De-risking Low Saturation Gas (LSG) using Controlled Source Electromagnetic Data and Multiphysics Interpretation in Deep Water Trinidad & Tobago

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Summary

Woodside and bp made multiple gas discoveries in the Pliocene/Miocene section of Barbados Trough Basin (BTB), deep water Trinidad; however, significant challenges exist for appraisal of these deep-water gas accumulations. Extensional faults normal to SSW-NNE regional structural and stratigraphic trends are believed to seal and hence provide compartmentalization from adjacent segments. The total number of unpenetrated compartments pose significant uncertainty for appraising and development of these gas discoveries.

After evaluating different alternatives for appraisal, we decided to collect Controlled Source Electromagnetic data (CSEM) over these gas discoveries to assess the risk of low gas saturation (LSG).

A detailed feasibility study was carried out to establish the applicability and potential robustness of CSEM technology for appraising these fields. Through multiple modeling scenarios, we designed a 3D CSEM survey with adequate data coverage through source and receiver configuration as well as good sensitivity to target reservoirs given the range in the source frequency. With favorable acquisition conditions, we were able to collect high quality data ahead of schedule. Data QC and analysis show that the noise level in the survey is very low. A good S/N ratio was achieved through a combination of a high-power transmitter (~7000 A) and a relatively low noise environment.

CSEM technology can be used for appraisal when geological conditions are appropriate. The technology was applied over subtle faulted traps with a sedimentary sequence dominated by deep water clastic deposits. Depth of investigation was appropriate for the technology given signal recovery and resistivity contrast, both of which decrease with depth. RT scanner data from exploration wells were essential for calibration, despite a strong resistivity casing effect around the wells. Good match between pre-survey modeled synthetic results and preliminary field data provided confidence on the quality of the survey. Processing and several inversion tests were performed to gain confidence on the reliability of the CSEM data. Scenario testing incorporating net pay maps from seismic data established a framework for an integrated interpretation of both seismic and CSEM inversion results. Finally, a rock-physics based approach was applied to generate risk maps combining seismic amplitudes, velocities and CSEM resistivity maps.

Once calibrated to local wells, the Multiphysics interpretation of CSEM data combined with seismic analysis and inversion presents a cost-effective way to de-risk gas accumulations in this part of the basin.

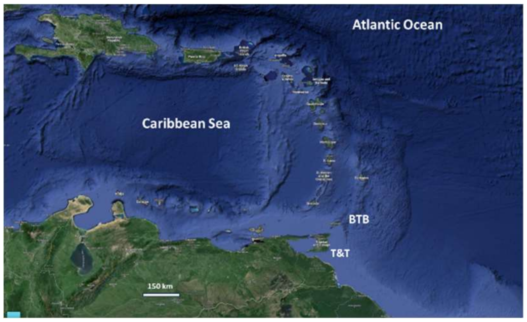


Figure 1. Location of Barbados Trough Basin (BTB) in deep water offshore Trinidad & Tobago (T&T) -image from Google Earth-.

Introduction

During the first decade of this century CSEM was introduced as a new direct hydrocarbon indicator (DHI) technology, presenting an alternative to seismic amplitude variation with offset (AVO) and bright spots, which were already known to have false positives associated to residual or low gas saturation, a significant challenge for exploration. Fundamentally, the relative insensitivity of seismic velocities and impedances to varying gas saturation levels limits the sensitivity of seismic data to identify reservoirs with low-saturation gas (LSG). In contrast, resistivities are overly sensitive to water saturation within the reservoir, hence the potential of CSEM as a DHI. Many CSEM projects have been conducted for exploration, yet with mixed results (Berre et al, 2020; Hesthammer et al, 2010) up until now.

A feasibility study for the application of CSEM for appraisal indicated that the technology had the potential to reduce the risk of LSG in two gas discoveries in BTB basin in DW Trinidad (Figure 1). The study leveraged existing geologic models and incorporated resistivity scanner (RT) data for calibration of normal and vertical components. These results were used by Woodside Energy to design, plan and execute the Calypso CSEM Project as summarized in Figure 2.

Main objectives of this CSEM survey were to: (1) de-risk potential LSG in non-penetrated segments of these two gas discoveries; (2) reduce uncertainty in discovered resources in these fields; (3) establish likelihood of potential upside in surrounding areas and (4) identify possible shallow hazards, like gas and hydrates. The project achieved all these goals through a careful integration of CSEM and seismic inversion results, calibrated to log data from exploration wells.

