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Challenges in Shallow Water CSEM Surveying: A Case History from Southeast Asia

Sandeep K. Chandola*, Rashidah Karim, Amy Mawarni, Russikin Ismail, Noreehan Shahud, Ramlee Rahman, Paul Bernabe ; PETRONAS Carigali Sdn. Bhd., Kuala Lumpur, Malaysia ; Ketil Brauti, EMGS AS, Trondheim

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Summary

CSEM survey in marginal water depths and complex geological setups poses several challenges due to the interference of airwave with electromagnetic field and the background resistivity variations. Recently, PETRONAS conducted a pilot marine CSEM survey in Southeast Asia in relatively shallow water depths. We present here the challenges encountered and the methodology adopted in analysis of CSEM data and the value addition achieved through the survey.

Introduction

Controlled Source Electro-Magnetic (CSEM) surveys have proved to be useful in de-risking the hydrocarbon prospects in the deep water environment, due to their capability to distinguish between the brine and hydrocarbon saturated reservoirs. However, the diffusion of EM waves through the sub-surface is a complex process and this complexity is compounded by the airwave effect and background resistivity variations. Under such conditions, simplistic interpretation schemes might lead to wrong estimation of the sub-surface resistivities.

In the year 2006, PETRONAS conducted a pilot CSEM survey in one of its offshore block in Southeast Asia with the following objectives:

1. To understand key risks of two hydrocarbon prospects prior to drilling by integrating seismic and CSEM data.
2. To evaluate the strengths and limitations of the CSEM technique for its future application in shallow water depths and complex geological setups.

We adopted an objective driven workflow for modeling, acquisition, processing and interpretation of CSEM data to address various issues likely to affect the data.

Geological Setup and Challenges

The two hydrocarbon prospects identified in the survey area allowed rigorous testing of known limitations and challenges in CSEM survey and the interpretation of data. One of the prospects (Prospect-A) is a faulted anticline structure formed in Late Pliocene with sandstone reservoirs as the primary and secondary targets. . The challenges posed by the CSEM survey over this prospect included complex geology, proximity of primary target to a resistive basement, marginal water depths (200-500 m) and rugged sea-bed topography (Fig.1). The other prospect (Prospect-B) is a thrusted duplex structure, with a four-way dip closure generated in the Middle Miocene. The main reservoir objective is the Early Miocene platform carbonate. Water depths over this prospect range from 500-700 m which is well within the known limits of the CSEM technique. This prospect, however, has a conceptual geologic model built on seismic data with no immediate well control which required intensified workflows for modeling and interpretation. Also, two shallow bathymetric humps present to the east of the prospect could affect the EM response and therefore needed detailed analysis (Fig. 2).

Early CSEM surveys demonstrated that the method is effective in areas of relatively simple geological structures, including deepwater turbidites and channel systems. However these settings represent only a small proportion of potential exploration regimes. The survey area does not fall into the category of relatively simple geological regimes due to the factors mentioned above. In shallow water depths, ǿairwaveǿ, i.e. signals that have interacted with the extremely resistive air can have a severe impact on the recorded signals and can dominate the CSEM response at source-receiver offsets which are sensitive to resistivity structure at the depths of reservoirs. In addition, the effects of rugged sea-bed and resistive basement mentioned above, were also expected to pose a challenge in interpreting the CSEM response and hence needed to be understood well (Fig. 3).

Forward Modeling

In view of the above challenges, comprehensive forward modeling was carried out to understand the CSEM response for different background resistivity models. The modeling was done in two stages:

1. Plane layer 1D feasibility modeling helped in getting an initial estimate of the expected magnitude and phase response and to optimize the base transmission frequency for the survey (Fig.4a).

