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Electro-Magnetic Sensitivity in the Bengal Basin: Implications for Exploration in Myanmar, Bangladesh and NE India

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Abstract

The Ganges Brahmaputra Delta and the associated Bengal Fan is the world's largest delta/submarine fan complex. The deepwater areas of the Bengal and Rakhine Basins are relatively underexplored frontier areas. In 2003 the large Shwe gas field was discovered in Lower Pliocene turbidite fan sediments with reserve estimates of 6-9 tcf. As additional blocks are licensed, new data will be acquired to evaluate the area including 3D CSEM which is being considered as a complementary exploration method to seismic data.

The controlled-source electromagnetic (CSEM) method has been applied to oil and gas exploration and production for more than 10 years. EM data are used to indicate the presence of hydrocarbons, since hydrocarbon saturated rocks display higher electric resistivity compared to water-filled reservoirs. CSEM is an excellent technique to define the lateral extent of hydrocarbon accumulations and is particularly useful in determining the existence and extent of stratigraphic accumulations.

3D modelling indicates CSEM is sensitive to the Shwe Field reservoirs and can define the lateral extent of the pay zones. 3D CSEM forward modelling has been performed over a range of target sizes within the economic limitations of deepwater drilling, and the modelling shows that CSEM would be sensitive to those targets.

Based on these results, it is concluded that CSEM 3D data will detect the presence of hydrocarbon accumulations and thus, high-grade exploration areas in the greater Bengal Basin.

Introduction

In this paper we describe how the deepwater reservoir sediments in the Bay of Bengal, dominated by a deepwater turbidite depositional process, is the ideal geologic setting for detecting resistive anomalies related to hydrocarbon accumulations. Turbidites, by nature, are anomalous deposits of sand encased in shale. When saturated with hydrocarbons, they are more resistive than the surrounding shales, allowing them to be detected using the marine controlled source electromagnetic (CSEM) method. CSEM is sensitive to the large Shwe field accumulation on the shelf, offshore Myanmar and is used in this study to illustrate the ranges of detectability in the adjacent deepwater areas (Fig. 1).