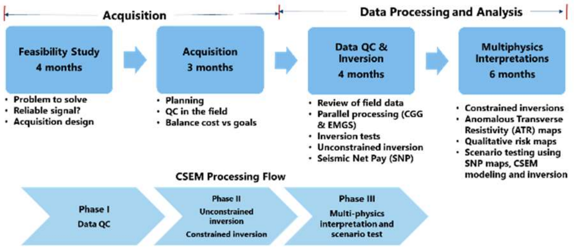


Figure 2. Calypso CSEM Project, from feasibility study to final interpretation.

Pre-survey modelling and survey design

Extensive pre-survey modeling and sensitivity analysis were carried out to verify that CSEM could reliably detect LSG segments, and to optimize the acquisition parameters. Final parameters are summarized in Table 1, the final survey configuration is illustrated in Figure 3, and the source waveform is presented in Figure 4. The survey focused on gas discoveries GD-1 and GD-2 and did not include GD-3 discovery because that has a deeper and structurally more complex target.

Survey Coverage	571.5 km^2
Towlines	14
Towline length	750 km
Towline heading	29.4 deg
Line spacing	1.5 km
Receiver spacing	1.5 km (3.0 km in the NE)
Water depth	1790-2360 m
Source	Deep Blue (7,000 Ampere)
Source frequency (Hz)	0.15, 0.3,0.6,0.9,1.2,1.5,1.8,2.1,2.7

Table 1: CSEM survey acquisition parameters.

Data acquisition and QC

A total of 210 receivers were available on board and the operations team took a rolling patch approach with a maximum of 189 receivers on the seafloor at a given time, and with three live receiver lines. The weather conditions were moderate during the survey time which helped ensure the completion of the survey ahead of schedule. While good arguments can be made for high tolerance for receiver drop location, we made sure our Rx drops were within 250 m of the planned locations. Any receiver that was dropped beyond the 250 m radius was re-deployed.

Data QC were carried out both on-board and onshore to catch possible equipment and human errors. Figure 5A shows one of the plots used to identify receiver problems. Relatively high noise at about 7 km offset can be observed on receiver 01Rx112. Noisy data like this was either muted or down weighted during inversion. Figure 5B illustrates the overall receiver health and their distribution. Data noise levels for different frequencies were estimated and compared to a historical database. Very low noise levels were observed in the data set, probably due to a combination of low geoelectrical activities (low latitude), a quiet weather window and a stronger source. Excellent data quality and calibration around GD-1 is illustrated in Figure 6, showing a comparison between a synthetic scenario with saturated gas sandstones and the acquired real data.

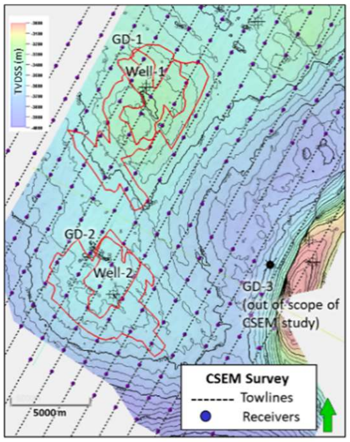


Figure 3. CSEM survey design over gas discoveries under appraisal: GD-1 and GD-2.

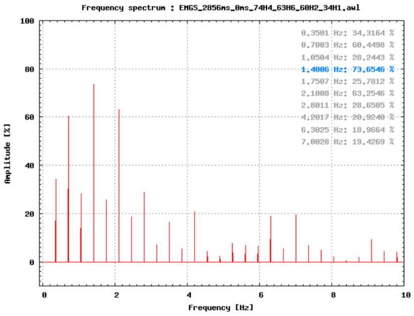


Figure 4. Source Waveform in frequency domain Survey.

CSEM data inversion

CSEM inversion is required to generate a resistivity structure of the subsurface. Several inversion tests were conducted varying initial background resistivity and applying regional and local inversion parameters, to test the sensitivity of the data. While it is understandable that the data has limited sensitivity which decreases with depth, these tests gave confidence that the data had good sensitivity to the targeted intervals and beyond. Cai et al (2024) describe the inversion work carried out in more detail.

The presence of a strong resistivity anomaly over GD-1, as shown in Figure 7, prevailed in all inversion results, while a weaker anomaly around GD-2 became apparent after adjustments of the background resistivity and depth of the inversion model. These resistivity anomalies coincide with seismic amplitude and velocity anomalies related to the presence of porous sands with gas, as indicated by the exploration wells (Well-1 and Well-2). Although the lateral extension of these anomalies can help delineate the boundaries of these gas accumulations, and the magnitude can be used to estimate gas in place, CSEM resistivity results have low resolution compared to seismic data and therefore an integrated analysis and interpretation combining these data sets is necessary.

