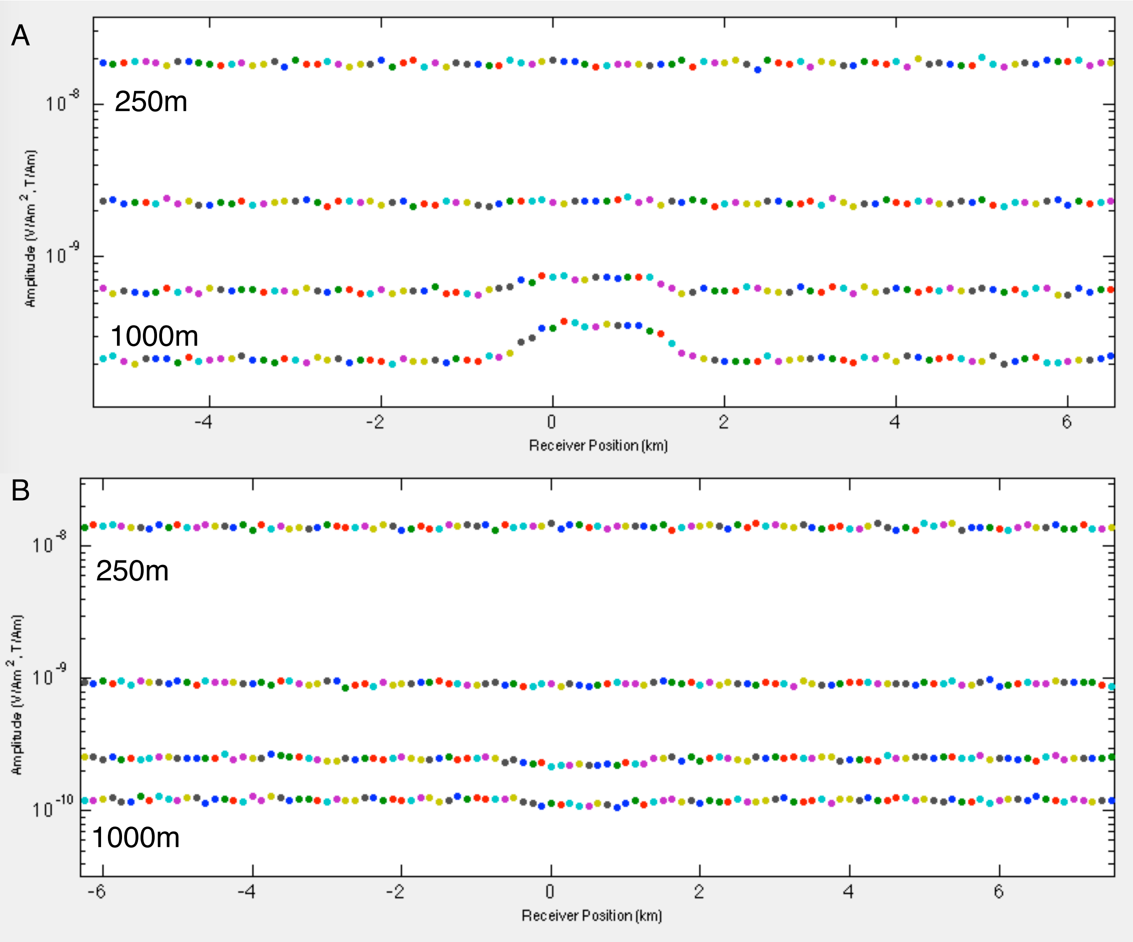


Figure 8. Raw amplitude data of the deep buried reservoir model for towed only data. Section A is .75Hz and Section B is 8.25Hz. Only at the lower frequencies and the longest offset is the restive feature visible in the amplitude data. The distances are approximate Rx-Tx offsets.

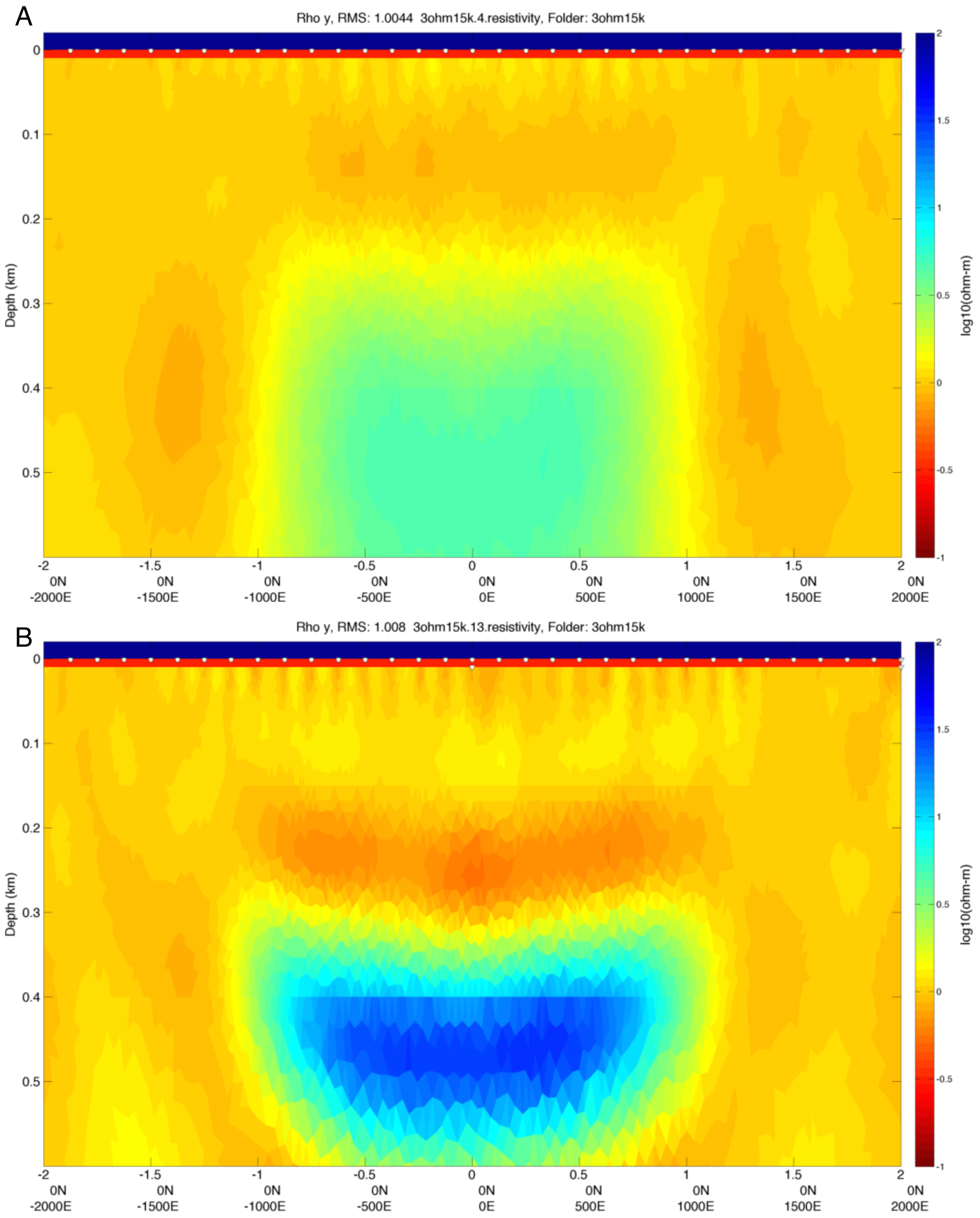


Figure 9. Inversion of towed data (A) and towed plus seafloor instruments (B) over the 400m deep reservoir. Only the longer offsets of the seafloor data are sensitive to the deep structure. Converged to a RMS of 1, log resistivity scale.