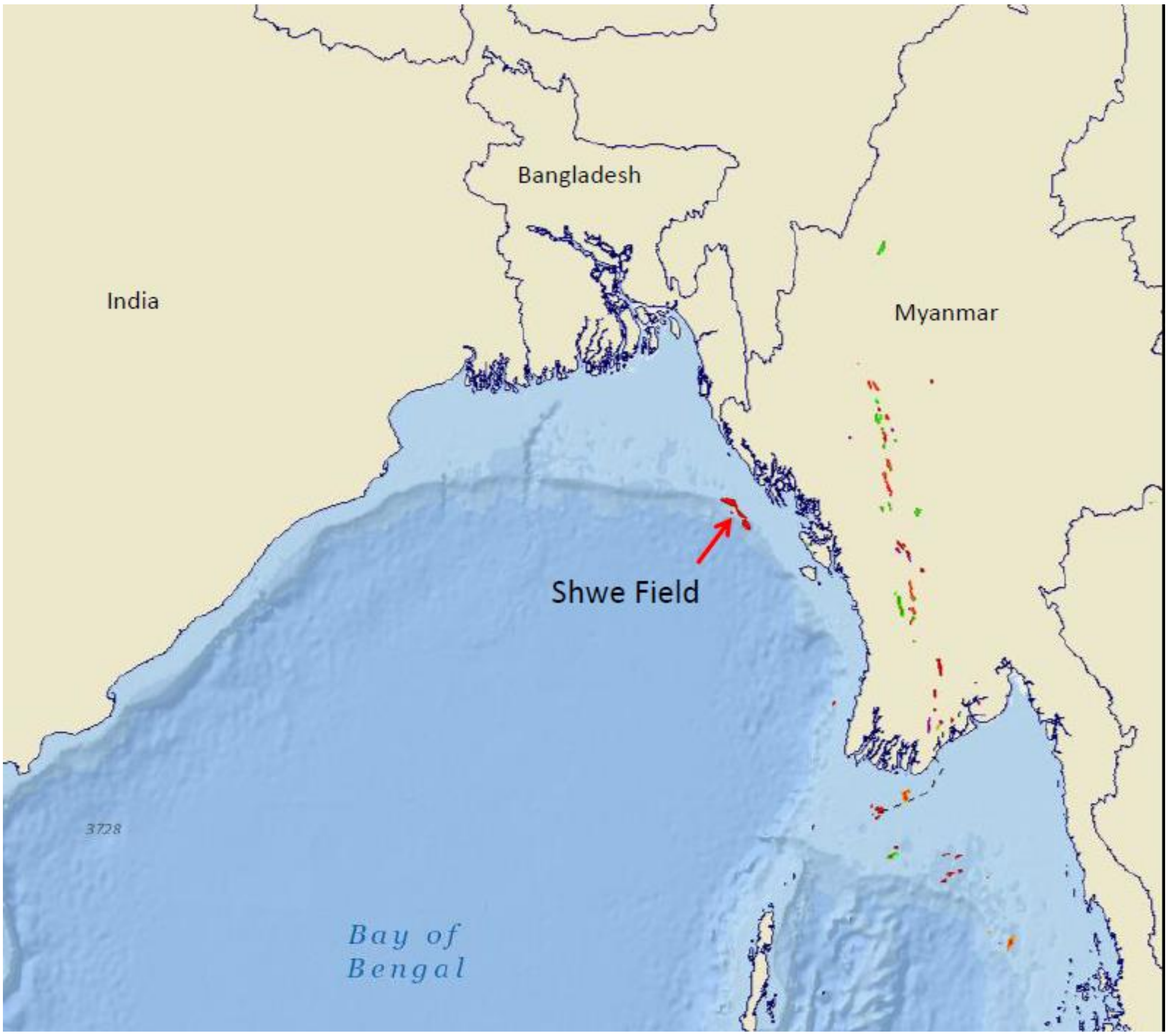


Fig. 1. Bay of Bengal and Shwe field location

Depositional Environment of the Bengal Fan

The Ganges Brahmaputra Delta and the associated Bengal Fan is the world's largest delta/submarine fan complex, approximately 3x10^{6} km$^{2.}$ (Curray et al., 2003, Yang & Kim, 2014). Over 20 km of sediment has accumulated in the Bengal fan since the Cretaceous period. Deepwater shales and turbidites occur in Eocene and Palaeocene outcrops and DSDP drill cores on the active fan encountered Miocene and Pliocene turbidites. Together these indicate that the entire basin has filled with turbidite sediments from episodic pulses related to tectonic and/or climatic fluctuations (Basu et al., 2010; Curray et al., 2003). A constant accumulation of pelagic sediments encase the coarser grained turbidites. Hi-resolution seismic shows that the modern progradation of the base of the continental slope is a system of incised canyons funnelling turbidites to the deepwater. This main part of the Bengal fan has been accumulating for at least the last 20 million years (Frans-Lanord et al., 2000).

Deep water turbidite sediment accumulation is generally restricted to the currently active channel with maximum sedimentation on the flank of the channel levees and initial terraces. Overbank deposits and canyon mouth fans accumulate 20 to 100 km away. This leads to a high degree of lateral, vertical and temporal variability and limited sediment continuity (Frans-Lanord et al., 2000). Near surface, high resolution seismic profiles show the relief created by the episodic pulses of sedimentation down canyons and spilling over and outside the channel system. These structures and folding related to differential compaction would influence deposition and locally pond turbidites into thicker packages. This type of deposition is difficult to map using seismic data. The large Shwe field is mapped as an accumulation of coalescing debris flow/turbidites ponded against a local structural high (Yang & Kim, 2014). The following discussion addresses the use of the CSEM method as an aid in the identification of any potential hydrocarbon accumulations within these deposits.

Explanation of CSEM Sensitivity

CSEM has been used as an exploration tool for over a decade. Certain geologic occurrences can be thought of as a three-dimensional geo-body, such as an accumulation of hydrocarbons. Hydrocarbon accumulation with high saturation creates a resistivity contrast to the surrounding media and an anomaly can be detected.

