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The Marine CSEM and Seismic Methods: An Integrated Approach to Derisking a Frontal Toe Thrust Exploration Prospect Offshore West Africa.

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--***ABSTRACT***---

Marine Controlled Source Electromagnetic (CSEM) data was acquired in a Frontal Toe Thrust Belt offshore Niger Delta over a prospective area delineated by 3D Seismic anomalies. The CSEM survey consisted of three towlines totalling 94.5Km with 28 receiver points. An integrated analysis of the Electromagnetic and Seismic data was carried out to evaluate the hydrocarbon potential of four prospects in the study area. Regional and Prospect scale Seismo-stratigraphic interpretation of reservoir tops within the anomaly complex was carried out using the 3D seismic data and provided appropriate input surfaces for subsequent 2.5D constrained CSEM inversion. Normalized Magnitude Versus Offset (MVO) and Phase versus Offset (PVO) were calculated at all offsets to generate anomalies at the corresponding source-receiver mid points. Frequency and Resistivity windows for the Forward calculation ranges from 0.25–0.05Hz and 2.2-100 Ohm-m respectively. A progressive complexity modeling approach was adopted for both the Forward modelling and inversion of the CSEM data. Integrated analysis of resulting models showed that the most promising prospects with high anomalous resistivity values (100 Ohm-m) indicative of hydrocarbon presence were not consistent with the prospects having high seismic anomalies. However, convergence of both the seismic and CSEM anomalies was observed in an area South East of the study area with potential for possible hydrocarbon presence.

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I. INTRODUCTION

Geophysical methods provide unique opportunities to the scientific community to carry out a study of the subsurface remotely by exploring its physical properties down to great depth that is too expensive to drill. The physical properties are thereafter interpreted in relation to the geology of the subsurface, which may be ambiguous given that certain geological formations have similar physical properties. Consequently, it becomes very beneficial to combine different geophysical methods with focus on their different physical parameters in order to gather unambiguous geological information. This study combines marine Controlled Source Electromagnetic (CSEM) and reflection seismic data to study the hydrocarbon potential of some complex toe thrust prospects offshore Niger delta Basin. Nearby borehole data provided opportunity for calibration of both the CSEM and Seismic models.

The CSEM and Seismic data are sensitive to different physical parameters and can complement each other in interpretation of subsurface geology.

For example, analysis of global well failure statistics showed the limitation of relying on seismic methods alone for well drilling decisions.

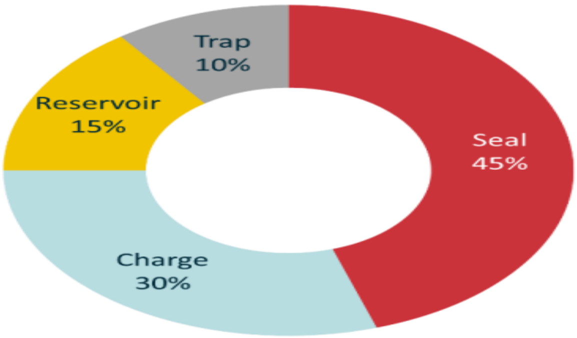


Figure 1.1: Global Well Failure Statistics (Source: Super Major)

The inability of the seismic method to reduce Seal and Charge risks was highlighted and reinforces the need for a complimentary method that can help in closing the gap.

The CSEM method, in comparison, is more sensitive to bulk volume changes in resistivity, and different levels of pore space occupation with resistive material are differentiable (Constable, 2010;Aigbedion and Okougbue, 2023). Consequently, combination of CSEM and Seismic techniques reduces ambiguities in the interpretation of features than from an individual analysis alone.

The Seismic Technique

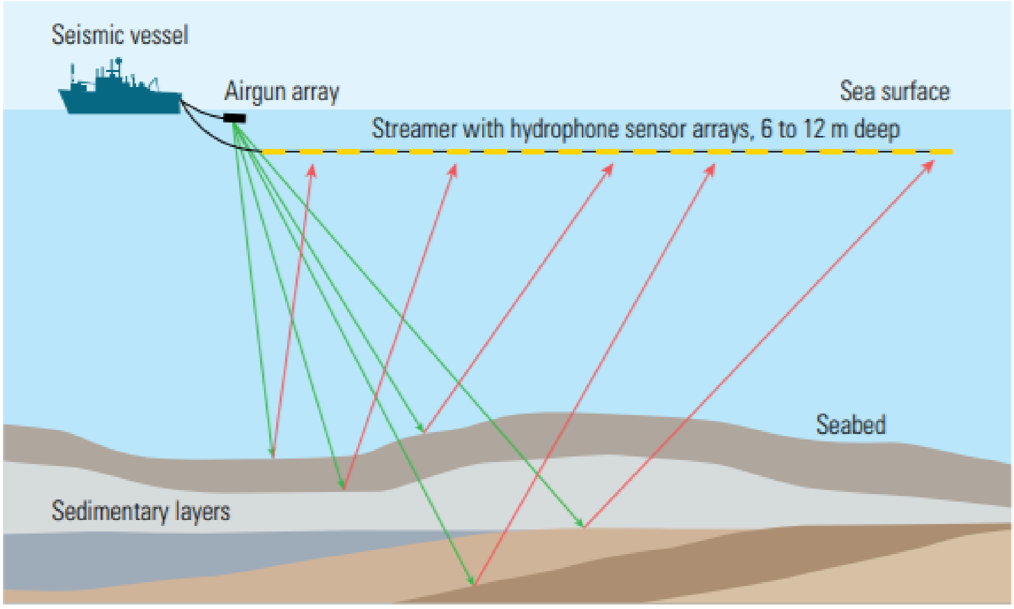


Figure 1.2: A typical Marine seismic data acquisition showing an airgun array

The seismic technique has long held prominence in hydrocarbon exploration, reservoir properties description as well as in production monitoring. The seismic art was well entrenched, and nobody expected it to be otherwise. Advances in seismic imaging techniques have made it possible to X-ray complex subsurface formation geometries.

The Marine CSEM Method

The marine controlled-source electromagnetic (CSEM) method has, in the last two decades, proven successful in hydrocarbon exploration (Ellingsrud et al., 2002; Constable, 2010; Constable and Weiss, 2006).

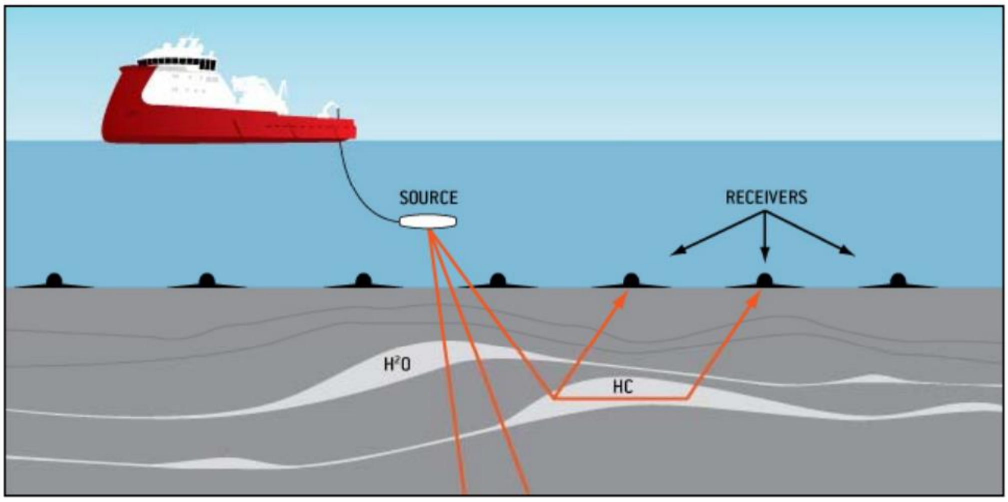


Figure 1.3: A typical Marine CSEM Acquisition Array

The marine CSEM method (fig 1.3), loosely analogous to seismic method in terms of theory and acquisition; uses electromagnetic rather than acoustic energy and an array of sea floor receivers instead of streamers, is based on the study of the propagation of low frequency electromagnetic fields in the earth. The electromagnetic fields are useful in geophysics since they interact with the medium in which they propagate, by inducing currents that propagate through the media. From this interaction it is in principle possible to measure certain physical properties of rocks, such as the electric permittivity(ε), magnetic permeability (μ) and the electric conductivity (σ).

The electric conductivity can provide information about the pore fluids, as well as the porosity of geological formations. The resistivity will increase with increasing hydrocarbon saturation of rocks, hence, creating a strong contrast in resistivity between hydrocarbon saturated rocks and brine saturated rocks.

Mitigation Of Pitfalls Through Integration of Seismic and Marine CSEM Methods

Exploration in the frontal toe thrust belt is complicated by the complex geology, reinforcing the need for an integrated approach useful to overcome the challenges of traditional seismic methods of exploration. The Seismic and marine CSEM are obvious complementary geophysical methods as they provide different sensitivity characteristics (Fig 1.4) Structural information is provided by the seismic data, while information on formation pore fluid can be gleaned from the CSEM data. There is as yet no single method that can parameterize subsurface data to characterize hydrocarbon reservoirs from CSEM, seismic data that is currently in use in the global oil industry today.