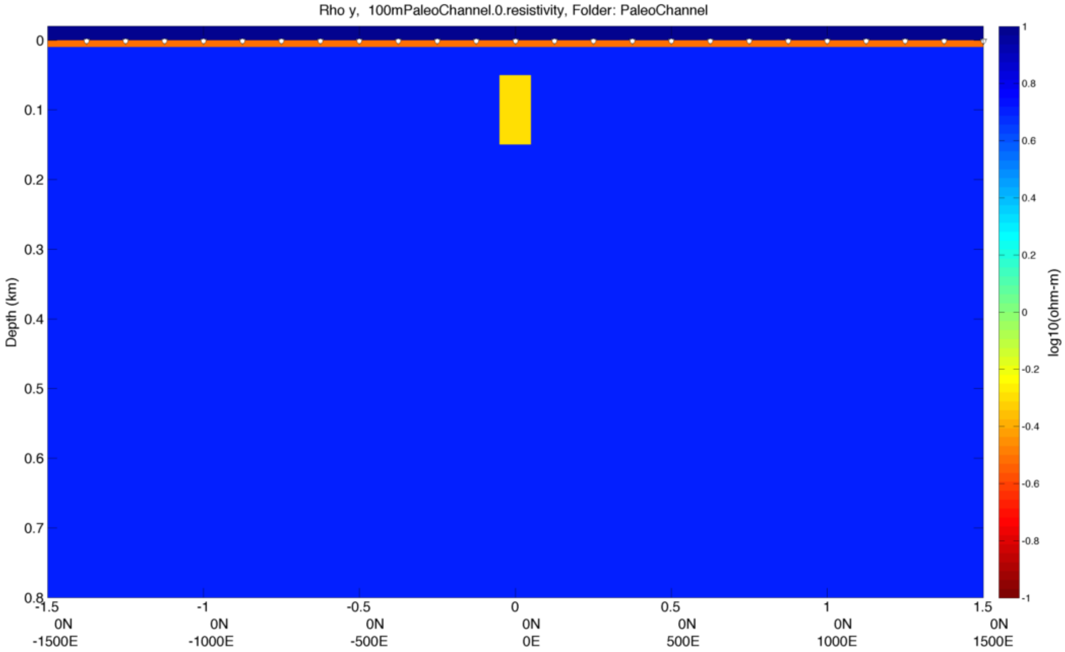


Figure 10. Model of buried conductor. 0.5Ω 100m x 100m conductor buried 50m in a 5Ω halfspace. Logarithmic resistivity scale used.

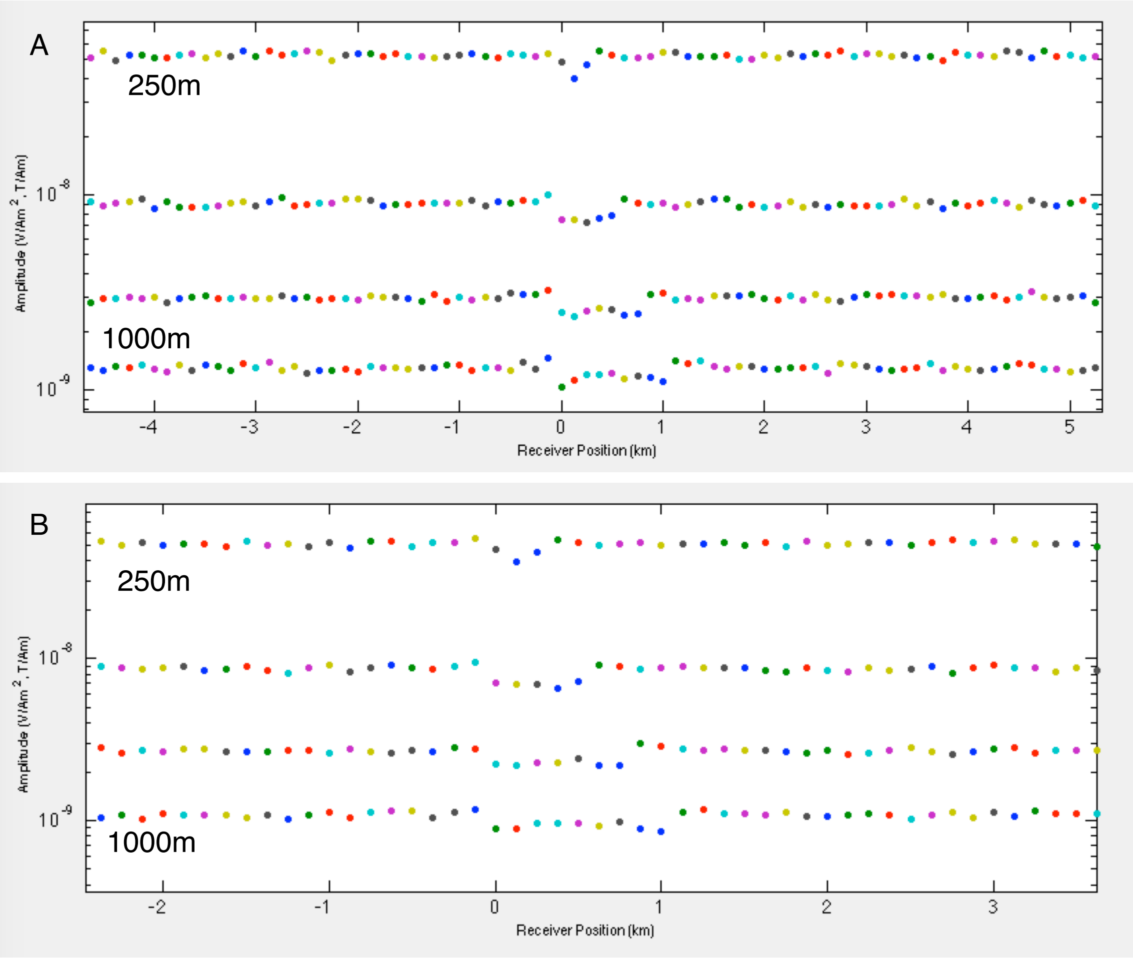


Figure 11. Raw amplitude data of the buried conductor model for towed only data. Section A is .75Hz and Section B is 2.25Hz. The distances are approximate Rx-Tx offsets.

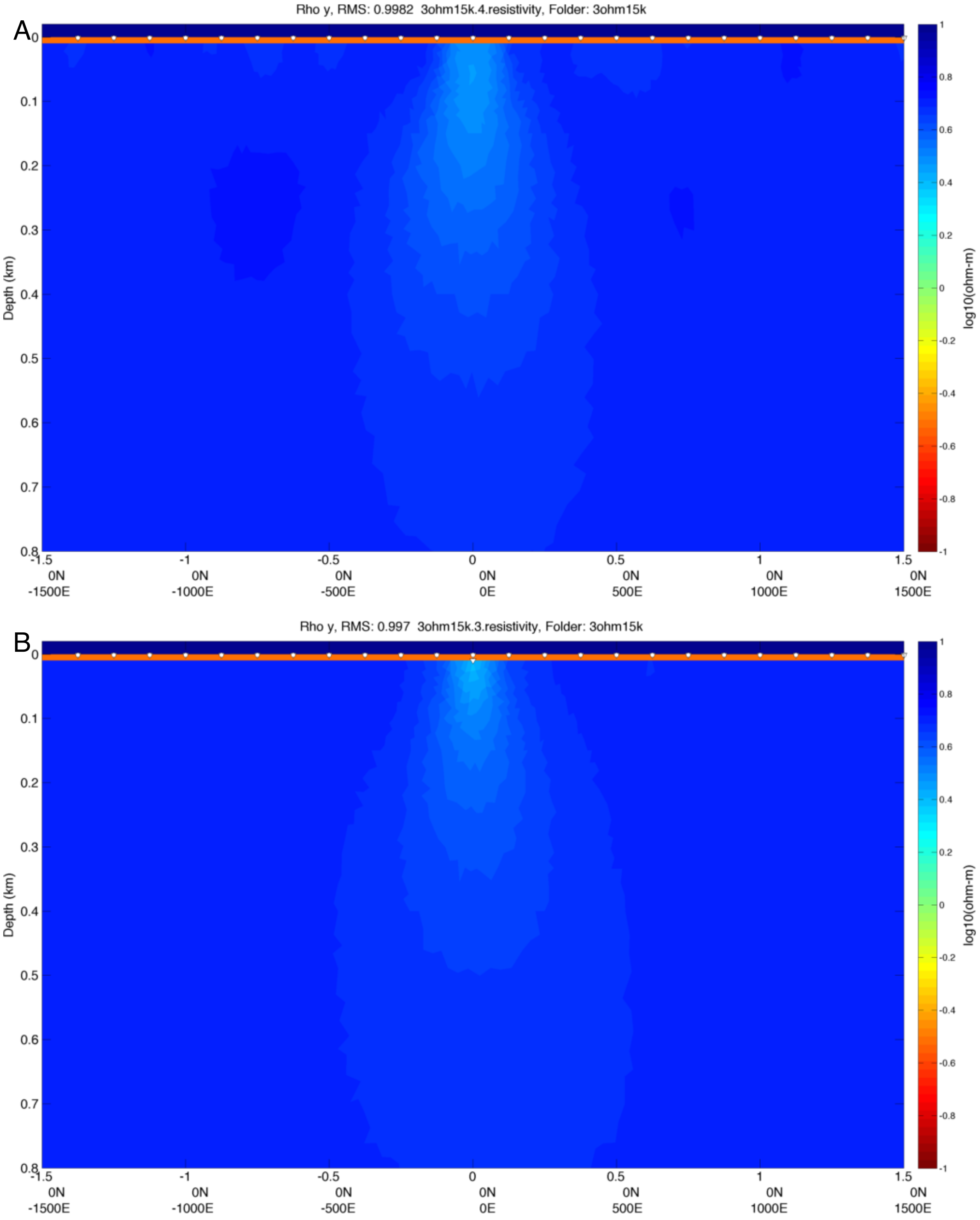


Figure 12. Inversion of towed (A) and seafloor plus towed (B) data over 100m x 100m buried conductor.

difficulty modeling the resistive features. The towed data starts to be sensitive in the longest offset, but is not enough to accurately image the structure alone. The survey with seafloor instruments and towed instruments had long enough offsets to image the 400m deep resistor.