The use of EM to define hydrocarbon accumulations is well documented (Fanavoll et al., 2010). Recently, CSEM has been incorporated into the exploration plans in Norway, Brazil and the Gulf of Mexico (Gabrielsen et al., 2013; Alcocer et al., 2013; Pedersen & Hiner, 2014). 3D CSEM is sensitive to the transverse resistance of a target. Transverse resistance is the product of the thickness and resistivity of a geobody. The response depends on the resistivity, thickness, burial depth and area of the geobody, as well as the resistivity of the sediments the electromagnetic wave field passes down and back through. To evaluate the sensitivity of CSEM in a given area, modelling based on *a priori* knowledge has been performed. The sensitivity metric is the relative difference between the response from a HC saturated case and the response from a water saturated case weighted by the relative uncertainty and ambient noise level (equation 1) and illustrated in Figure 2. Equation 1 is a reasonable approximation to the total uncertainty in the offset range used in CSEM (Mittet and Morten, 2012).

$$sensitivity = \left| \frac{F_{target} - F_{background}}{\sqrt{\alpha^2 \left|F_{target}\right|^2 + \delta\phi^2 \left|\overline{F}_{target}\right|^2 + \frac{\eta^2}{d^2}}} \right| \qquad [1]$$

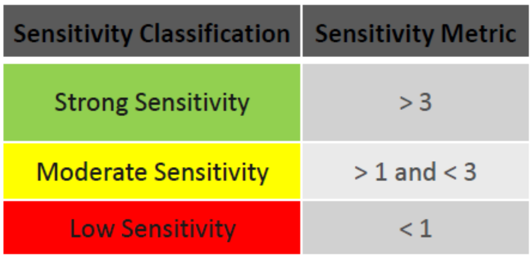
F is the field (standing for E and H)

α is the relative uncertainty (1.5 - 2.5%)

η is the unscaled ambient noise level which is dependent on the latitude and water depth of the receiver

φ receiver orientation uncertainty (± 2 degrees)

d is the source dipole moment

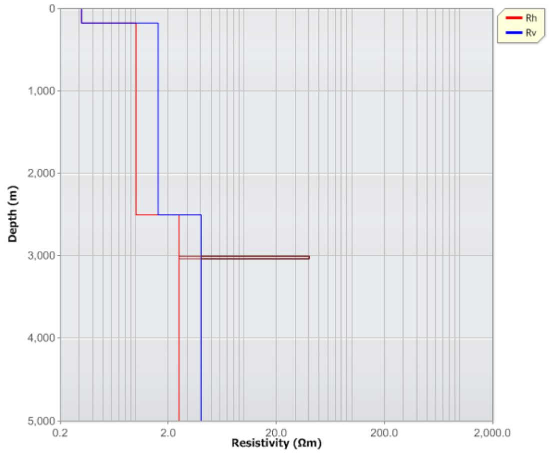


Sensitivity Classification	Sensitivity Metric
Strong Sensitivity	> 3
Moderate Sensitivity	> 1 and < 3
Low Sensitivity	< 1

Fig. 2. Sensitivity Computation

The relative uncertainty value, α, used in this study is set to 1.5 and 2.5% for the shallow towed source and deep towed conventional source respectively. The unscaled electrical ambient noise level in the frequency band 0.05 to 5 Hz, is set to be in the range $7.81 \cdot 10^{-10}$ to $7.81 \cdot 10^{-11}$ [V/m] and $9.4 \cdot 10^{-11}$ to $9.4 \cdot 10^{-12}$ [V/m] for 175m water depth and 1500m water depth respectively. These are all conservative estimates based on expected CSEM equipment performance as well as expected ambient noise level at the given water depth and latitude for this case.

In this study we model CSEM sensitivity to the Shwe field, discovered in 2003 by Daewoo and well documented by Daewoo geoscientists. The Shwe field sensitivity was modelled using data from recent publications (Yang & Kim, 2014). A background resistivity model is built using existing well data. Target thickness and resistivity are determined from the published well logs and a model of the subsurface sensitivity is derived (Fig. 3).