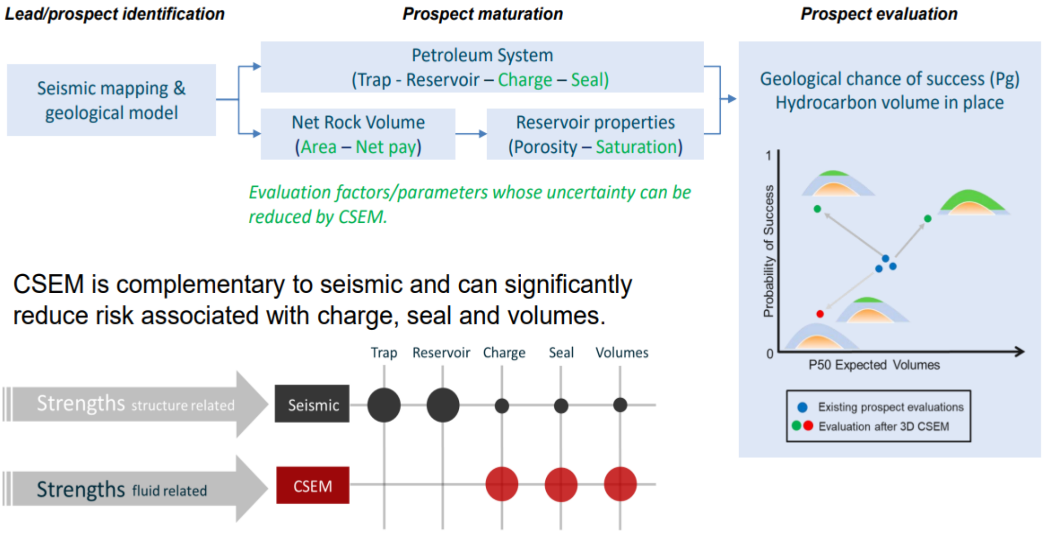


Figure 1.4: Integration of CSEM and Seismic in Prospect Evaluation Workflow

LOCATION OF THE STUDY AREA

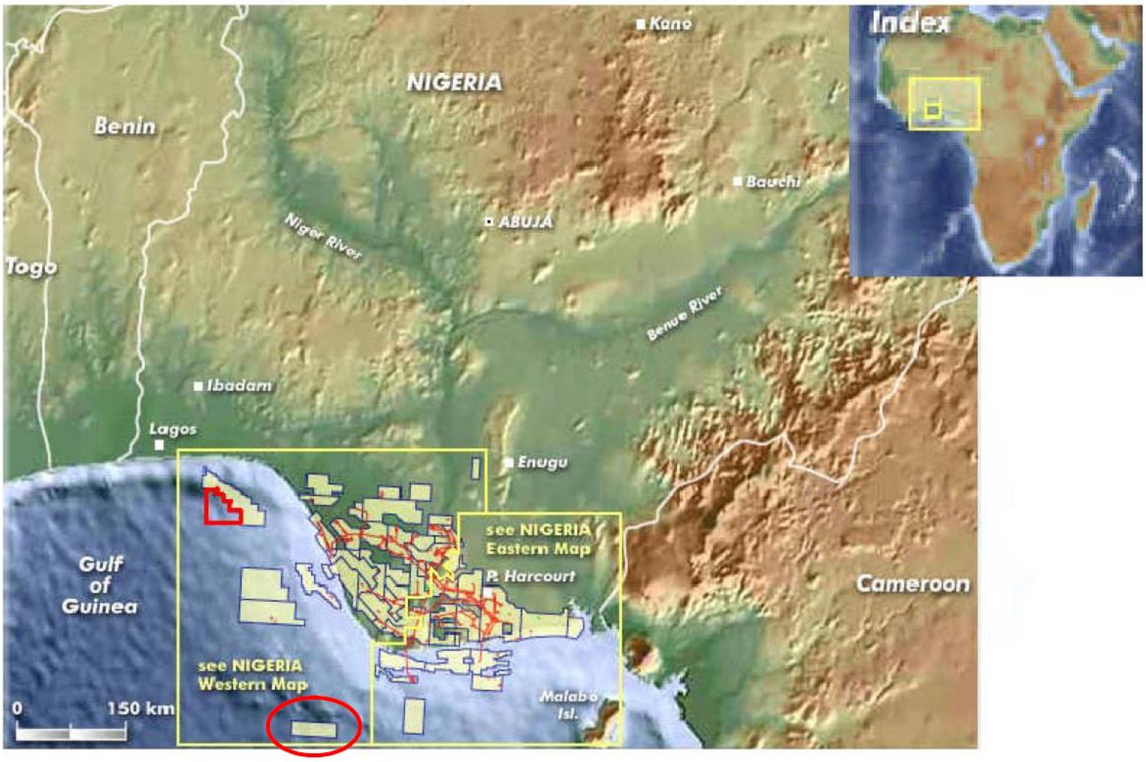


Figure 1.5: Location of the Study Area

The Study Area (Fig 1.5) is located in the Southern deep and Ultra-Deepwater Province of the Nigeria Offshore where water depth varies from 1900m to 2960m. The most striking geological feature in the Niger Delta Basin is a huge prograding deltaic complex whose shoreline, since the Cretaceous, gradually moved toward South West over a distance of some hundreds of km (Doust and Omatsola, 1990). In deltaic systems, simple facies distribution models are based on subdivision in shelfal, slope and basinal depositional settings. This simple model is complicated by a syn-depositional tectonics activity affecting both the sediment dispersal pattern and sand accumulation.

Four areas each with a different structural style can be recognized (Corredor et al, 2005).

- an Inner Domain, called the Extensional Domain, limited to the Niger Delta shelf. It is characterized by extensive growth faulting coupled with counter regional faulting. Each couple of major faults defines a so called “macrostructure”: a high sedimentation rate and high subsidence sub-basin capable to capture large amounts of delta-front sands. These “small” basins are then structured as positive features due to rollover bending or block tilting.
- an Intermediate Domain, called the Translational Domain, where the structural setting is dominated by the occurrence of shale diapirs, sometime piercing up to the sea bottom. Evidences of a fault control on the location and development of the shale diapers are widespread; old and now partly hidden, mainly extensional faults seem to play a major role.
- an External Domain, called the Compressional Domain, that is characterized by the occurrences of several alignments of imbricate thrusts. Some of these show a pronounced relief at the sea bottom causing the occurrence of frontal collapse-gliding and re-sedimentation. All the thrusts merge to a unique basal decollement.
- An undeformed Basin, where the sedimentary succession is not affected by significant tectonics, lies in front of the outer thrust front.

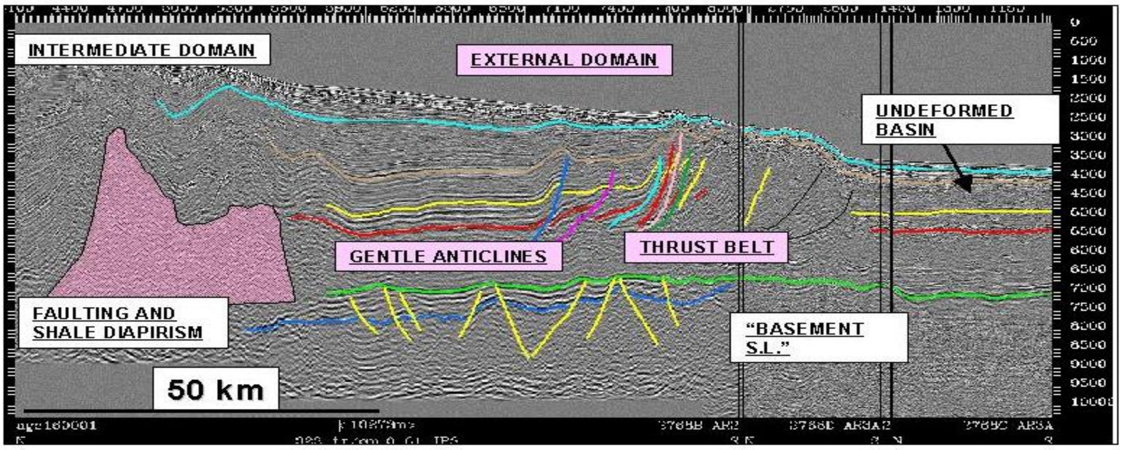


Figure 1.6: Transverse seismic section across the study area

The study area (Fig 1.6) is located at the transition between the External Domain, and the Undeformed Basin. The structural setting of the area, dominated by either external verging thrusts or internal-back verging thrusts, is complicated by the presence of deep-seated "basement tectonic".

The prospective series is represented by a thick Oligocene to late Miocene clastic succession related to the evolution from more continuous ("lobe-prone") to more discontinuous ("channel-prone") turbidite facies.