2.4 Shallow Buried Conductor

This model (figures 9-11) is a square target 100m by 100m that is located 50m below the sea surface. The resistivity structure is 0.5Ω target in a 5Ω half space. A few geologic targets can be more conductive than the surrounding area such as more porous paleo channels, magma chambers, or metal ores. Typically CSEM methods have a more difficult time imaging conductive targets compared to the MT method. Both of the survey configurations had difficulty with constraining the structure, even though the structure is shallow.

2.5 Vertical Resistor

The vertical resistor model (figure 12-15) was considered after looking at the Miocene dike offshore SIO (Kennedy et al. 2008, Abbot. 1999). The 100Ω, 50m wide dike daylights at the seafloor and extends indefinitely to the bottom of the model. This could also be useful for modeling gas seeps or fluid flow along faults. This truly illustrates the depth limit of the towed only system, with four functioning Porpoise receivers of around 400m, and how the additional data from longer offsets of the seafloor receivers add a lot of value to the inversion result. The vertical resistor also illustrates the loss of resolution with depth, that is inherent to all CSEM soundings.

2.6 Discussion

Synthetic modeling studies show that the towed data alone can image down to ~400m using the towed only system, and the data density allows for the separation between resistors. Due to the nature of CSEM soundings, conductive targets are difficult to image with or without seafloor instruments, even when the target is shallow. Typically the seafloor instruments allow a deeper depth of investigation and clean up deeper structure, but for shallow resistive targets the added time of a survey with seafloor deployment might not be necessary. The Scripps Porpoise system is a viable economical option for mapping near surface geological features in the transition zone, where seismic acquisition is difficult.

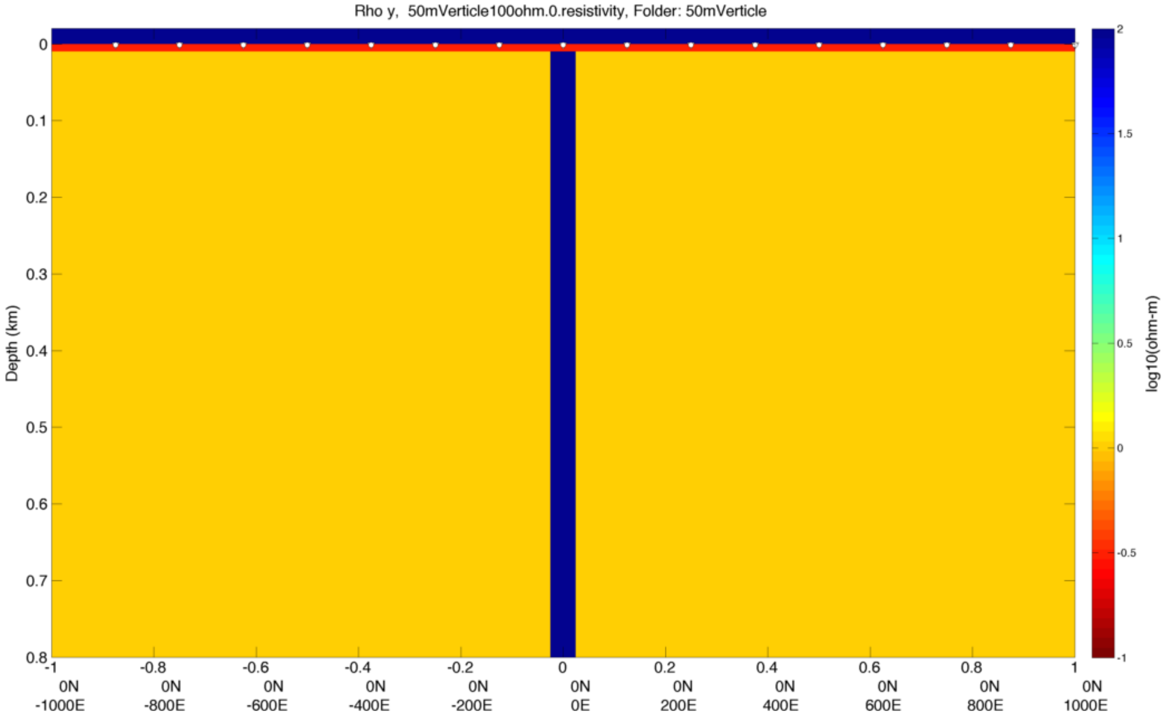


Figure 13. Vertical resistor Model. 100Ω 50m wide resistor in a 1Ω halfspace that extends indefinitely to the bottom of the model. logarithmic resistivity scale used.

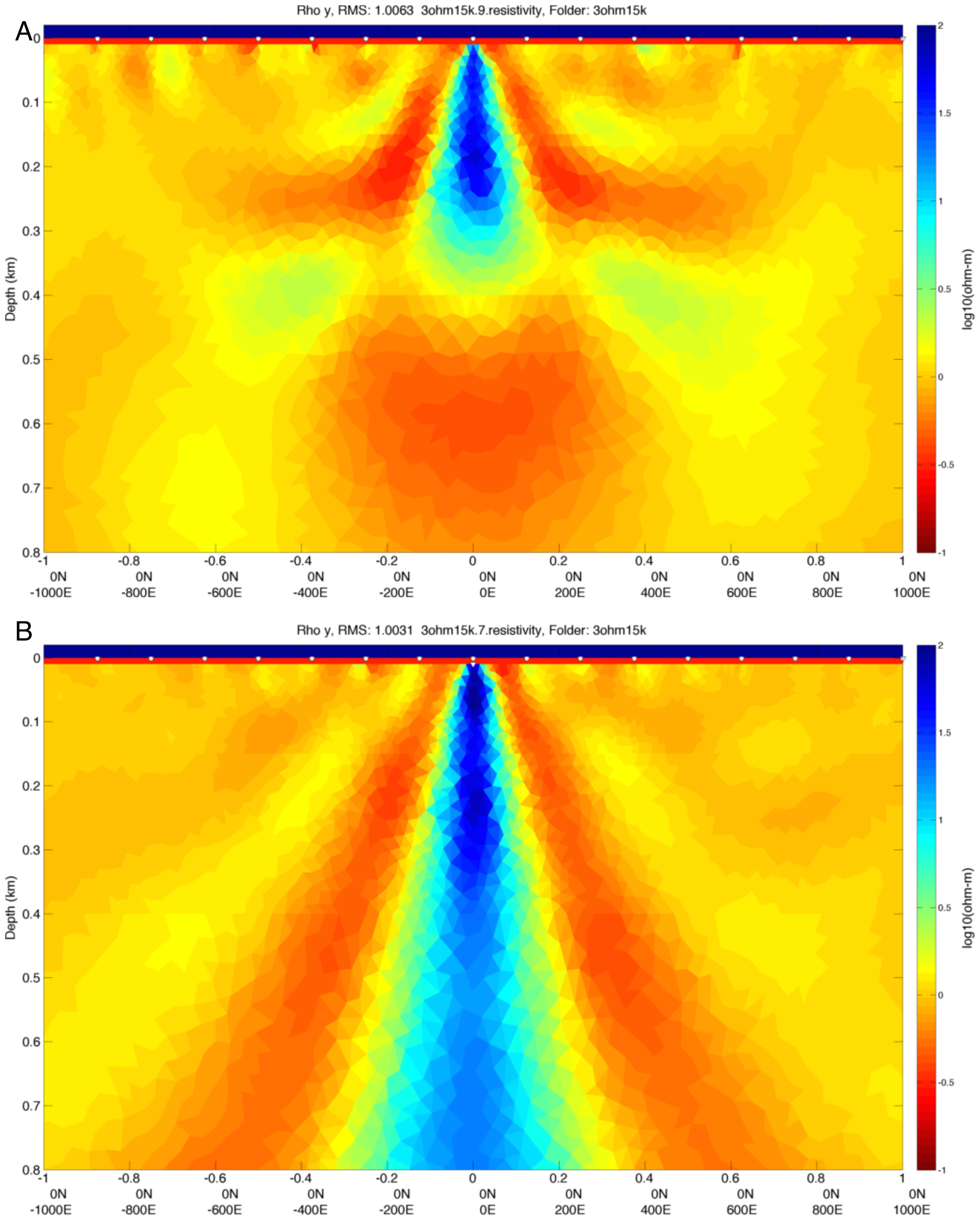


Figure 14. Inversion of the towed data (A) and towed and seafloor data (B) over the vertical resistor. The sensitivity to the vertical resistor with the towed data stops around ~400m which agrees with the deep buried reservoir model.