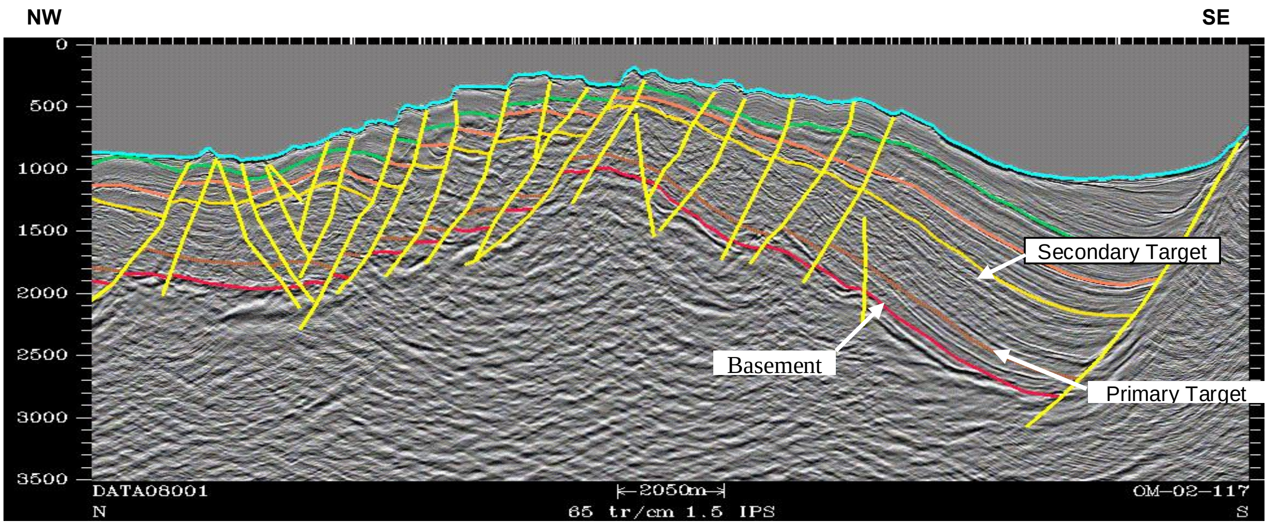


Fig. 1, Seismic section through Prospect-A showing the hydrocarbon targets and the basement. Note the proximity primary target to the resistive basement.

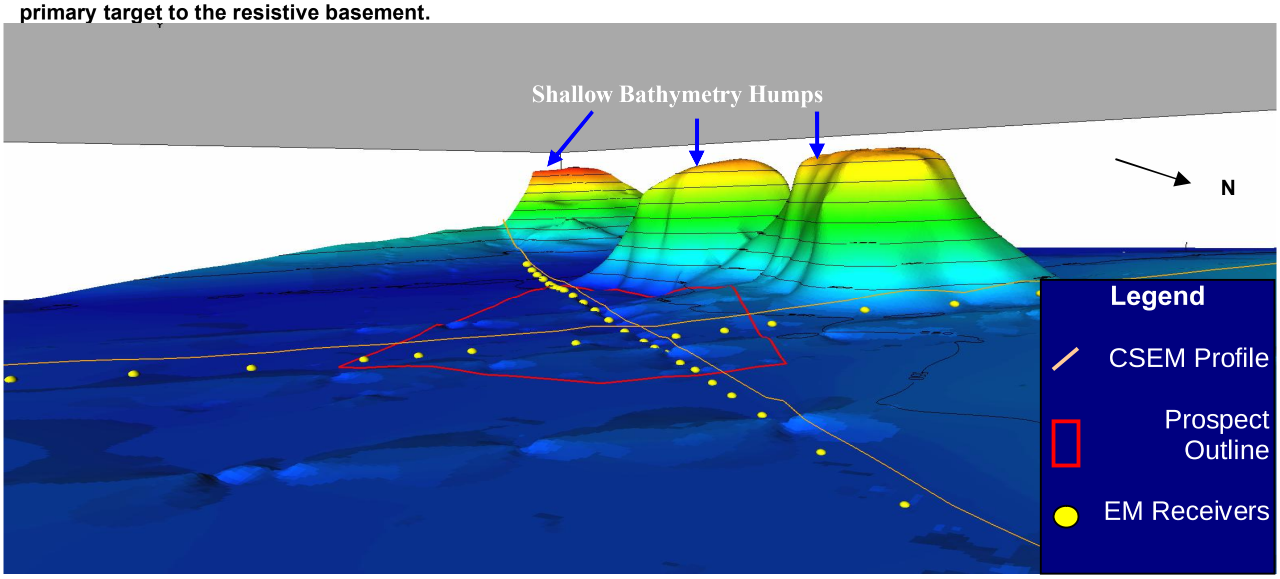
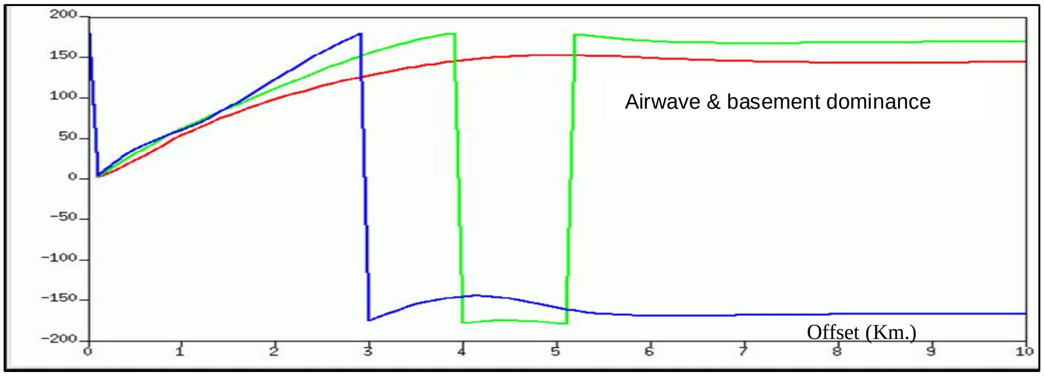