COMPLEXITIES IN THE STUDY AREA

The Study Area presents some unique challenges and complexities to any solo geophysical exploration technique.

Volume Risk

First, there is the prevalence of smaller fold closures in the outer toe thrust belts. Secondly, there are serious challenges in Seismic imaging of steeply dipping structures (Kostenko et al, 2008) and the well associated difficulty interpreting closure architecture.

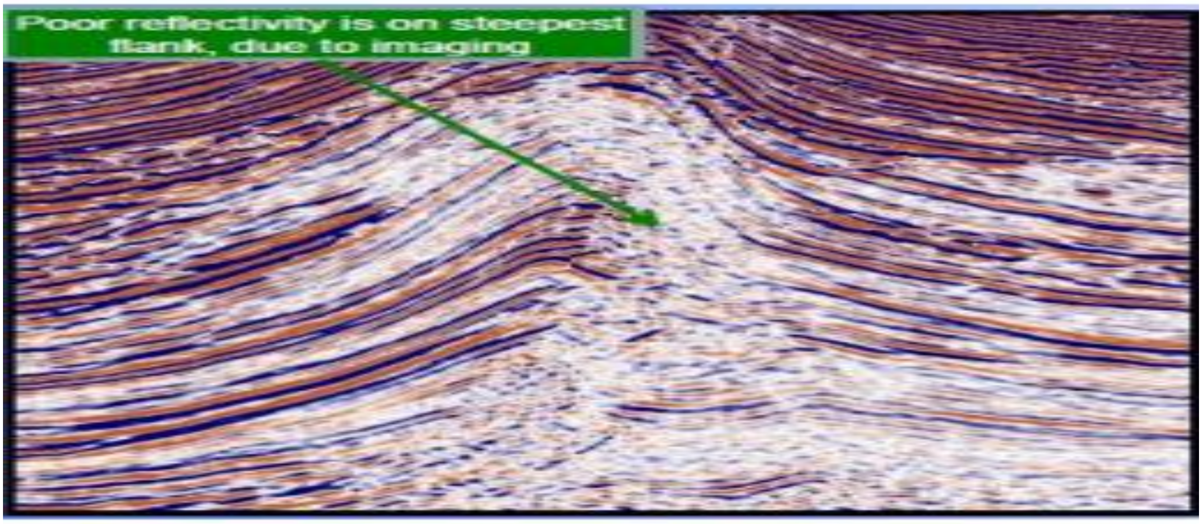


Figure 1.7: Seismic section showing poor seismic imaging of a steep flank (After Kostenko et al, 2008)

Charge Risk

a.) The petroleum system of the Niger Delta deep offshore toe thrust belt is not yet fully understood (Kostenko et al, 2008).

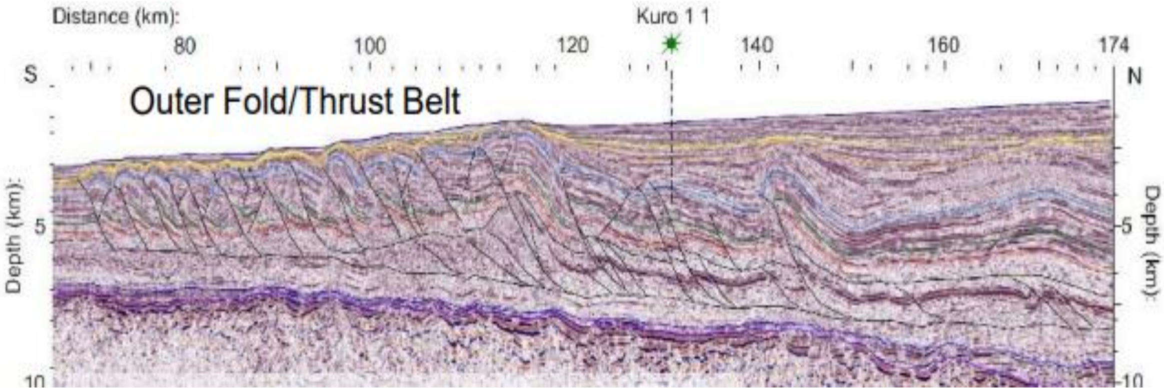


Figure 1.8: Seismic section highlighting causes of charge risk in the thrust belt (After Kostenko et al, 2008)

b.) There is lack of thermogenic hydrocarbon.
c.) Widespread sediments thinning limits source maturity.
d.) Migration by-pass

Seal Risk
Up dip leakage in stratigraghic traps (Mathew AAPG, 2010)

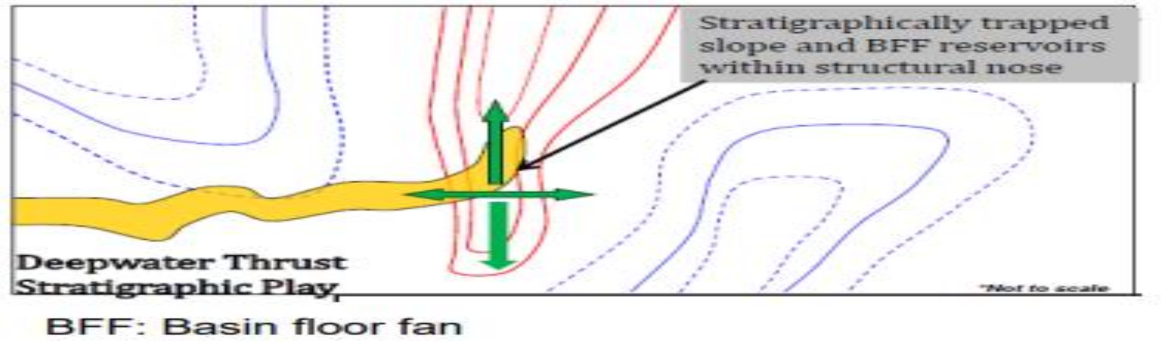


Figure 1.9: Stratigraphic trapping in the fold and thrust belts. (After Mathew, AAPG 2010)

DATA
Available dataset include 3D Seismic, 2D marine CSEM and petrophysical data from an offset well within the study area used for model calibration and validation.

SEISMIC DATA
The seismic input data for the study consist of the Narrow and Wide Partial Angle Stacks (5-15 and 25-40 Incidence Angle Degrees) covering the whole study area. Seismic Processing was carried out with an Amplitude Preserving processing sequence including Kirchhoff PSTM and 4th order Anisotropic Move-out. The data was in SEG-Y format.

CSEM DATA
The CSEM data used in this study comprised of three CSEM survey towlines AE, BE and DU for a total of 94.5Km and 28 receiver sites .

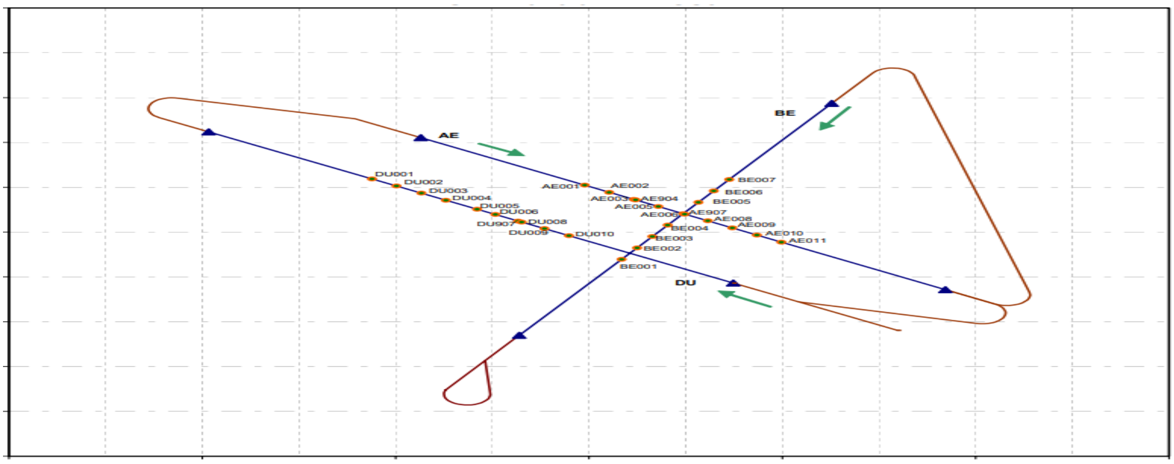


Figure 1.10: Acquisition Layout showing the towlines and the 28 receiver sites

The survey area covers about 177 km2 close to the Dou-1 well, about sixteen nautical miles from the Nigeria coastline and about 2000m of bathymetry. In the study area several prospects of interest have been evaluated as shown in Figure 3.4: (the prospects are indicated with capital letters).

WELL DATA

Data from the exploration well Dou-1 was available for calibration and validation of resulting models. Gas was encountered at upper levels and the final vertical drilled depth was 4304 meters. Gross sand thickness encountered was 600m and net sand was 418m with Net to gross ratio of 70% and bottom hole temperature of 75 degrees. The encountered gas was mostly biogenic C1 gas components. Water samples were collected from two points which indicated presence of heavy hydrocarbon components.