Chapter 3

Torrey Pines and Del Mar Case Study

3.1 Overview of Survey

The survey took place on May 14th, 2014. This was initially designed as an engineering test to use the Porpoise system in the Arctic to map methane hydrate, with a secondary thought to the geology. The vessel used was the M/V Outer Limits, a 65' ship that harbors in San Diego, CA. Both survey lines were collected in one field day.

3.2 Torrey Pines and Del Mar Geology

Coastal geology in the Del Mar region of northern San Diego County is comprised of marine derived sediments that span from near shore and subaerial fluvial sediments to deep-water marine shales. The cliffs north of Scripps Institution of Oceanography (SIO) are natural laboratories for studying sedimentary processes, (Posamentier and Weimer 1993) and are very similar to the processes and sedimentary packages that are offshore today. The shallow inner shelf of the survey area is fault controlled to the west by the Rose Canyon-Newport Inglewood fault system. Faulting plays a major role in sedimentation and accommodation on Holocene and younger sediments (Hogarth et al. 2007, Le Dantec et al. 2010) above Eocene formations. There is a time unconformity of ~30MYA from the Eocene packages below the transgressive surface (Hogarth et al. 2007) that differ in porosity and composition than the more

Figure 15. Overview of survey area. Yellow line is approximate survey line. Survey is offshore of Del Mar, California in northern San Diego Country.

Figure 16. Sandstone (Modern) infill into Eocene formation with a fault on the southern end. Picture taken on San Diego route 21 in Torrey Pines State Natural Reserve. As interpreted in Abbot 1999.

modern holocene and pleistocene sedimentation. A short description of both sedimentary sequences are provided below.

Holocene to Pleistocene sedimentary infill that is onshore is dark brown-red in color with varying clast size from football sized clasts to medium sands. The formation is poorly sorted, brown to red shallow marine/inshore deposits of siltstone, sandstone and cobbles. This modern infill is described by Kennedy (2008) as Moderately permeable. Modern beach sand in San Onofre (45km north of Del Mar) has porosity as high as 57% (Atkins and McBride, 1992). This value will provide a maximum porosity for future modeling.

The Eocene sedimentary formations range from a deep-water anoxic grey-green shale to gold-yellow mid shelf sandstones. Previous analysis puts the range of porosity in these Eocene formations from twenty to thirty-five percent, with the Ardath shale (middle Eocene) being the least porous (Strigt et al. 2014).

The processes that made the cliffs at Blacks Beach (~ 3 km south of Torrey Pines State Natural Reserve (TPSNR)) was formed by multiple offshore channel cut and infill events. This geologic process that existed in the Eocene could exist today in the survey area. Offshore of Los Penasquitos Creek and the San Dieguito River are previously mapped paleochannels (figure 15) (Darigo and Osborne 1986) identified with seismic data. (Kennedy and Moore 1971)

The geologic record that is preserved and exposed in the cliffs of the survey area, and previous work offshore offers a guide to possible structures in the offshore survey area. Since we do not have access to reflection seismic data from the survey area, the nearby inshore geology and composition aids in final interpretation and

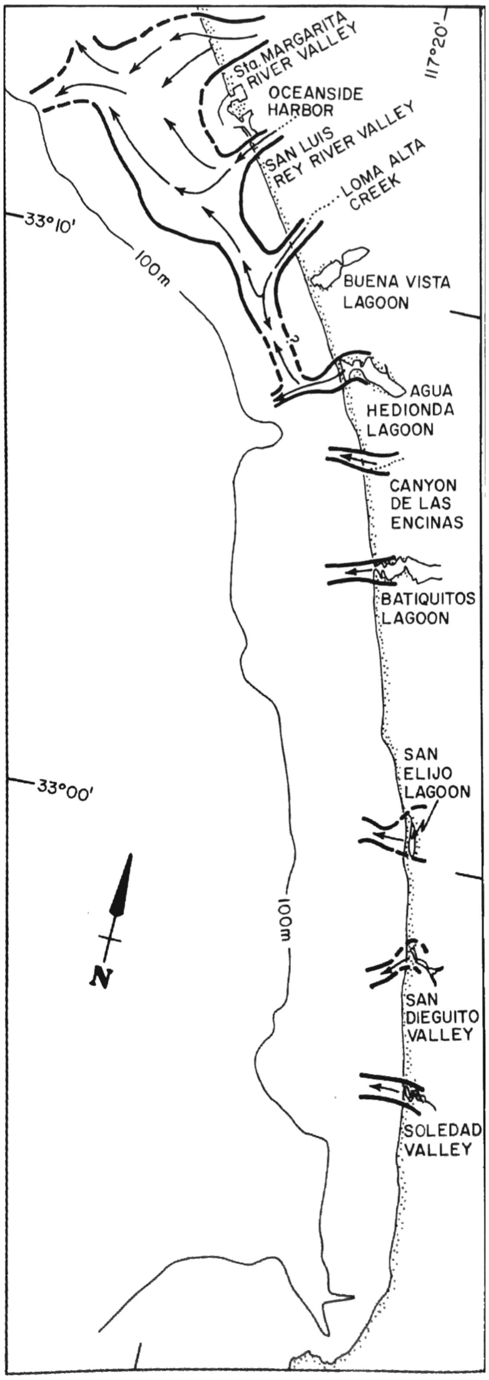


Figure 17. Figure modified from Dario and Osborne (1986). Dashed lines are inferred and solid lines are mapped Paleo Channels from reflection seismic data. The survey covers the San Dieguito Valley and Soledad Valley paleo channels No access to the seismic data is available at this time. No scale implied.

conclusions. Knowledge of nearby porosities, constrained by coring data is helpful to ground truth the interpretations. Onshore in TPSNR previous work has found the porosities range from 20-35% (Stright et al. 2014). The packages measured at TPSNR are indicative of the geology mapped offshore and below the transgressive surface (Kennedy et al. 2008, Hogarth et al. 2007). Measured Offshore San Onofre the Holocene beach sand has porosities ranging from 47-57% (Atkins and McBride 1992). This will provide a guide for the porosity section (figure 21).

3.3 Raw Amplitude Data

During data acquisition both amplitude and phase were collected, with a fundamental frequency of 0.5Hz. Due to an uncertain timing error, the phase was off up to 3-4 degrees and therefore was not used for inversions. The waveform and data processing of the towed CSEM data adhered to standard procedures (Myer et al. 2011). Before modeling the data, it is important to examine its variations and to identify errant data points. It was quickly apparent that the longest Rx-Tx offset had excessive noise due to unconstrained receiver movement in the waves, and from possible kelp snags. For future work, a larger tail drogue or drag weight behind this last receiver should help reduce this source of noise.