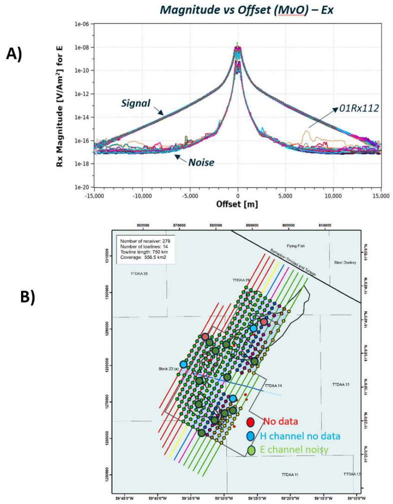


Figure 5. Data QC: (A) Magnitude vs offset for all the Rx on one tow line: (B) Rx issues identified across the survey.

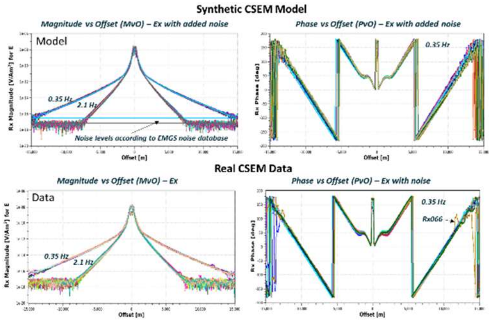


Figure 6. Comparison between synthetic scenario with fully saturated gas sands in GD-1 (top) and real CSEM data collected over the gas discovery (bottom).

Unconstrained and constrained inversion methodologies were applied. The former uses CSEM data as main input and updates a background model until minimizing the difference between the modeled results and the data. The constrained inversion uses seismic horizons as additional inputs to guide the lateral continuity and thickness of the main resistors. Although the feasibility study indicated that CSEM unconstrained inversion should be able to separate the two main reservoirs in GD-1, this separation was only achieved after applying constrained inversion.

Several scenario tests were conducted to gather insights into the range of possible scenarios that could explain both the CSEM and the seismic data, within the known geologic setting and the rock properties observed in the wells. Seismic net pay (SNP) maps calibrated to well data were provided as input for a few of these scenarios. Figure 8 presents a comparison of constrained and unconstrained inversion results for GD-1, as well as a scenario test using SNP results.

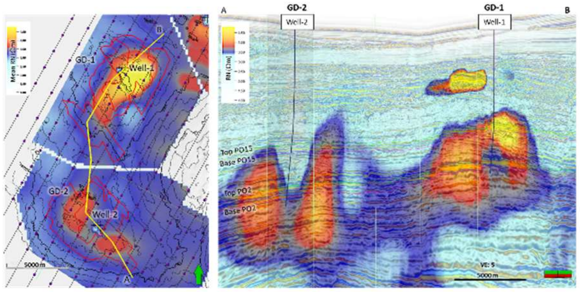


Figure 7. Co-rendering of seismic amplitudes and vertical resistivity from final unconstrained CSEM inversion results. Map on the left shows an average resistivity map from top PO15 to base PO2.

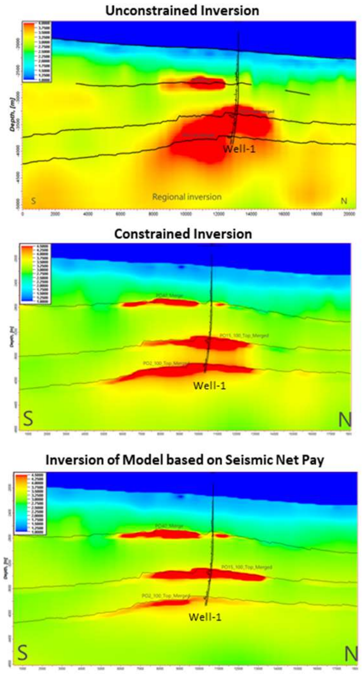


Figure 8. Comparison of unconstrained (top) and constrained (middle) inversion results, and inversion results from a scenario based on seismic net pay results (bottom) over GD-1.

Integration and interpretation

Interpretation of both seismic and CSEM data poses challenges related to the scale of observation, variability in response to rock properties, fluid saturation, and anisotropic behavior. Several iterations of constrained inversions and scenario testing were conducted to address these complexities in scale and rock properties. In addition to these processes, a rock-physics based qualitative approach was developed for interpretation of these data sets and illustrate the impact of CSEM results on reducing the risk of LSG in these fields.