Multiple well logs were accessible, with the most important being gamma ray, spectral gamma ray, density, neutron porosity, resistivity with micro, medium and deep measurements.

II. METHODS AND RESULTS

The method adopted for this study was based on few fundamental principles that guided the entire workflow, from data Q.C. to prospect ranking. They are the following:

a) The CSEM inversion problem is strongly ill posed and ill conditioned.
b) Running CSEM data inversion without properly understanding the data itself can be misleading.
c) The data space must be extensively explored before applying any sophisticated interpretation tool.
d) The model space must be extensively explored using an approach that becomes progressively more complex.
e) Seismic information and any other independent data should be used at each step

The above principles reflect the basic truth that running directly multidimensional inversions without deep understanding of both the data and model spaces can be risky. Of course, multi-dimensional inversion is the most sophisticated interpretation approach, but it can lead to wrong solutions when the inverse problem is ill-posed and illconditioned, as in the case of CSEM. Non-uniqueness is a common problem in the practice of electromagnetic data inversion, and it cannot be completely avoided, even though constraints are used, unless the data is completely noise free. Of course, noise is always included in any experimental data set. As a consequence, the most logical approach should be based on a progressive understanding of the data/model spaces, in order to exclude artefacts and meaningless solutions when constrained inversion is finally applied. Using this philosophy, the main steps adopted for this interpretation workflow can be summarized as follows:

- Post-acquisition Data Q.C.
- Exploration of data space through 1D modelling
- Electromagnetic attributes mapping
- Introduction of seismic constraints
- 1D layered model building
- 1D sharp constrained inversion
- Preparation of 3D resistivity models in depth
- 3D forward modelling
- 2.5-D unconstrained Inversion
- 2.5D Constrained Inversion
- Model assessment and resolution analysis

- Inversion results vs. geological interpretation
- Inversion results vs. AVO seismic analysis
- Prospect ranking

EXPLORATION OF DATA SPACE THROUGH 1D MODELLING

1D modelling is a quick procedure for exploring the consistency of the data. It involves calculating the synthetic response for several different resistivity scenarios and then comparing the predicted (or synthetic) with the observed (or measured) data at each receiver location. This model was called "Resistive Model" or "Model 1" (Figure 4.5). Next, the synthetic response using the same "Model 1" was calculated but excluding the resistive gas layer. This was called the "Conductive Model" or "Model 2".

Finally, several responses for different conductive uniform half spaces (1 Ohm m, 2 Ohm m, 3 Ohm m etc) were calculated. These models are called "half-space1, half-space2, half-space3 etc.

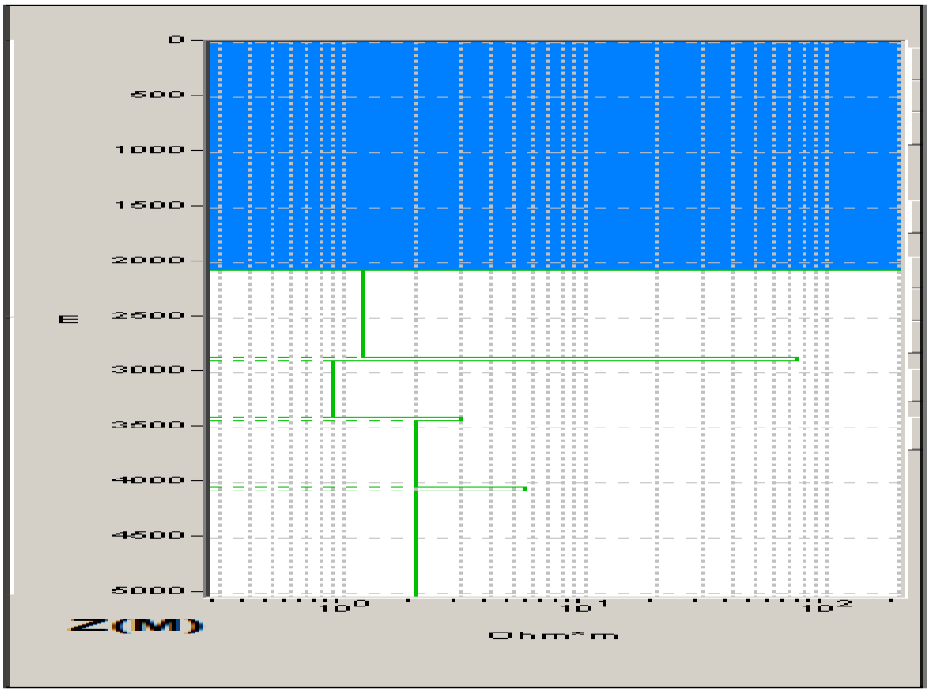


Figure 2.1: Synthetic 1D Resistive Model predicted from Dou-1 well logs

The synthetic responses for all the above models were calculated for all the frequency values representing the true frequency spectrum of the real data (0.25Hz plus the first three harmonics; 0.05Hz plus the first three harmonics).

Figure 2.2 shows the synthetic responses of uniform half spaces along line AE at receiver 03 location, out towing.

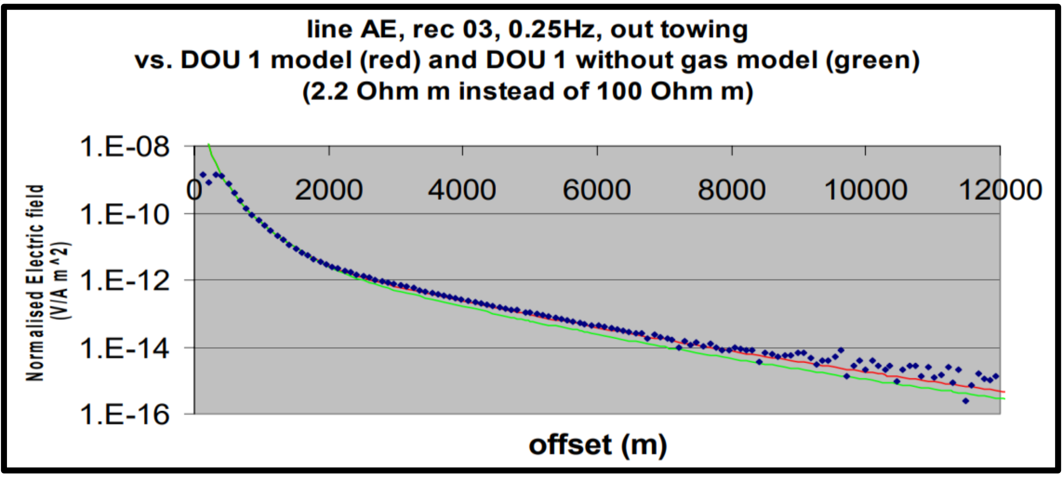


Figure 2.2: Synthetic Responses of conductive half spaces in line AE, receiver 03, out towing

1D forward modelling allowed immediate discovery of areas of significant anomalies with respect to the conductive scenarios. The main anomalies correspond to well Dou 1 anomalies. In fact, in this area the electric MVO is generally higher than the synthetic response associated with conductive models. The source-mid-points associated with these receivers, for middle to large offsets fall in the area of the well, suggesting that the high values of the electric field are caused by the high resistive gas sands drilled at that location.

The resistivity blocky model at the well Dou-1 was used for calibrating the electromagnetic anomalies. This model fits well with the observations near the well Dou-1.

ELECTROMAGNETIC ATTRIBUTES MAPPING

Electromagnetic attribute refers to any meaningful information obtained from some mathematical manipulation of the electric and magnetic fields observed at the receivers. The anomalies are produced after normalization of the attributes with respect to some reference response.

The most commonly used electromagnetic attribute for preliminary interpretation of the electromagnetic data, is the normalized magnitude vs. offset (normalized MVO). The assumption underlying this attribute is that the MVO measured from a resistive environment is expected to be higher than the reference MVO that is, commonly, selected as a conductive response. This conductive response can be measured, for instance, at a location outside the study area, or from a proven conductive environment. Alternatively, it can be calculated from an assumed conductive model.

With this approach the normalized MVO plot represents an attribute that can reveal the presence of resistivity anomalies. It can represent a good interpretation starting point, but of course, it is just an initial approach that must be complemented with more sophisticated approaches, such as modelling and inversion. Consequently, mapping of the normalized MVO plots calculated at all offsets was carried out to generate anomalies at the corresponding source-receiver mid points. The acquisition lines are indicated together with the positions of the prospects (A, B, C AW and E).