Fig.2, Three dimensional view of seabed topography around Prospect-B showing shallow bathymetry humps to the east of the prospect in an otherwise gentle surrounding.



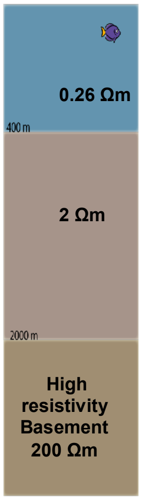


Fig.3, Simple plane layer model of Prospect-A (right) showing the effect of airwave and resistive basement on Ex phase response for frequencies of 0.45, 0.75 and 1.05 Hz.

2. 3D modeling took into account the dimensions of the target, seafloor topography and other geometrical effects caused by the different layers in the subsurface. 3D models are based on interpreted seismic horizons together with the prospect outlines provided by the interpreter (Fig.4b). Different background resistivity models were used for each prospect and each model was run with two reservoir resistivity values of 20 and 40 Ohm-m (based on resistivity data of nearby well). The effect of background resistivity on EM response was removed from the gross response to obtain the net normalized magnitude and phase response caused by the probable reservoirs (Fig. 4c and 4d).

The 1D and 3D forward modeling indicated that although background resistivity itself may cause MVO and PVO response, the net response after removing background effects caused by the probable reservoirs, was measurable.

Survey Design and Data Acquisition

For both the prospects A & B, a nominal receiver spacing of 1.5 km was used with closer receiver spacing near the edges of the prospects. Additional receivers were deployed broadside of the source tow direction to get azimuthal resistivity information, particularly in view of the complex geology and bathymetric variations. The source consisted of a horizontal electric dipole towed at depth of 30 meters above the seabed, with a base frequency of 0.15 Hz. emitting a continuous square wave signal. In general, data quality over both the prospects was good up to source-receiver offsets of 10-12 km for the base frequency. Processed data presented as both individual receivers and line summary showed magnitude and phase anomalies on both the prospects.

Data Processing and Interpretation Methodology

The key drivers for the CSEM data processing and interpretation were estimation and removal of effects of the airwave, seabed topography, shallow carbonates and the resistive basement. Currently in the industry, different approaches are adopted to address the issue of airwave including:

a. Understanding the physics behind the airwave phenomenon to design data acquisition and processing to mitigate its effect (e.g. up-down separation using EM wave field decomposition).
b. The magnitude and phase of the airwave is also sensitive to the sub-surface resistivity. Therefore appropriate interpretation and inversion schemes should be adopted to derive the resistivity structure from the measured EM fields in the presence of airwave (and other background effects).

We adopted a combination of both these approaches for processing and interpretation of the data. While up-down separation on Prospect-A did not show any improvement (probably due to the fact that the ñairwave effectò is not significant when compared to the contribution from the resistive basement), for Prospect-B, the phase anomaly increased significantly after up-down separation (Fig. 5).

The data processing was supplemented by the interpretation scheme consisting of the analysis of EM-responses based on post-survey 3D modelling of sub-surface resistivity structure. The measured EM response over the two prospects were interpreted and compared with the modeled response. Comparisons were made for a representative receiver located over the target for each of the lines as well as for normalized magnitude and phase difference values to see if there are similarities in response between modeled and measured response. Other diagnostics like CMP offset plots were also analyzed to minimize the possible pitfalls associated with interpretation of the MVO and PVO responses alone.