Name	Top (m)	Rh (Ωm)	Rv (Ωm)	Anisotropy (Rv/Rh)
Water	0	0,3125	0,3125	1,0
Upper	175	1	1,6	1,6
Overburden	2500	2	4	2.0
Target Top	3100	20	40	2,0
Underburden	3125	2	4	2.0

Fig. 3. Shwe Field sensitivity modelling

3D sensitivity modelling software allows the user to vary parameters such as target thickness, depth, background resistivity, target resistivity, shape and area of a target. Recent publications show the saturated thickness in the Shwe field varies between 15 and 50 meters (Kim, Yang and Kim, 2012). The horizontal resistivity logged within the turbidite reservoir sands is approximately 18 ohm m. Both the horizontal and vertical resistivity is modelled. The true horizontal resistivity of a reservoir is likely to be higher than what the logging tool measures, due to limitation in the logging tool resolution. This effect increases for thin resistors or reservoirs interbedded with shales. In addition, some anisotropy of the sediments should be expected so that the horizontal resistivity measured and shown on a well log is typically lower than the true vertical resistivity. In this case we assume the field is buried 3100 meters below the sea bed, the area is 80 km^2, the reservoir is 25 meters thick and vertical resistivity is 40 ohm m. Figure 4 illustrates the target sensitivity as these parameters are varied.

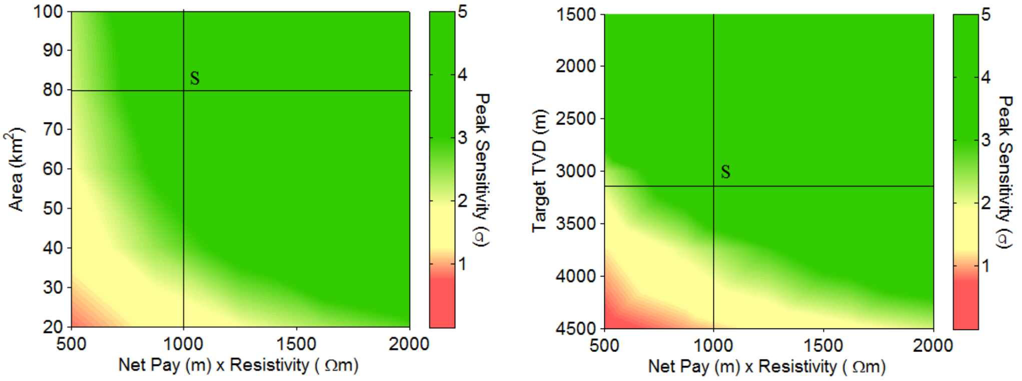


Fig. 4. Shwe Field sensitivity, S=average Shwe field measurements

One can see that a variety of plots can be derived to test sensitivity to depth, resistivity, and thickness. If any parameters are assumed to be constant, then others can be derived. For instance, sensitivity of net pay times resistivity versus area (left plot of figure 4), shows high sensitivity (sensitivity (σ) > 3) for a target area larger than ~45 km^2 at a burial depth of 3100 meters below sea bed, reservoir thickness of

25 meter and resistivity of 40 ohm m.

The Shwe field is interpreted as overlapping, coalescing, turbidite fan lobes. Yang & Kim (2014) used amplitude extractions from the seismic data to map the thickest and thinnest accumulations. Existing fan lobes act as barriers and divert successive fan lobes decreasing the chance for multiple, stacked reservoirs. Porosity and other rock properties are derived from seismic (Kim, Yang & Kim, 2012) but seismic is not sensitive to water saturation. CSEM will indicate if a target reservoir is more resistive than the background, leading to the indication the reservoir is likely hydrocarbon charged and has a low water saturation. Therefore, a combination of seismic and CSEM integrated together can hi-grade exploration targets that neither could do on its own. Figure 5 shows a structural map displayed together with a seismic amplitude extraction on the left and CSEM horizon slice co-visualized with the same structural map to illustrate how CSEM can hi-grade seismic anomalies.