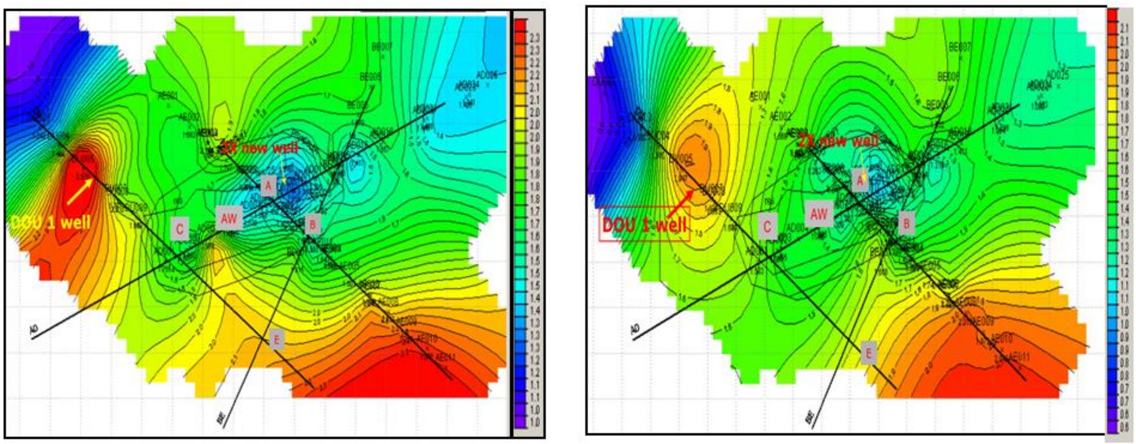


Figure 2.3: Normalized Magnetic magnitude map and MVO gradient map at 0.25Hz, values plotted at source-receiver mid points.

The distribution of this anomalous trend changes with varying offset range and frequency, but in general it is visible at the same receivers with almost equal intensity.

All the electromagnetic attribute maps seem to indicate low probability of finding commercial hydrocarbon accumulation in the area crossed by line AD in the central portion of that line where the new wildcat well is proposed.

1D CONSTRAINED CSEM INVERSION

The workflow continued with the introduction of seismic constraints deduced from the interpreted 3D seismic depth sections. Figure 2.4 show a 3D seismic depth section extracted from the 3D volume along line A-E and the main seismic horizons that were used as constraints for the electromagnetic inversion.

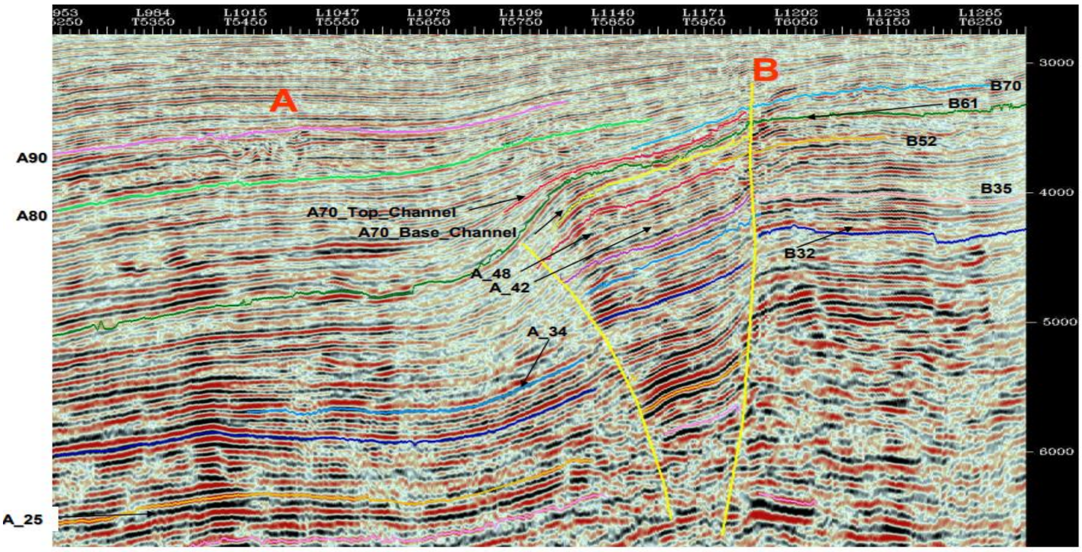


Figure 2.4: Depth Seismic volume showing interpreted targets along line A-E

1D layered models were extracted from the main interpreted seismic horizons corresponding to each single receiver. This information was used as an apriori information for constraining the 1D inversion process. 1D constrained inversion was then performed at each receiver, using both fundamental frequencies of 0.25 Hz and 0.05 Hz and, occasionally, their harmonics.

The inversion of the electric data corresponding to well Dou-1 provided a model very consistent with the drilling results (Figure 2.5).

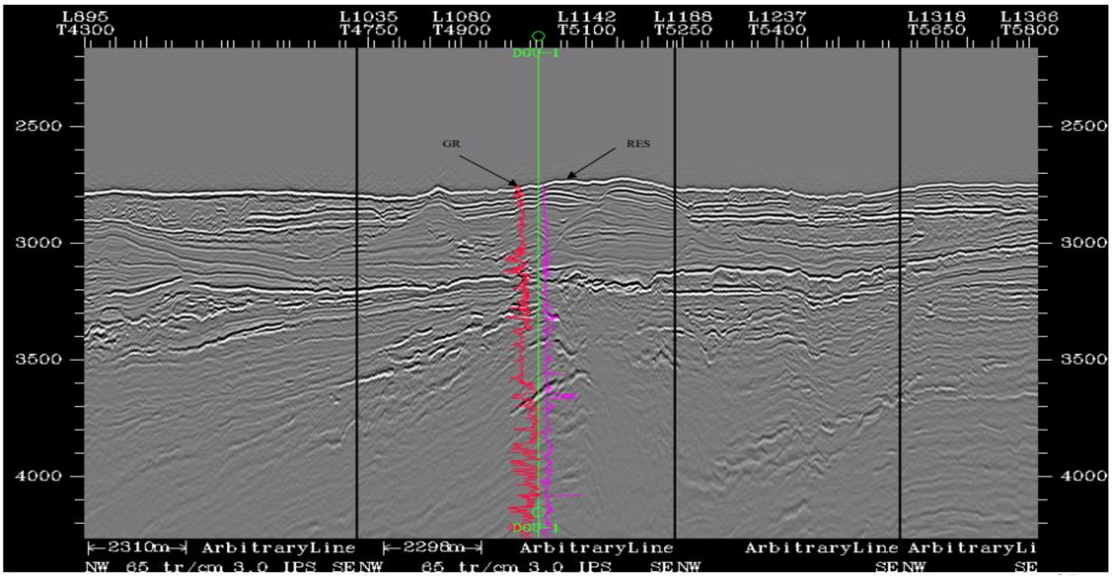
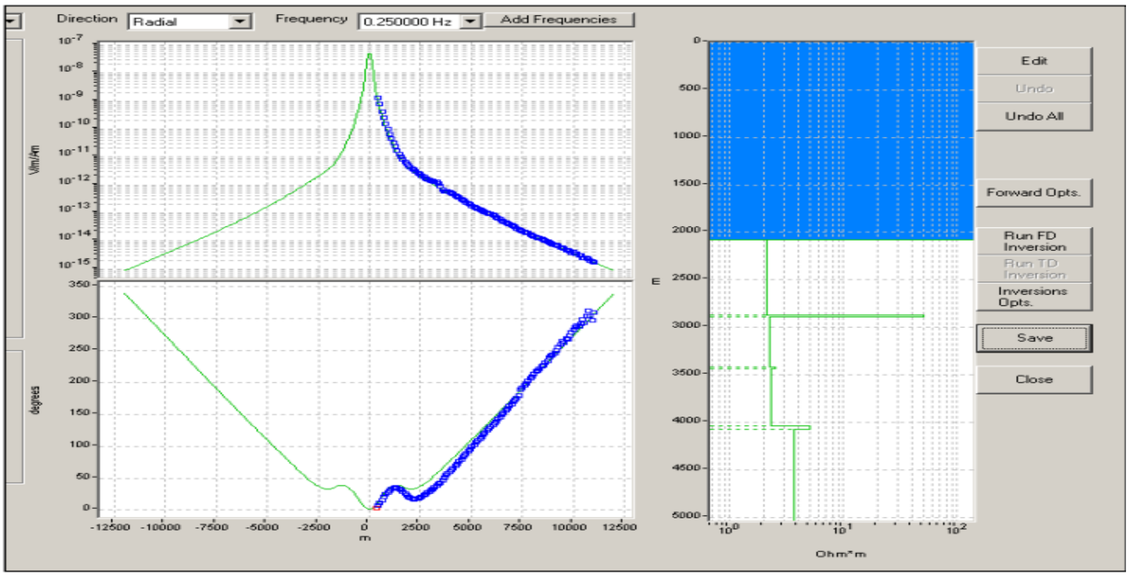


Figure 2.5: Arbitrary Seismic line across well showing resistivity log measurements on target layers used in the constrained inversion.



Direction: Radial

Frequency: 0.250000 Hz

Figure 2.6: 1D constrained Inversion at location close to well Dou-1

The 1D constrained inversion confirmed a generally high resistive environment in the southern part of the block along line BE and a quite conductive background along line AD.

However, away from the Dou-1 well vicinity, this result seem not to be consistent with the AVO anomalies generated through seismic amplitude analysis as can be seen in Figure 2.7 below.