Depth Migration and Post Survey Modeling

Depth migration of CSEM data estimates lateral extent and depth to a resistor. While carrying out the depth migration of CSEM data, its differences with the seismic depth migration need to be understood. One basic difference is that CSEM depth migration typically uses 4-5 discrete frequencies for imaging while seismic migration uses a dense and almost continuous frequency spectrum. The algorithm adopted in our study is a pre-stack depth migration method that incorporates the Maxwell equations together with an imaging principle suitable for the CSEM method. The transverse resistance (product of resistivity and thickness) of the resistor is used as an input to migrate the data. Depth migration on Prospect-A was particularly challenging due to the presence of resistive basement close to the primary target. Three frequencies 0.45, 0.75 and 1.05 Hz were used for depth migration while the base frequency of 0.15 Hz was discarded due to poor resolution and low sensitivity to thin resistors above resistive basement. Inline rotation and up-down separation were performed on data before depth migration to minimize the possible effect of shallow bathymetry. The depth migration of line Tx02 for Prospect-A shows interesting results (Fig.6). The lateral extent of the resistivity anomaly observed on the MVO plot on top of the figure is significantly reduced after depth migration and the resistivity anomaly observed in the SE part of the line is attributed to the possible 3D effect of the resistive basement. There is also an indication of lower background resistivity than the value used in forward modelling (conductive anomaly) in the shallow part.

Another important part of the interpretation workflow was the post survey 3D forward modelling using different background resistivity models. For each model, the synthetic magnitude and phase responses of individual representative receivers as well as the normalized responses were compared with the measured response to look for similarities. This approach was particularly helpful in ruling out any significant impact of shallow bathymetry bumps and the carbonates on the measured CSEM response for Prospect-B.

Therefore, depth migration and post survey forward modelling helped in refining the simplistic interpretation of the data based on magnitude and phase plots alone.