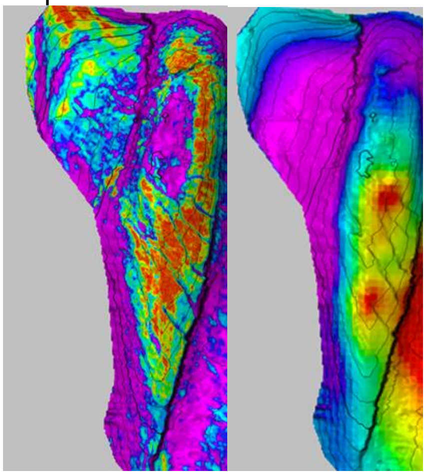


Fig. 5. A structural map displayed together with a seismic amplitude extraction (left) and CSEM horizon slice co-visualized with the same structural map (right) to illustrate how CSEM can hi-grade seismic anomalies.

Integrating available data and analysis of CSEM anomalies allow interpreters to determine the saturated rock volume at each drilling location. This helps to de-risk the selection of well locations.

Current commercial equipment has been used successfully at water depths as deep as 3500 meters. In shallow water (less than ~400 meters), the powerful (7200 Amps) shallow towed source is typically applied, which has been operating in water as shallow as 19 meters (EMGS, 2013). If the water is too deep to deploy the shallow towed system, then the conventional (1250 Amps) source is used. The Shwe field is buried between 2900 and 3100 meters below the mud line in shallow water ranging from 50 to 150 meters. As shown above, the Shwe field accumulation is detectable using the shallow towed source. When extended to a water depth of 1500 meters using the conventional source, CSEM has high sensitivity (sensitivity (σ) > 3) for an accumulation above 3650 meters (TVD) or 2150 meters blow the mud line, given similar size, thickness and resistivity as the Shwe field (fig. 6). This result shows that burial depth is the dominant factor versus area in detectability, when the area is larger than ~30 km^2.

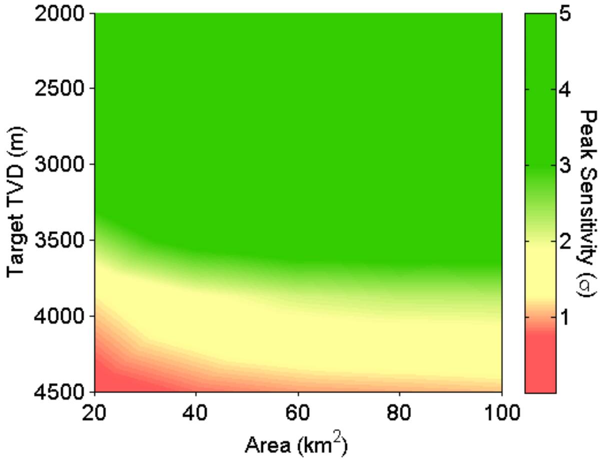


Fig. 6. Sensitivity to a deepwater Shwe analogue using the conventional source in 1500 m water.

Other important factors for the detectability of anomalies would be the resistivity contrast towards the background (the shale) and the thickness of the anomalies (hydrocarbon saturated turbidite sand bodies). Recent CSEM acquisition in this area has indicated that the background resistivity increases with depth and is likely to be a function of compaction. If we assume the targets are turbidite sand bodies encased in shale, it can also be assumed that the compaction rate of the sediments differs. In this case, the shales would compact faster and possibly the resistivity of the background would increase to a point where there is not enough resistivity contrast for CSEM to be sensitive to the target.

This resistivity increase related to sediment compaction can reduce the threshold for which CSEM if effective. However, seismic data shows the stratigraphic column thins in deep water areas and the Shwe field stratigraphic section is not as deeply buried (Fig. 7). In addition, the observed resistivity increase with depth occurs in a stratigraphic interval that is older than the Shwe field.