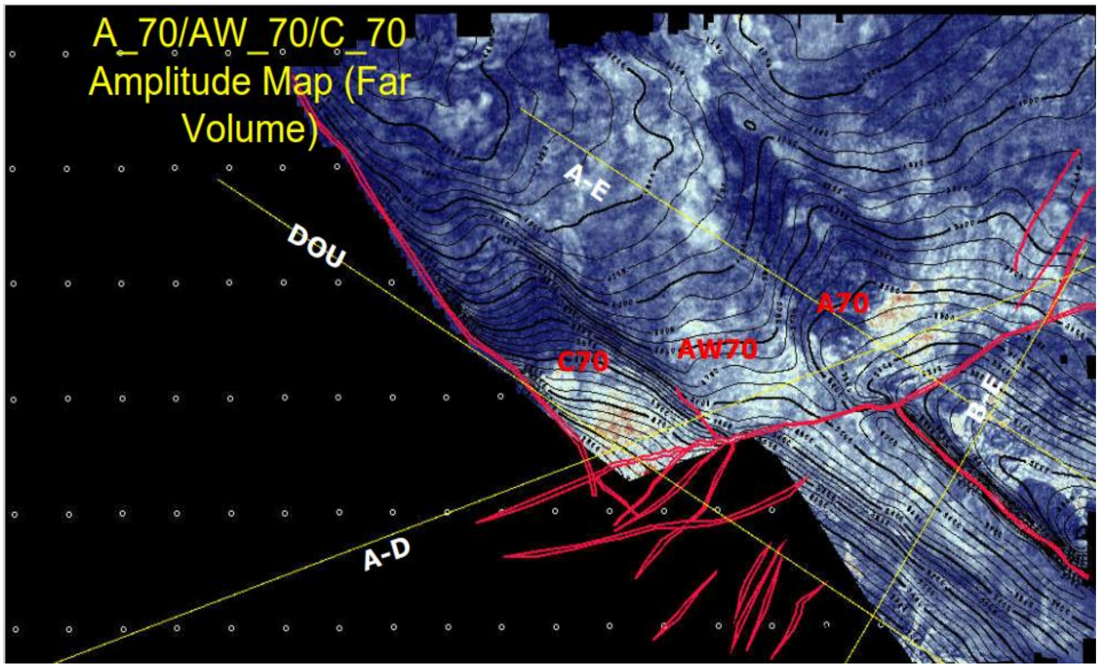
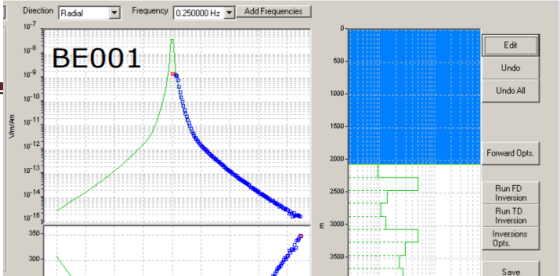


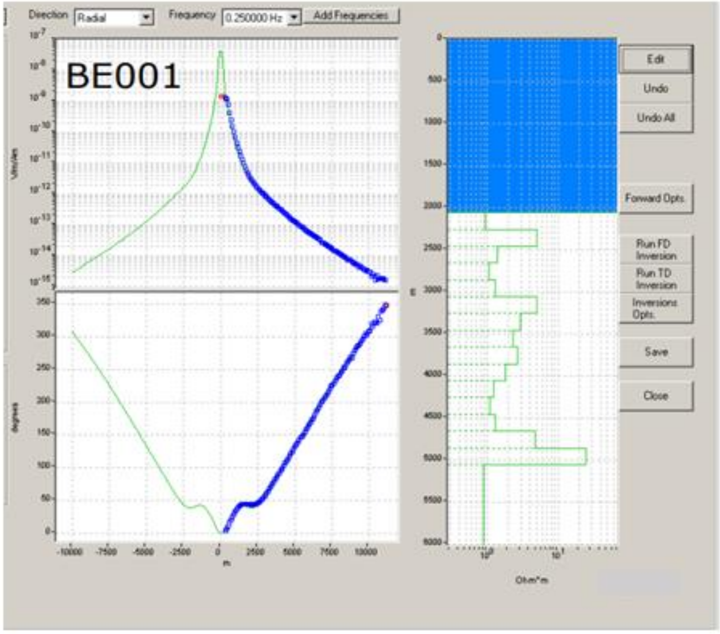
Figure 2.7: Seismic amplitude extraction along CSEM line A-D.

Figure 2.8 show inversion results along line AD away from the well Dou-1. The fit between predicted (solid line) and observed (dots) is shown and, on the right side, the corresponding resistivity model is displayed.



Direction: Radial

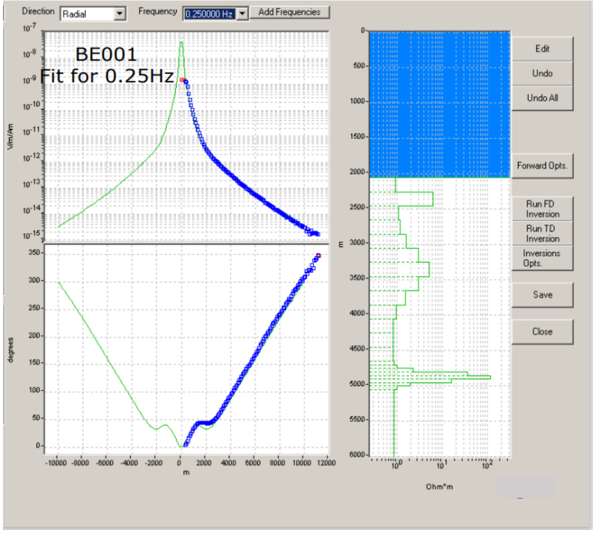
Frequency: 0.250000 Hz

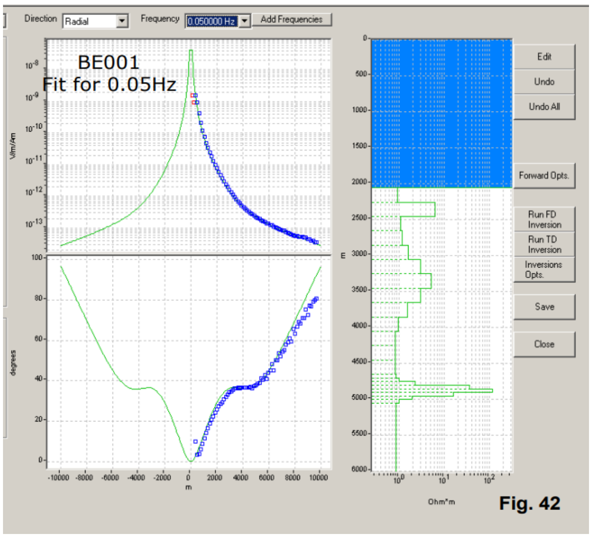


Figures 2.8: 1D Inversion results on line AD and BE with frequency 0.25Hz.

The high amplitude anomalies show non-conformance with the low resistive anomalies from CSEM inversion along the same line. It appears that seismic anomalies are not confirmed by the electromagnetic anomalies along line **AD**.

Furthermore, inversion results for some receivers located along line **BE**, in southern part of the Study area, in the area of prospect “E” are shown in Figure 2.9. Some resistive layers are present in that part of the study area and are consistent with the maps of the electromagnetic attributes.