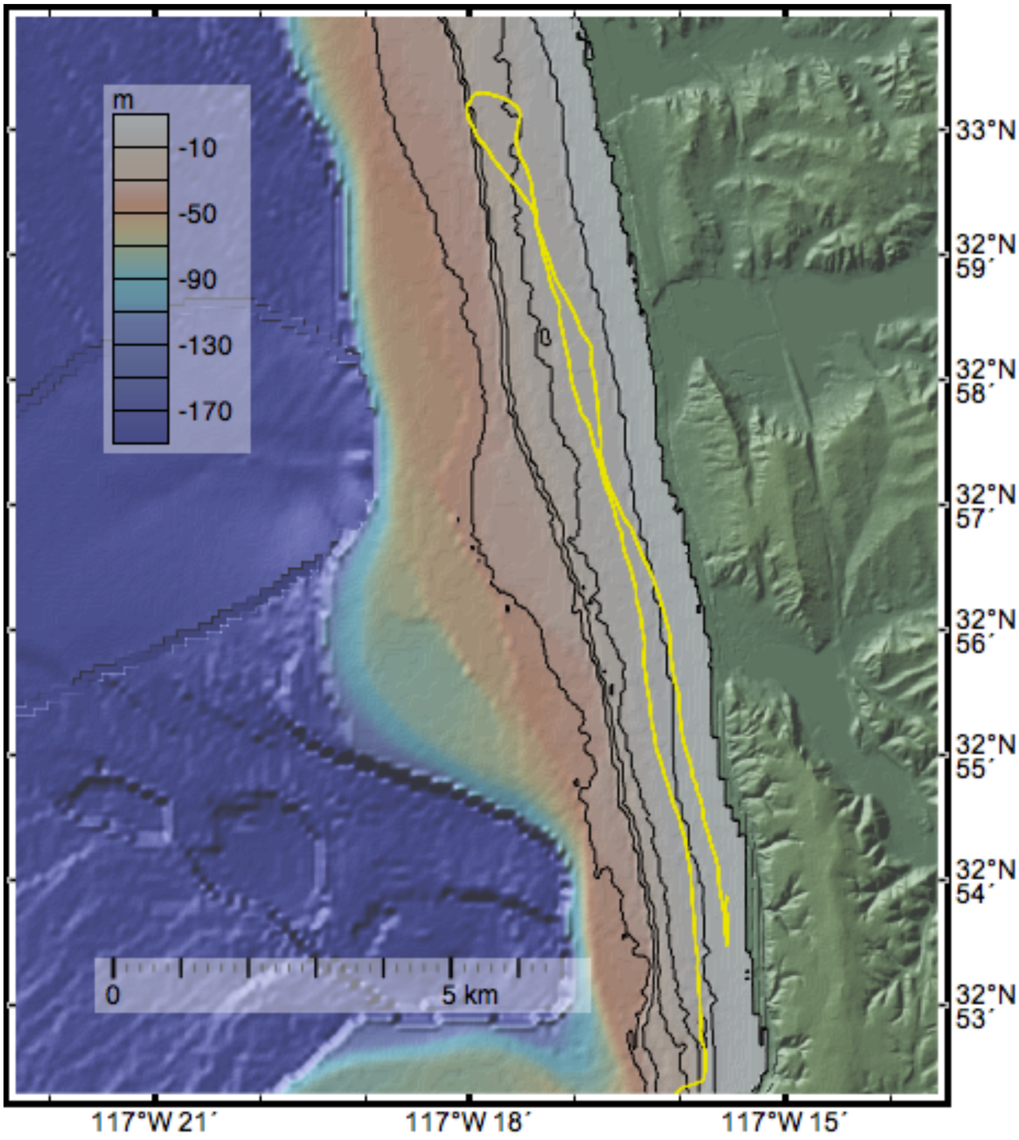


Figure 18. Survey track line and overview of survey area. Bathymetry in the survey area ranges from 5 to 20 meters. Base map by Ryan et al. (2009) and created with GeoMapApp (http://www.geomapapp.org/), an open source mapping tool.

3.4 Inversion Parameters

When using MARE2DEM or any inversion algorithm there are many options in the parameterization and model set up. Based on the observed data scatter a relative noise floor of 5% was used. Rx-Tx reciprocity was not used, because with towed data it is not advantageous for processing. With the 60 second stack of the waveform and acquisition speed of 2-4 knots, this translates into a discrete transmitter and receiver about every ~100m.

Five frequencies were used for both lines one and two; 1.5, 3.5, 6.5, 11.5 and 18.5Hz. 18.5 Hz data from the third porpoise was also omitted due to high noise.

The inversion mesh uses a quadrilateral mesh instead of a triangular mesh used in the synthetic modeling studies, but this does not have a large effect on final output as MARE2DEM is a finite element code and uses a conforming mesh.

3.5 Resistivity Inversion Profiles

Figures 16 and 17 and line 1 and 2 of the survey area as modeled using MARE2DEM. MARE2DEM is an iterative inversion algorithm that took about 1500 core hours on the Triton Shared Computing Cluster (http://idi.ucsd.edu/computing/) using approximately 160 Intel Xeon processors and 10 iterations to stop on normal convergence. A logarithmic resistivity scale is used for both figures. Both of these inversions stopped on normal convergence at a RMS of 1.

3.6 Porosity Profile

Using a modified Archie's Law (e.g., Constable et al. 2009) a 2D porosity plot (figure 18) can be generated by setting the cementation exponent to two and using a local geothermal gradient (Constable et al. 2009).

3.7 Reflection Seismic Data

Seismic data of various vintages and types is available in the region. Inshore CHIRP data overlaps with the southernmost end of the survey lines. CHIRP is a shallow, frequency modulated zero offset acoustic geophysical tool that can image in typical sediments offshore of San Diego to ~50m. This data was collected in the early 2000's with a custom system made for the Driscoll Lab (http://neotectonics.ucsd.edu/) by Edgetech (http://www.edgetech.com/).

Further offshore vintage multi-channel seismic data was collected in 1977 by Chevron for hydrocarbon exploration but this data does not overlap with the EM survey lines. The data showed horizontal sedimentary sequences with minimal deformation on the shelf, and no indicators for gas. (Geopentech et al. 2013)

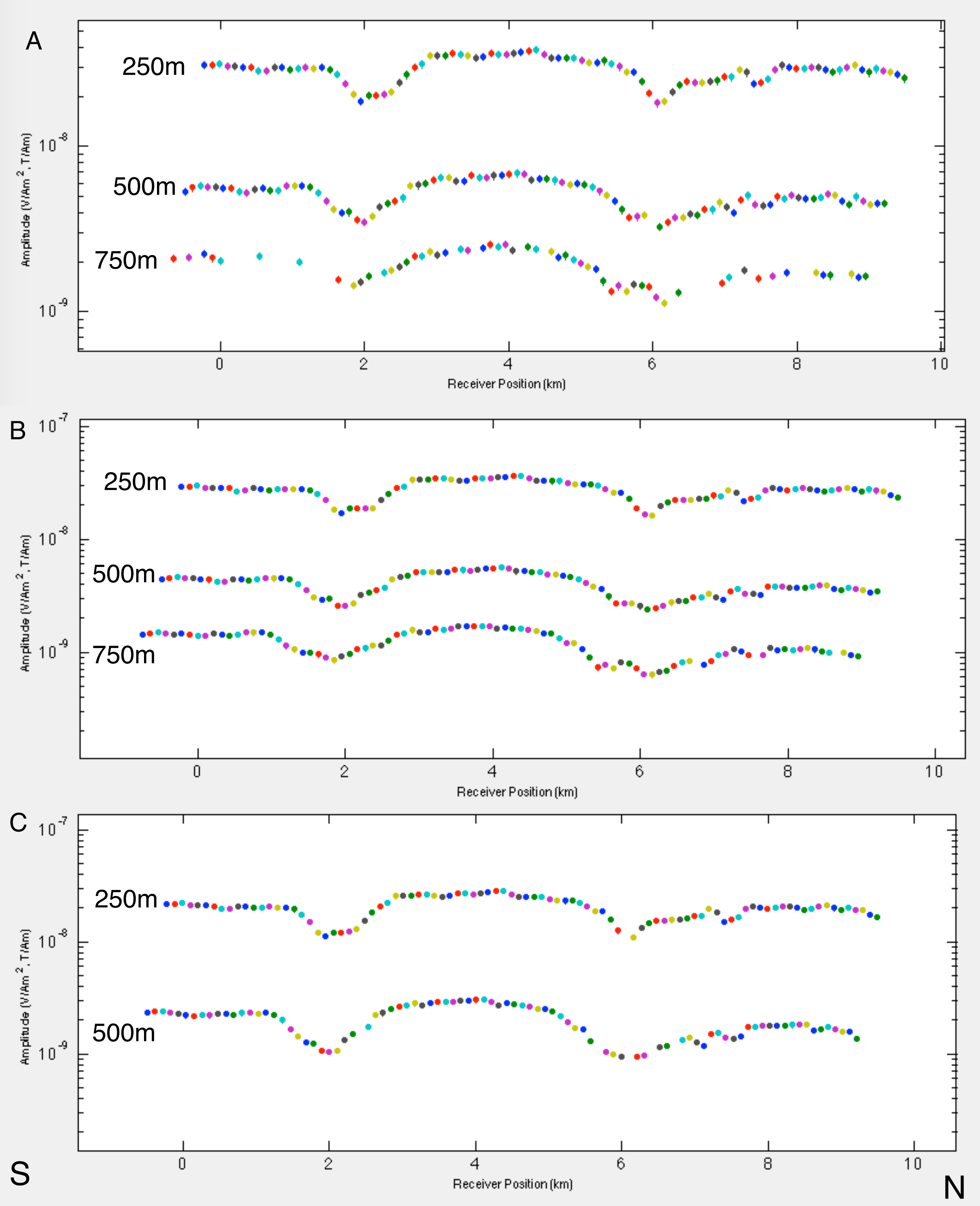


Figure 19. Raw amplitude data from line 1 of the survey. Section A is 1.5Hz, B 6.5 Hz and C is 18Hz. The distance labels are approximate Rx-Tx offsets