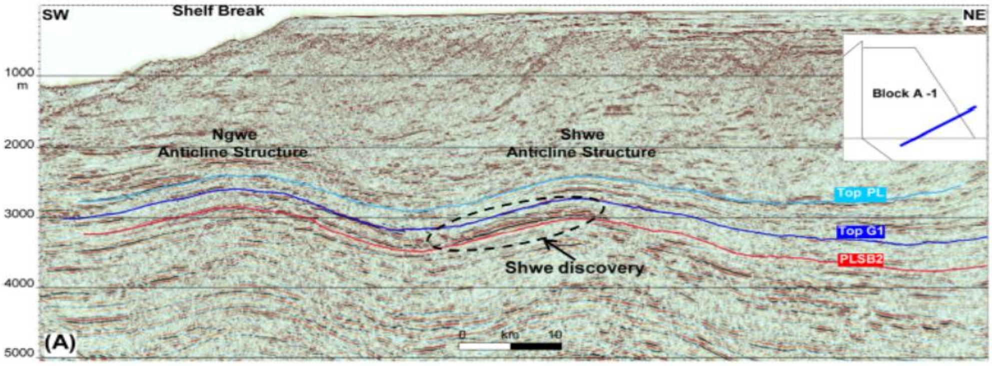


Fig. 7. Seismic section shows the stratigraphic column thins in deep water areas and the Shwe field stratigraphic section is not as deeply buried (Yang & Kim 2014)

CSEM for Exploration

The deepwater Bengal Basin and the Rakhine sub-Basin are dominated by deepwater turbidite deposition. When exploring for stratigraphic traps of basin floor fans, one can build a stratigraphic model and using data and analogues, determine transport direction to map sandy accumulations. Using seismic data you can map the thickest accumulation. Seismic amplitude extractions are related to rock properties and fluid content. CSEM will indicate which part of the sedimentary package is more resistive, an indicator of reduced saline water saturation.

A variety of conditions combine to yield exploration targets in basin floor fan deposits. Whether it’s ponded against a bump in the seafloor or the termination of a debris flow deposit, the accumulation of coarse grain sediments is the exploration target. The turbidite, by nature, creates the reservoir and is surrounded by the seal. It can even carry its own source with it (Saller et al, 2006). However, explorationists would not be able to determine if this classic stratigraphic trap is charged. CSEM will answer that question and de-risk the drilling targets. There appears to be no other geologic layers in the stratigraphic column that would cause a resistor other than an accumulation of hydrocarbons.

We have previously described how to determine the range of sensitivity of targets with a predictable range of thickness and resistivity. The background of the sediments remains unknown. Modelling software can vary the parameters of the target size to determine if a resistive anomaly would be detected. It can also be used to assess the size of targets. The term “economic accumulation” varies depending on numerous, factors. Once that limit is established, reservoir engineers can estimate the volume of the accumulation dependent on burial depth. If the thickness and resistivity are assumed to be constants, the two-dimensional surface area of the minimum economic accumulation can be determined. Using CSEM, the area of a target is identified. Modelling can determine the minimum detectable two-dimensional area (Balter & Roth, 2013).

In the case of multiple, stacked pay sands, such as overlapping fan lobes, CSEM could not distinguish between the reservoirs and would only “see” a single anomaly. The overlapping portions would give the appearance of a very thick or very resistive target. However, understanding the geologic model and the limitations on the thickness, lateral size and resistivity of individual turbidite sands, it would be interpreted that there are possibly multiple pay intervals. This kind of integrated interpretation should always be a part of the prospect risking analysis.

Conclusion

In the Bengal Basin and Rakhine sub-basin deepwater Bengal Fan deposition is dominated by debris flows and the exploration targets are all deep water turbidites. These deposits themselves are anomalous sand deposits surrounded by shale and CSEM can determine if they are charged with hydrocarbons. CSEM is sensitive to the largest field discovered to date, the Shwe field complex on the Myanmar shelf and the under-explored deepwater areas have recently been offered in a licensing round. The integrated interpretation of 3D CSEM and seismic data will enable explorationists to determine the existence and extent of economic accumulations within the new licensing areas resulting in an optimized and de-risked prospect portfolio.

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