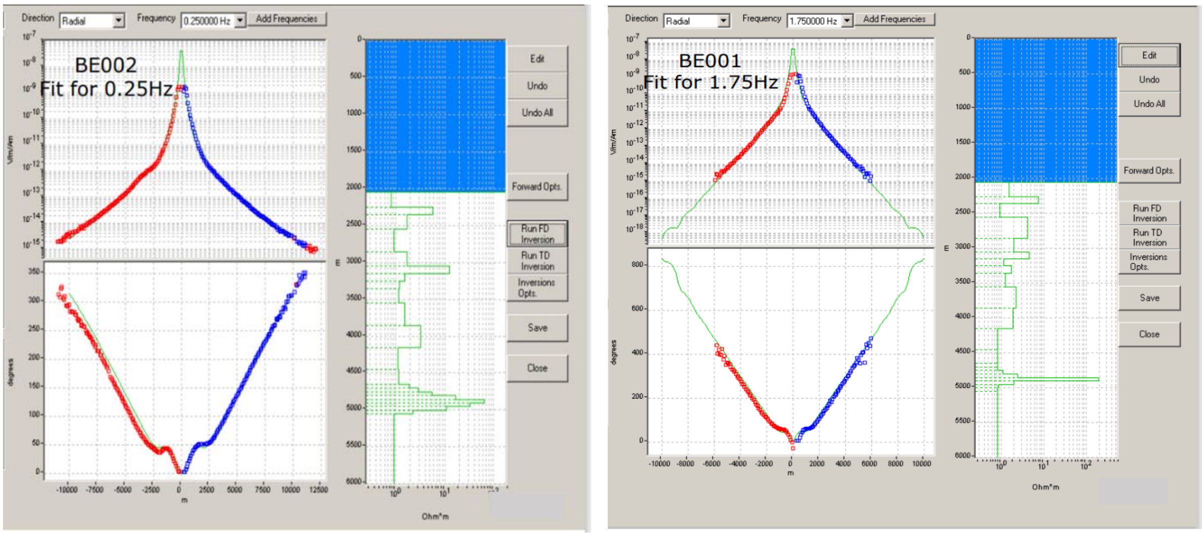


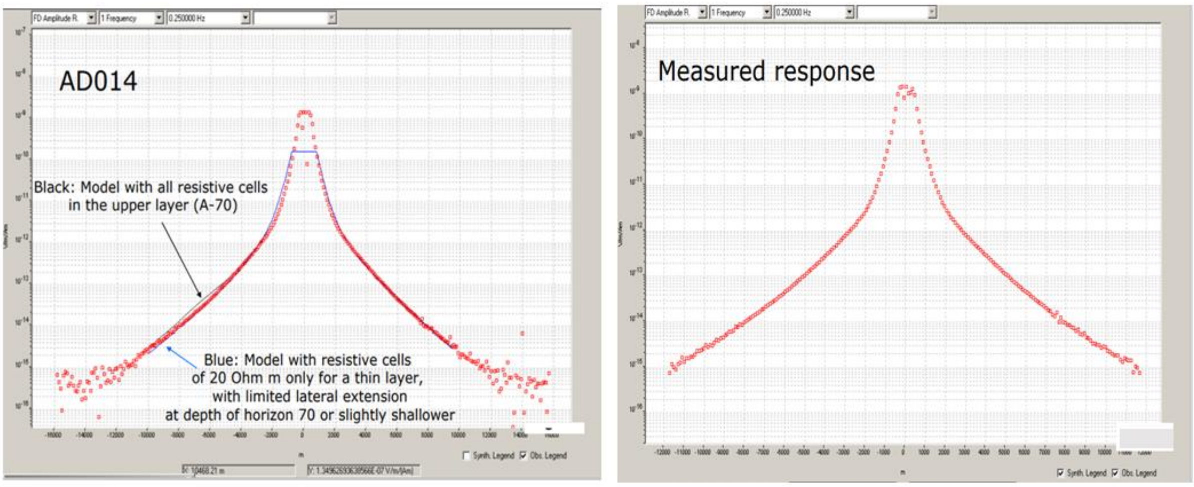
Figure 2.9: Multifrequency inversion result on line BE.

However, the electromagnetic attributes showed intrinsic limitations due to the 3D nature of the explored medium. For this reason, 3D modelling and inversion was executed as part of the workflow.

3D FORWARD MODELLING

The same seismic horizons used for constraining the 1D sharp inversion were imported into a grid for building a preliminary 3D resistivity model. Initial resistivity values were derived from the results of the 1D inversion at each receiver location and interpolated. Following several tests a 3D grid was defined. This grid was then populated with an initial resistivity distribution and a finite difference modelling algorithm was run.

Several trial-and-error forward modelling focused along line AD suggested that, along that profile, significant resistivity anomalies should be excluded. The maximum expectation could be to have small (thin and not too extended) resistive layers at 20-30 Ohm m.



Black: Model with all resistive cells in the upper layer (A-70)

Blue: Model with resistive cells of 20 Ohm m only for a thin layer, with limited lateral extension at depth of horizon 70 or slightly shallower

Figure 3.1: Magnitude vs. offset response at receiver 014 along Line AD

This preliminary conclusion is fully consistent with the results obtained at the previous steps, with reference to the maps of electric and magnetic attributes discussed in the previous paragraphs.

However, an entirely different scenario appeared along the profile BE. The corresponding seismic section is shown in Figure 3.2 while Figure 3.3 shows an example of 2D section extracted from the 3D model along that line.

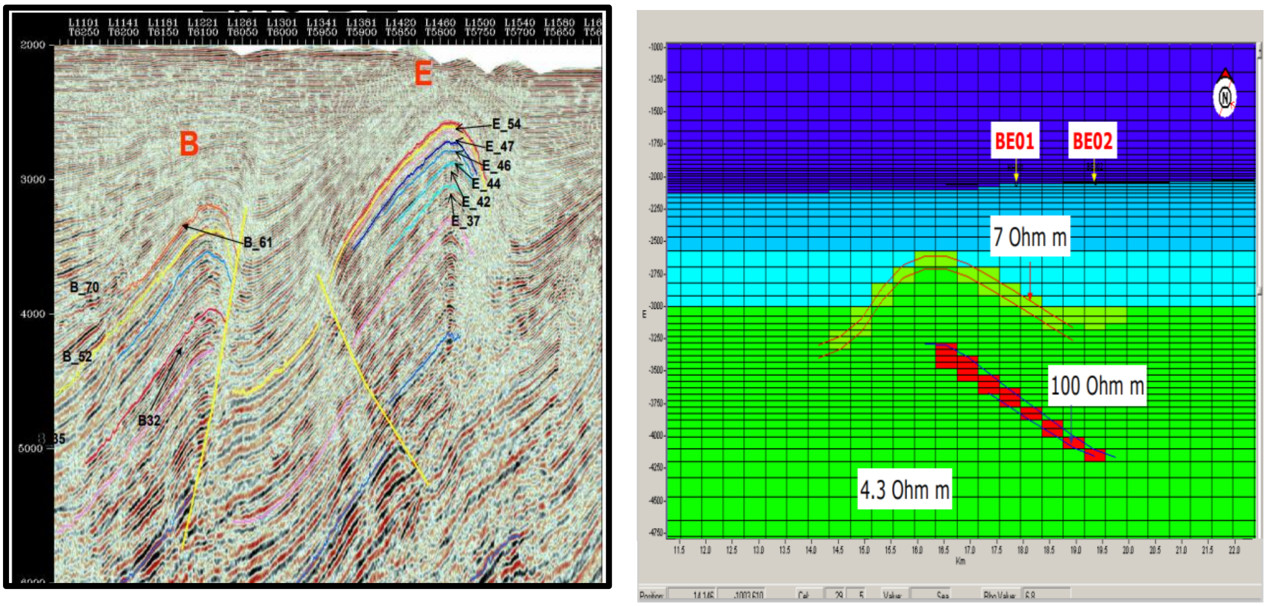


Figure 3.2: Seismic section along Line BE showing interpreted horizons

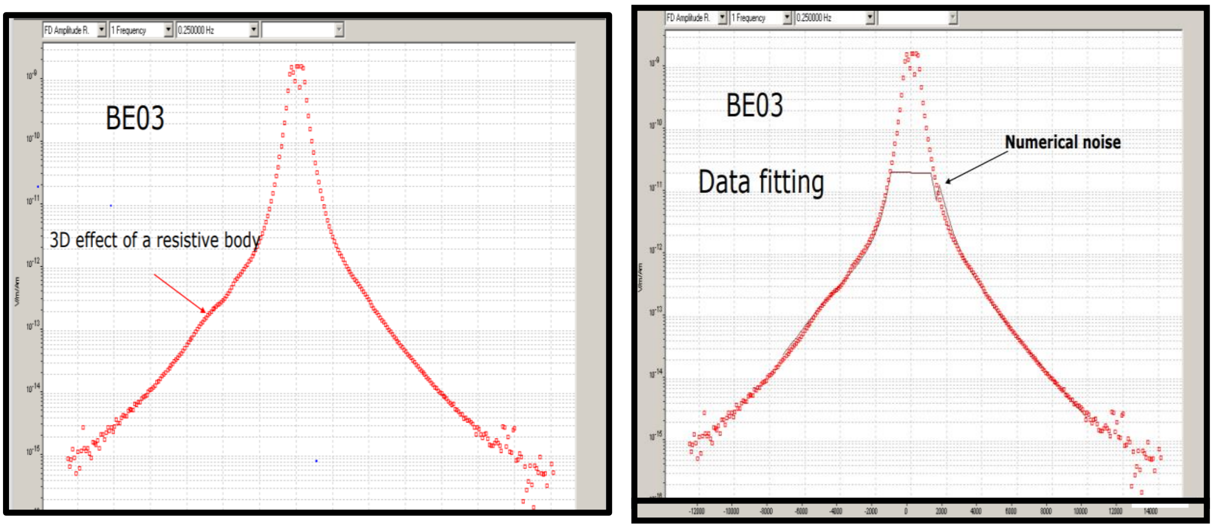


Figure 3.3: MVO response at receiver BE03 showing effect of a high resistive body.

Significant anomalies ("MVO bumps") are visible at different offsets (rapid variations of the MVO trend) which corresponds to local increases of resistivity at different depths. On this basis, hydrocarbon accumulations cannot be excluded along line BE.

This step is considered preparatory for the multidimensional inversion. Generally, the 3D models obtained through the forward modelling represented a good starting point for the optimized inversion performed along the same lines.