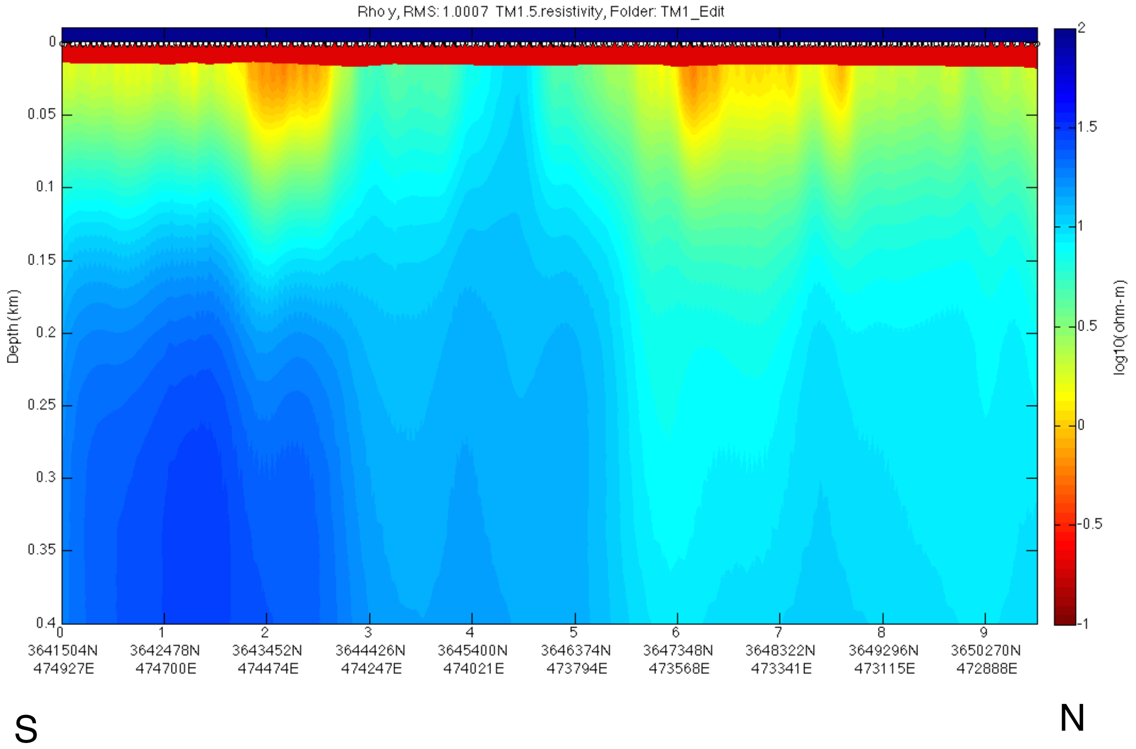


Figure 20. MARE2DEM Inversion of survey line one. Log resistivity scale, maximum depth of 400m.

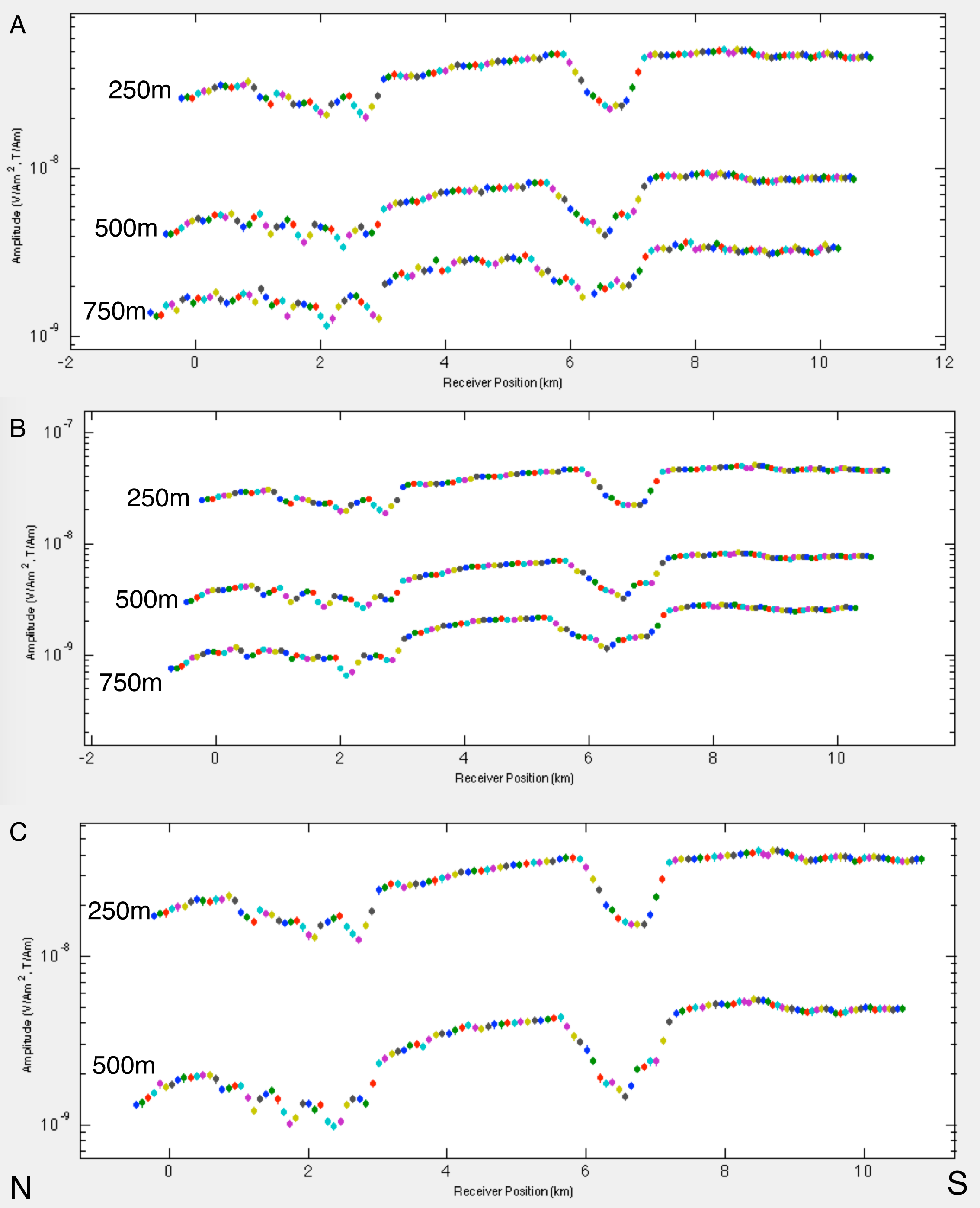


Figure 21. Raw amplitude data from line two of the survey. Section A is 1.5Hz, B 6.5 Hz and C is 18Hz. The distances are approximate Rx-Tx offsets