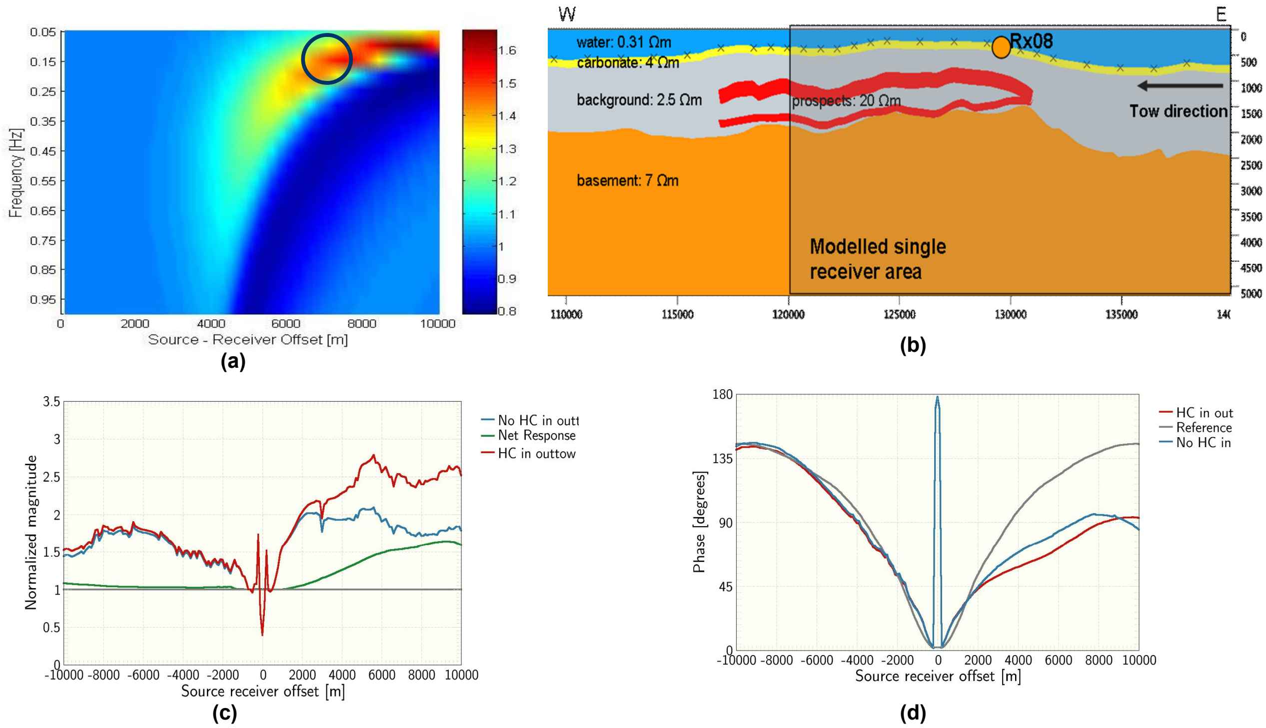


Fig.4, (a) Frequency scan (b) 3D resistivity model (c) Normalized electric field magnitude and (d) Normalized phase response for Prospect-A for the 3D model. Base frequency of 0.15 Hz was considered optimum based on the modeling.

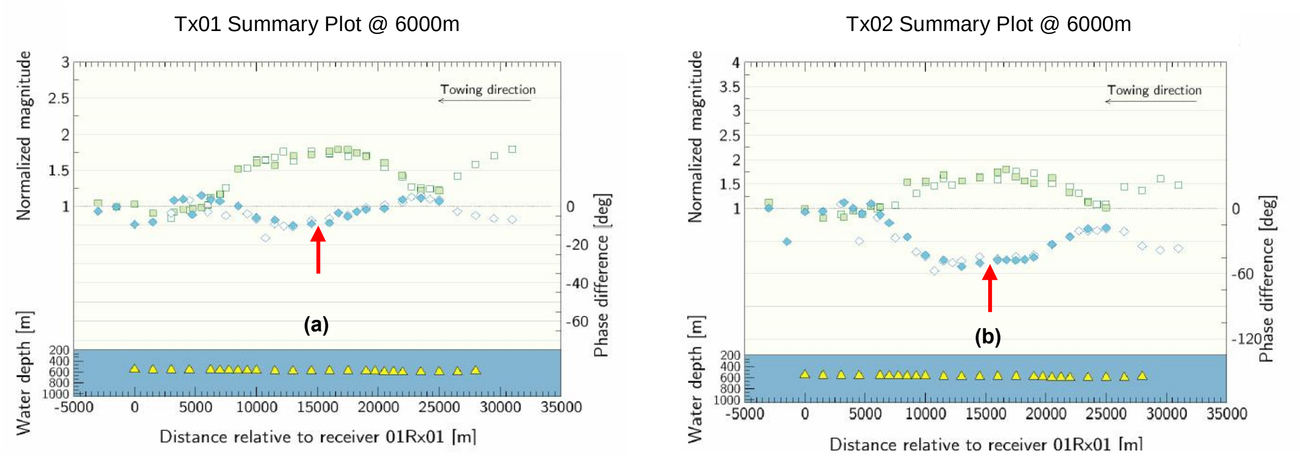


Fig.5, Line summary plots of normalized electric field magnitude for Prospect-B, (a) before and (b) after up-down separation showing resistivity anomaly on both datasets. Note the significant increase in phase difference anomaly after up-down separation.

Conclusions and Way Forward

Interesting results have been obtained from the pilot project conducted by PETRONAS paving the way for future application of CSEM surveys in de-risking offshore hydrocarbon prospects. An attempt has been made to address some of the major challenges in the CSEM prospecting such as shallow bathymetry, seabed topography, shallow carbonates, resistive basement etc. by adopting an interactive data processing and analytical interpretation workflow. In the overall assessment, CSEM data has helped in an improved understanding of the key risks associated with Prospect-A and the possible (at least partial) masking of the response from reservoir due to shallow bathymetry and resistive basement. On the other hand, it has also helped in eliminating few uncertainties concerning Prospect-B like the effects of offline shallow bathymetry humps and shallow carbonate layer.

Although pre and post survey modelling and depth migration have helped in evaluating and partially explaining the observed CSEM responses, some questions still remain to be answered. Future advancement in data processing and inversion algorithms may further improve our understanding of the CSEM response in shallow water environment under complex geological settings. 3D depth migration and anisotropic inversion of the 3D CSEM data could be the future, but at the moment, the cost and time factors associated with this approach are somewhat prohibitive. Multiple revisits to the acquired CSEM datasets may also be necessary with the ongoing research and advancement in processing and inversion algorithms. Post drilling calibration of background resistivity structure is also a valuable lesson learnt.