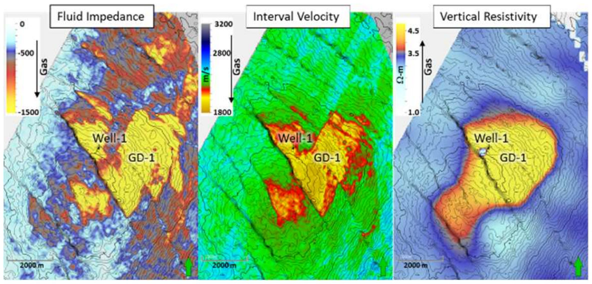
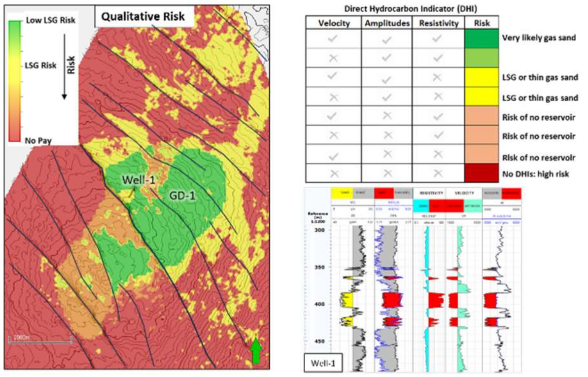


Figure 9. Maps of average properties for the PO15 reservoir in GD-1: average negative amplitudes (left), harmonic average of interval velocities (center), and mean vertical resistivity (right).



Direct Hydrocarbon Indicator (DHI)

Velocity	Amplitudes	Resistivity	Risk	
✓	✓	✓	🟩	Very likely gas sand
✗	✓	✓	🟩	
✓	✓	✗	🟨	LSG or thin gas sand
✗	✓	✗	🟨	LSG or thin gas sand
✓	✗	✓	🟧	Risk of no reservoir
✗	✗	✓	🟧	Risk of no reservoir
✓	✗	✗	🟧	Risk of no reservoir
✗	✗	✗	🟥	No DHIs: high risk

Figure 10. Risk map for PO15 reservoir sand obtained from the maps shown in Figure 9 (left), with color-code explained on the right. Bottom right shows key log data from Well-1.

The method uses maps of average rock properties extracted within a selected stratigraphic interval. As an example, we use the case of the upper Pliocene reservoir in GD-1. Maps of average properties for this reservoir are presented in Figure 9. The harmonic mean of interval velocities and the average negative amplitude (ANA) of fluid impedance were calculated from top to base of this reservoir. Mean vertical resistivity was obtained using the CSEM constrained inversion results. Cut-offs for these properties, based on log data, were used to create an indicator for each one of these properties separately. For every pixel in the map, the average value obtained for a given property provides either a positive or negative indicator. Based on this simple, although robust approach, it is possible to classify all the pixels in the map to generate a risk map like the one shown in Figure 10. When all the indicators are positive (green color in Figure 10), then we can conclude that there is a high probability to find fully saturated gas sands in that area. In contrast, when ANA indicators are negative (orange in Figure 10), or all the indicators are negative (red in Figure 10) then there is a substantial risk of failure because of either absence of the reservoir, wet sands, or poor rock properties. Notice that low resistivity from CSEM with positive ANA indicator (yellow in Figure 10) does not necessarily mean LSG, since it could also be the result of low net-to-gross or a thin gas layer, as is the case when the location is close to the gas-water contact.

Conclusions and Lessons Learned

CSEM data collected in deep water Trinidad show clear resistivity anomalies at the location of gas discoveries and only background resistivities at known LSG locations. Using CSEM data, we lowered the LSG risk in unpenetrated reservoir segments which has helped to narrow down the range of uncertainties of gas in place.

The feasibility study was a key enabler of the project, leading to a proper survey design and waveform selection. Long offsets were helpful to improve reliability of CSEM results with depth, although CSEM data were still low frequency and unable to separate stacked reservoirs. More energy and closer spacing of source frequencies could have improved results over deep targets; however, there remains a strong need to enhance vertical resolution with this technology.

Even with high quality CSEM data in a well calibrated area, there are still many challenges in fully integrating this data set into workflows for estimating reserves and much more effort is needed to address these challenges. Overall, CSEM data collected in deep water Trinidad met our expectations and the results have helped with future well planning and made a material impact on business decisions.

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