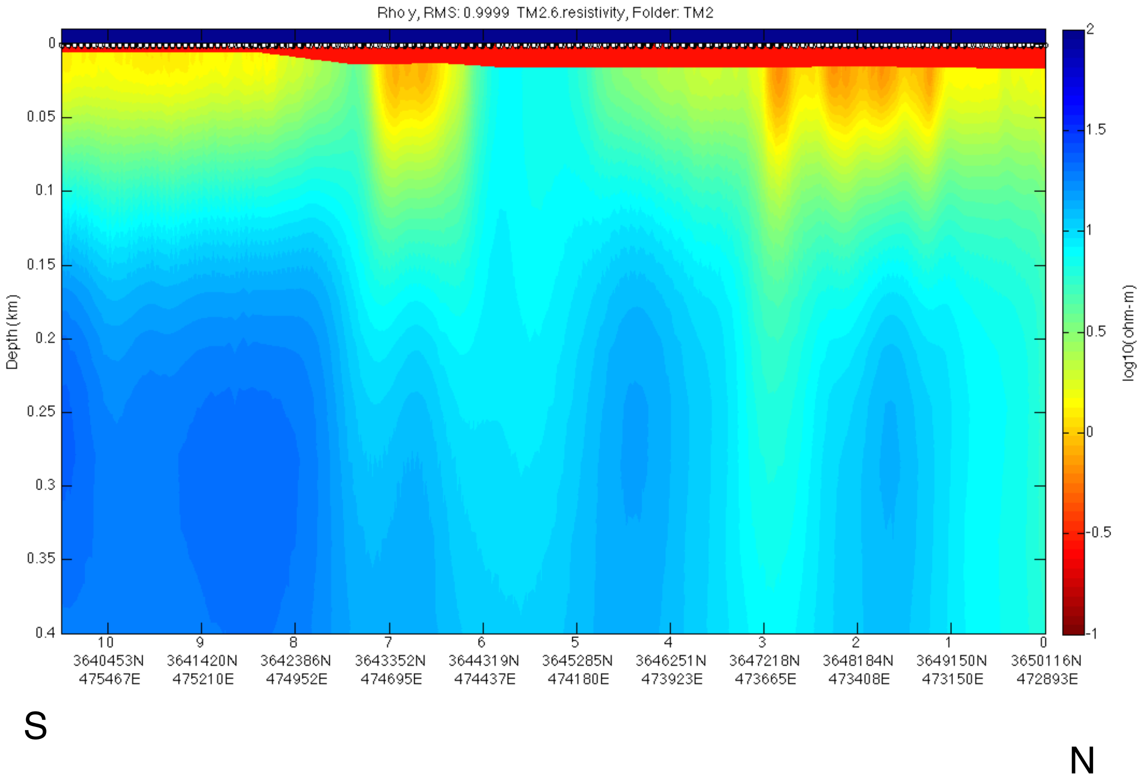


Figure 22. MARE2DEM Inversion of survey line 2. Log resistivity scale, maximum depth of 400m.

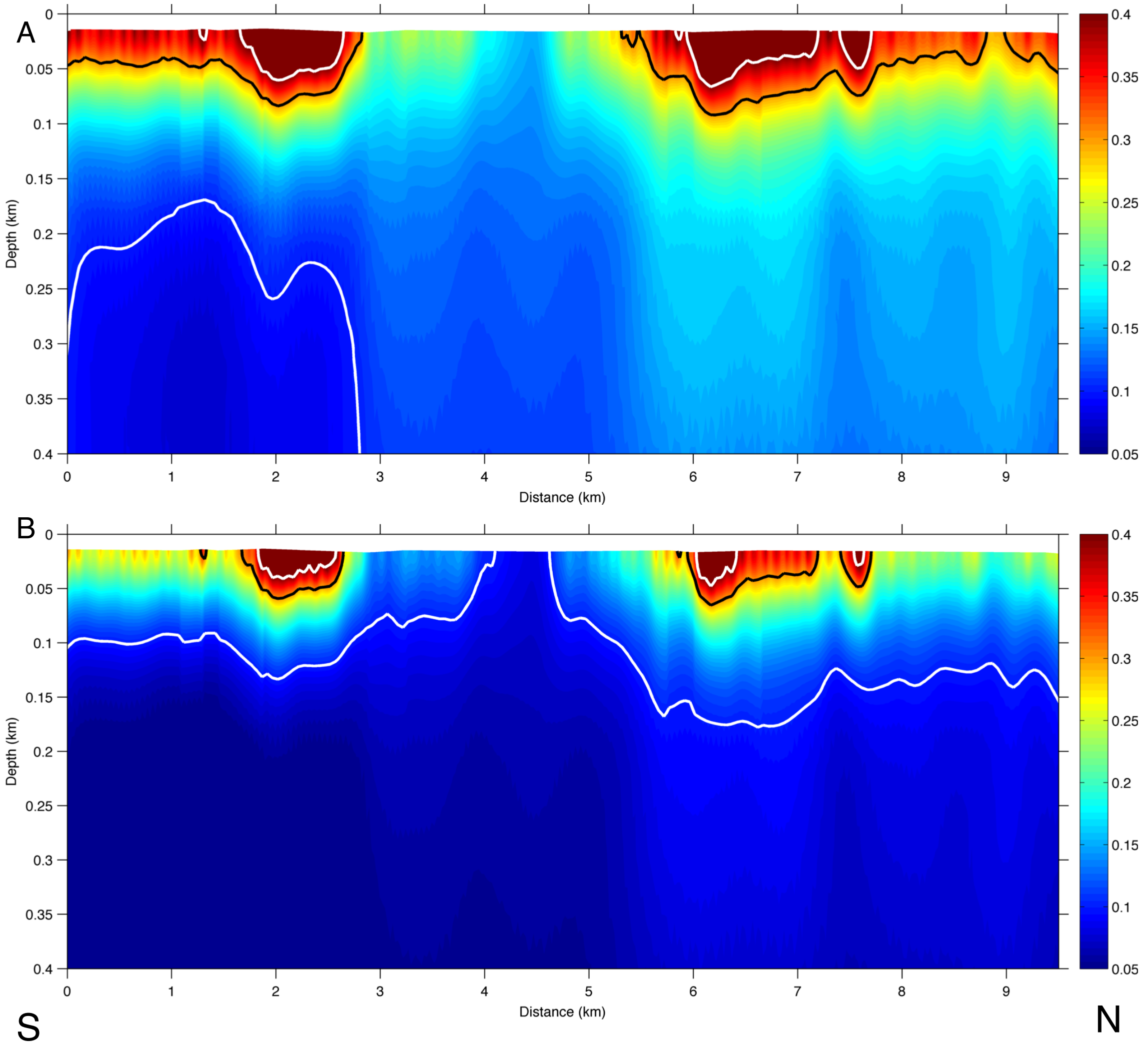
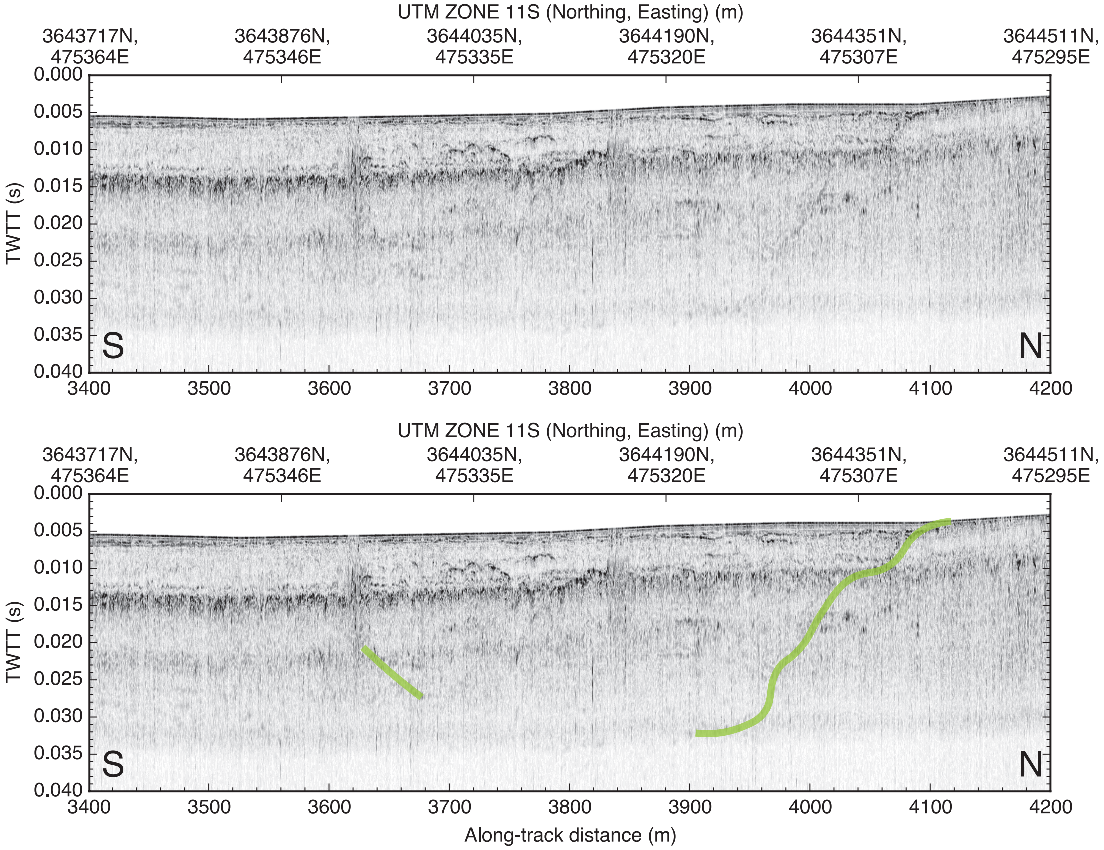


Figure 23. 2D Porosity plot as calculated using modified Archie's Law (Constable et al. 1999). The contour lines are for 10%, 30% and 40%. The 40% contour is a minimum porosity. Higher porosity could exist in the Paleo Channel areas, but a direct measurement would be better to make specific interpretations. Section A has a m exponent of 2, and section B has an exponent of 1.5 of Archies law as described in equation 1.