Acknowledgement

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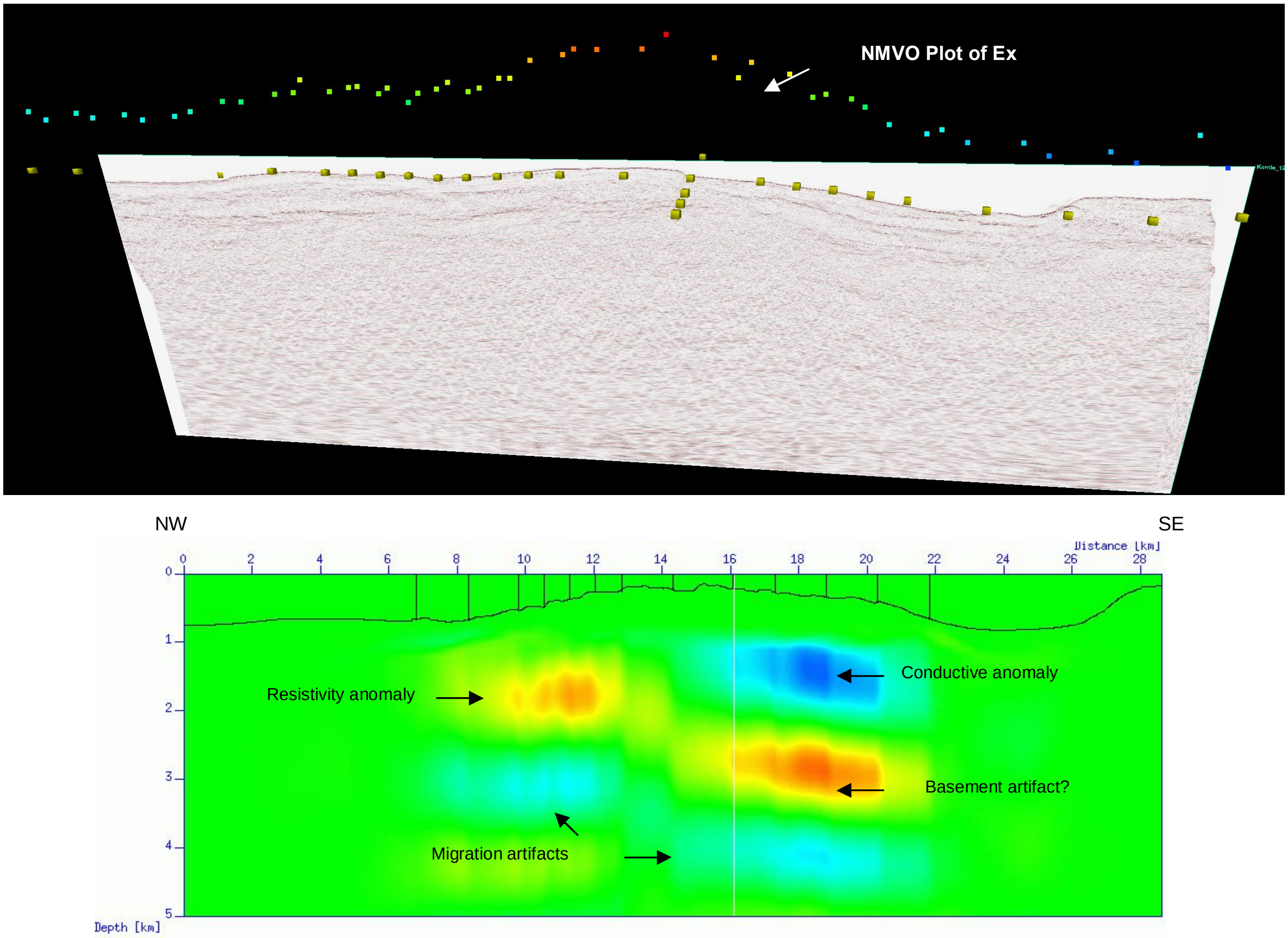

Fig.6, Seismic section (top) and CSEM depth migration of line Tx02 over Prospect-A (bottom). The depth migration results are significantly different from the NMVO response plotted on top.

<u>Note</u>: The views expressed in this paper are those of the authors and do not necessarily represent the views of PETRONAS Carigali.