2.5D INVERSION

The marine CSEM acquisition layout for this study had already conditioned the choice of the inversion strategy. Acquisition was performed along 2D lines, so 2.5D inversion was considered appropriate in this case. A Finite Difference algorithm was used for the forward calculation and a conjugate gradient optimization approach was applied for the inversion itself. Both unconstrained and constrained inversions have been performed (only for the lines AD and BE).

As a first step, unconstrained inversion for lines AD and BE were run. However, the geophysical significance of the unconstrained inversion was found to be limited. The 3D inverse problem of CSEM data is extremely ill posed and ill conditioned and any small margin of error in the data is sufficient for producing a high level of non-uniqueness.

However, when interpreted horizons derived from seismic depth sections were used as constraints for the inversion, while keeping the conductivity inside the layers constant, the inversion process became much better conditioned and stable.

Figures 3.4 and 3.5 represent the constrained inversion results (conductivity section in colours) respectively obtained for line AD and BE.

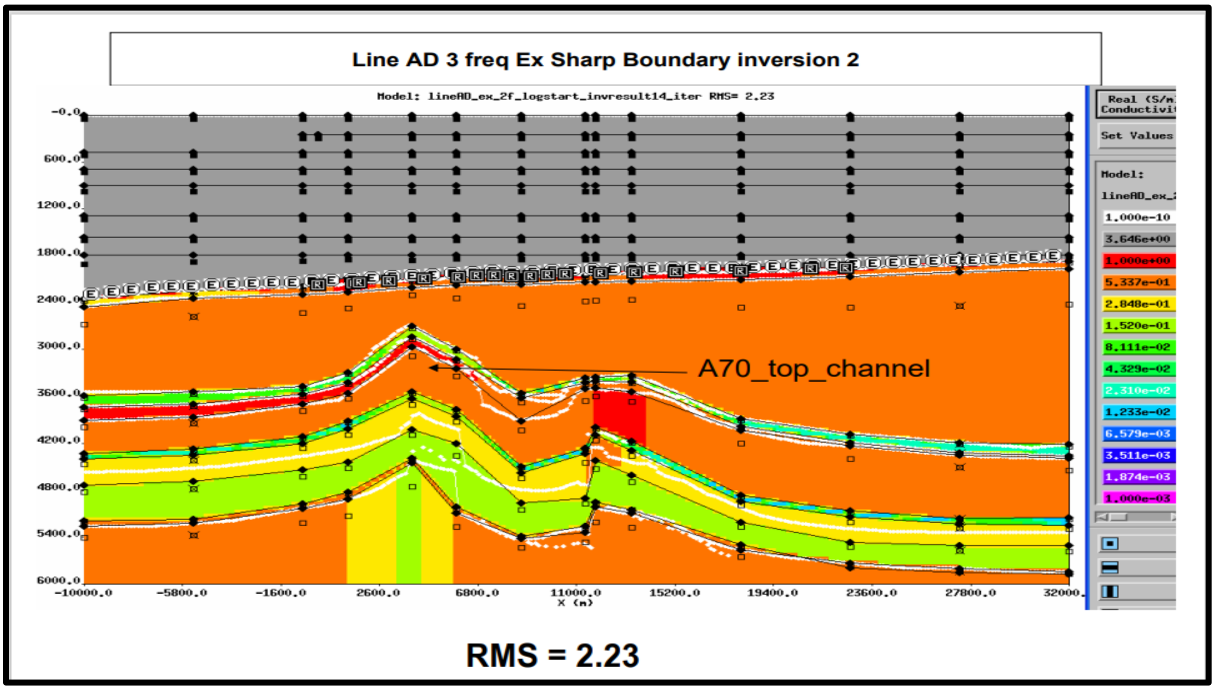


Figure 3.4: 3D constrained inversion results for line AD. Conductivity section is shown in colours on the right panel.

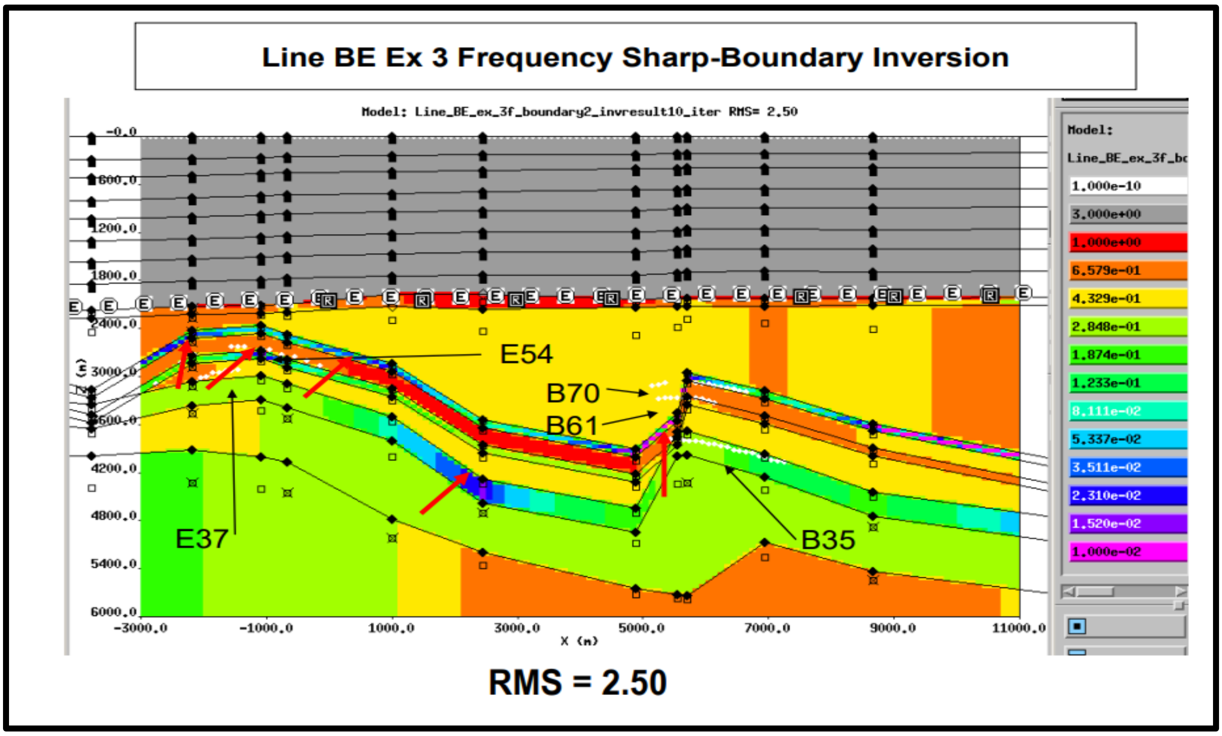


Figure 3.5: 3D constrained inversion results for line BE. Conductivity section is shown in colours on the right panel.

Similar to the forward modelling results, models obtained by 3D constrained inversion do not show any significant anomalies for the line AD. A good continuity in the conductivity values is quite evident along the section and no resistivity anomaly appears that could be associated with commercial hydrocarbon accumulations.

However, the scenario is somewhat different along line BE, where some interesting anomalies appear at different locations and at variable depths (see the red arrows in the Figure 3.5).

These anomalies represent bodies with relatively high resistivity (low conductivity) that are fully consistent with the fact that strong anomalies of the electric and the magnetic fields were observed at the sea floor.

III. CONCLUSION

A major highlight of the results of the modelling and inversion in the study area is the fact that prospects with significant seismic anomalies corresponds to areas where electromagnetic attributes showed low or null amplitudes. For instance, the A_70 horizon seismic anomalies on the prospect “A”, evident along line AD as shown in Figure 3.4. There are other seismic anomalies evident along the same line AD toward the west.

Surprisingly, the electromagnetic response along the same line AD was quite disappointing, suggesting very low probability of discovering commercial hydrocarbon accumulation in that area.

However, an entirely different scenario played out along the line BE. Prospect “B” along that line had an indication of moderate seismic AVO and electromagnetic MVO anomalies as shown in the electromagnetic attributes map. Furthermore, a very strong electromagnetic anomaly is evident in the area of prospect “E” along the same line, especially in the southernmost part of the CESM survey area.

RANKING OF THE PROSPECTS

The interpretation workflow adopted for this project has produced remarkable results which has allowed definition of variable exploration risks for the different prospects traversed by the CSEM lines which are summarized in Table 1.

TABLE 1: RANKING OF THE HYDROCARBON POTENTIAL OF THE PROSPECTS

PROSPECT	SEISMIC ANOMALY	CSEM ANOMALY	CSEM INVERSION	HYDROCARBON POTENTIAL
A	VERY STRONG POSITIVE SEISMIC (AVO) ANOMALY	VERY LOW ANOMALY	VERY LOW	VERY LOW
AW & C	VERY STRONG POSITIVE SEISMIC (AVO) ANOMALY	NIL	NIL	VERY LOW
B	NEGATIVE	STRONG POSITIVE RESPONSE	STRONG POSITIVE RESPONSE	MODERATELY HIGH
E	NEGATIVE	STRONG POSITIVE RESPONSE	STRONG POSITIVE RESPONSE	VERY HIGH

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