La Jolla, CHIRP, Line2b, R/V Saikon 2002 (VE = 26.6x)

Figure 24. CHIRP reflection seismic data processed by James J Holmes (SIO), collected by the Neal Driscoll Lab at SIO (http://neotectonics.ucsd.edu/). Upper section is the processed section, bottom section is the interpreted section. Depth scale in two way travel time, using a velocity model of 1500m/s for sea water, a TWT of 0.040 is roughly ~30 meters.

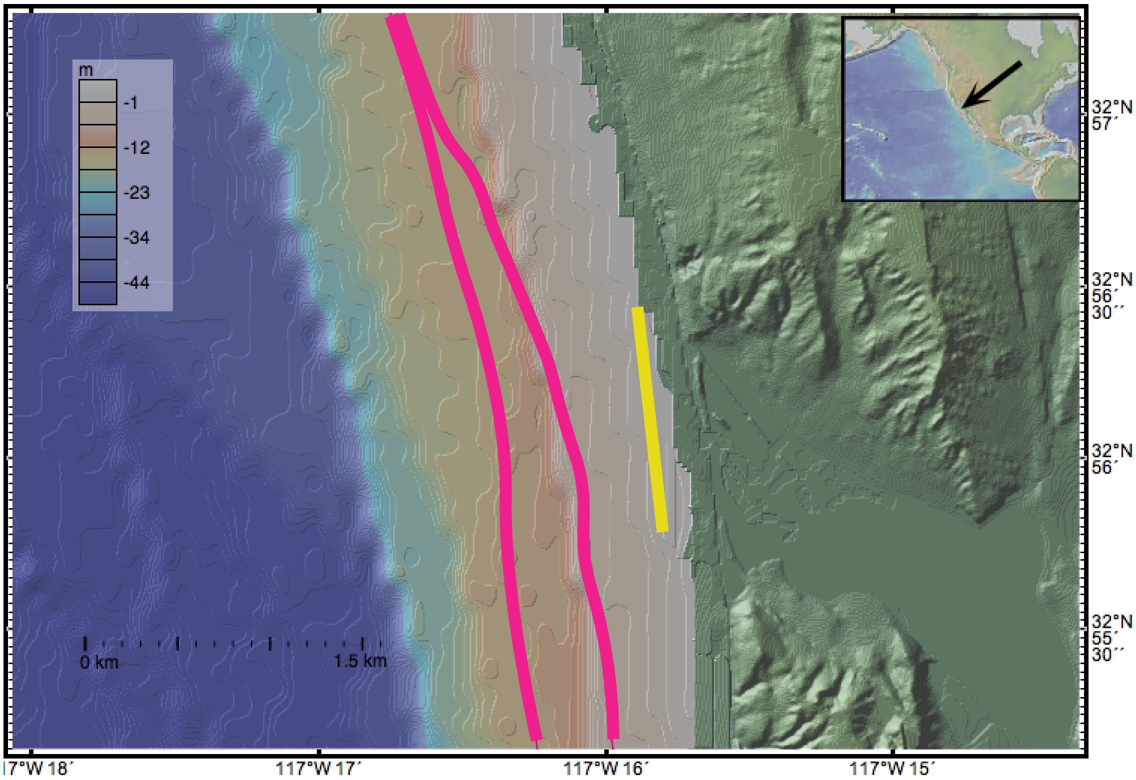


Figure 25. Close up of location of CHIRP seismic data (yellow) compared to Line 1 and Line 2 Porpoise EM data (pink). Base map by Ryan et al. (2009) and created with GeoMapApp (http://www.geomapapp.org/), an open source mapping tool.

CHIRP seismic data acquisition is similar to towed EM, but being a zero offset system it fits into one housing that is portable via a flatbed truck. With its limited depth of imaging, it is still an important geophysical tool as its high resolution lends itself to seismic stratigraphy, near shore and freshwater surveys. The survey in question was the primary source in quantifying the amount of modern sand above the Eocene formations and the transgressive surface.

Seismic acquisition in the shallow marine environment is one of the most challenging areas to acquire data. A lot of the noise sources for shallow water EM acquisition (waves, roll and pitch, wind) also affect seismic acquisition. One issue that affects seismic data alone is getting an appropriately sized acoustic source. The sub bottom profiler systems (CHRIP, 3.5Hz shipboard systems) have a maximum depth in San Diego sands of ~60m (Ellett and Henkart 2013). Other shallow water seismic acquisition systems like Boomer and Sparker systems have deeper depth penetration, but due to excessive “ringing” or energy in shallow water columns, data interpretation in shallower water depths than 20m is difficult at best. Boomer systems on the shelf in Northern San Diego County have maximum depth penetration of ~300m.

3.8 Interpretation

The higher porosity of near surface geology just offshore of two modern day river systems is interpreted to be younger infill of an excavated channel system, with minimum porosity of 40%. Without sediment cores it is impossible to date the timing of the infill. In between these two channel features is exposed Eocene formations or thin modern sediment cover over Eocene formations which coincides with locally well-known 4th and 15th Street reef breaks in Del Mar. The mapped fault onshore in Del Mar (Kennedy et al. 2008) could be a reason for the lateral resistivity change at 200m depth below the sea surface. The deeper Eocene geology ranges from deepwater shales to mid shelf sands and the range of resistivity and porosity agrees with previous work onshore.

One initial survey target was possible groundwater transport into the offshore (Evans et al. 2000), but nothing in the resistivity section lends itself to this interpretation. Fresh water itself is more resistive, not conductive (Constable et al. 2009). The steam flow in Penasquitos Canyon averages 1-4 cubic feet per second as San Diego is a fairly arid region and has been in drought conditions the past few years, so a large freshwater discharge is not expected.

3.9 Conclusion

The Porpoise towed system is a capable and efficient method of mapping sub surface resistivity in the near shore. Being limited only by the tow ship's draft, towed EM data can provide significant hyrogeologic information, with or without seismic data in shallow waters. With its data dense acquisition it is possible to interpret two paleochannel systems offshore Del Mar, California and porous sediment cover on the inner shelf with a possible fault that extends offshore. Future work for using this system for mapping geology in Southern San Diego County and offshore New Jersey is in its early planning stages and will provide greater understanding of the sub surface porosity structure, and the limitations of the method.

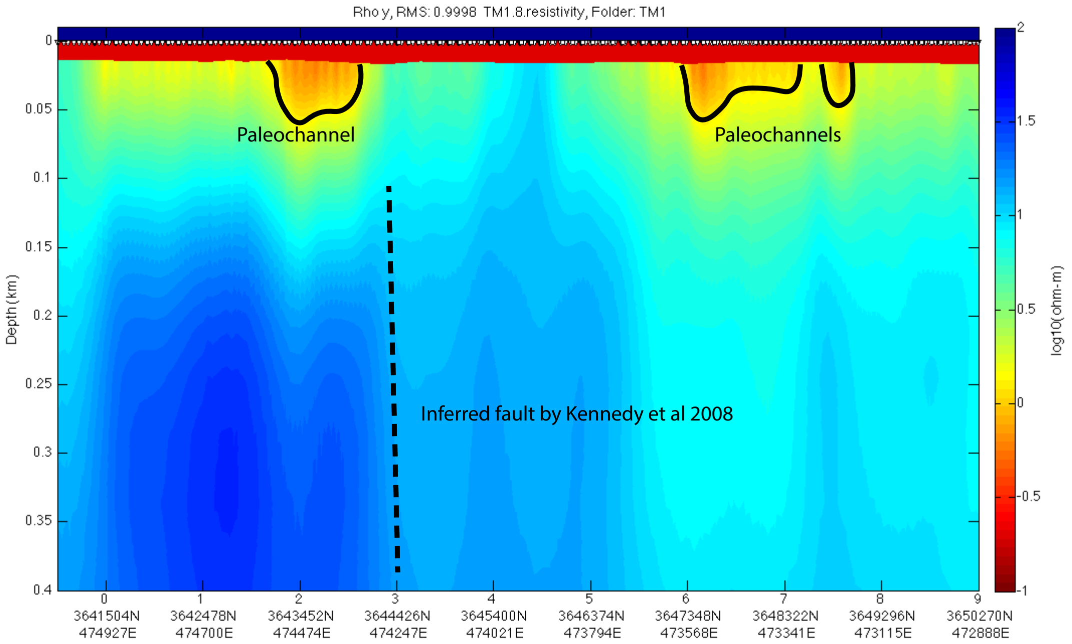


Figure 26. Interpretations on top of line one resistivity section. The mapped Paleo Channels are not necessarily true to depth, but true to horizontal location

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