Reducing uncertainty by integrating 3D CSEM in the Mexican deep-water exploration workflow

José Antonio Escalera Alcocer, Marco Vázquez García, and Humberto Salazar Soto, Daniel Baltar, Valente Ricoi Paramo, Pál T. Gabrielsen and Friedrich Roth show with four case studies how the inclusion of 3D CSEM resistivity data with seismic and other data provided more confidence in Pemex reservoir evaluations and so positively impacted the company’s exploration programme.

The addition of 3D CSEM derived resistivity to seismic data enables more certainty in the creation of a geologic model and provides higher confidence in the probability of success and reserve estimation evaluations.

To mitigate risk and prioritize an offshore exploration portfolio, it has become important for Pemex to adopt technologies that could improve prospect evaluation at a portfolio scale. After a pilot project in 2008, 3D controlled source electromagnetics (CSEM) was identified as one of these technologies. Between 2010 and 2012, Pemex acquired >12,000 km² of 3D CSEM over 35 prospects identified by 3D seismic data (see Figure 1). After drilling a number of these prospects, Pemex has found that integrating 3D CSEM data in its exploration workflow significantly reduced uncertainties in the evaluation of prospects and play types.

Building on the work of previous authors (Eidesmo et al., 2002; Stefatos et al., 2009; Fanavoll et al., 2010; Ridyard et al., 2011) this work focuses on the use and integration of 3D CSEM with other geophysical datasets to quantify and reduce exploration risk in four exploration cases subsequently validated by drilling results.

Statistical prospect evaluation
Prospects are usually evaluated based on three key parameters:
1. Probability of success
2. Minimum economic field size
3. Reserve estimation

The probability of success is the probability of finding a hydrocarbon accumulation that can sustain flow (Rose, 2001). In exploration settings the amount of available information is typically low; therefore the uncertainty on the probability assessment is high.

The minimum economic field size conveys engineering, geographical, and economic information and cannot usually be affected by the additional geophysical or geological information.

The reserve estimation typically suffers from such high uncertainties that it is statistical rather than deterministic. A recoverable reserve probability distribution is often generated using an equation similar to this:

\[
RR = \frac{A \Delta Z \theta S_{HC} RF}{FVF}
\]

Where RR are recoverable reserves, A is the area, ΔZ is the net reservoir thickness, θ is the porosity, \(S_{HC}\) is the hydrocarbon saturation, RF is the recovery factor and FVF is the hydrocarbon shrinkage factor. In an exploration scenario, the largest uncertainties are often in the area and net reservoir thickness.

The use and integration of 3D CSEM data in a statistical prospect evaluation reduces the uncertainty in the factors associated to probability of success and reserve estimation. This concept will be expanded in the next section.

Resistivity information from 3D CSEM

With scarce, distant, or not relevant well data, we typically rely on the structural images and elastic properties derived from seismic data and geologic analogues when evaluating an exploration project. Using the 3D seismic, we can evaluate the structure, seal (presence or absence), presence, and quality of the reservoir, fault patterns and then generate the surfaces for basin modelling. In some cases, seismic can be used to assess the presence of hydrocarbons in the reservoir and/or evaluate fluid migration.

The electrical resistivity of a sedimentary rock is largely determined by its porosity and the fluids occupying its pore space. A brine-saturated, good porosity reservoir rock will typically have low resistivity due to the low resistivity of brine. When hydrocarbon-filled, that same reservoir rock will become resistive. This concept has been the basis for the invention of resistivity logging in the 1920s and equally applies to CSEM. High formation resistivity, however, may also be a result of low porosity lithology, low pore space connectivity or very low salinity brine. Some hydrocarbon-filled
Integration of 3D CSEM resistivity

The integration of 3D CSEM with 3D seismic and geological information enhances the understanding of the subsurface by limiting the range of possible geological scenarios either by resolving an interpretation ambiguity or by reinforcing common, yet independent observations. This often translates to an improved understanding of the probability of success, and reserve estimation.

The following four case histories are integrated interpretations using 3D CSEM data with the aim of improving the prospect evaluation. In Case A, a positive CSEM response example, there is a clear fit between the seismic and 3D CSEM data and therefore, the integrated interpretation has a high degree of certainty. For Cases B, C, and D, the seismic or CSEM data have quality limitations or the fit between both data sets is not clear; therefore, the evidence has to be carefully weighed resulting in a smaller uncertainty reduction in the interpretation.

Case A

The prospect is located approximately 700 m below mudline and is a classic anticlinal trap. The reservoir interval is a known regional interval and seismic attribute analysis confirms the regional geology at the prospect level. The petroleum system is proven and is not considered a major risk. The top of the reservoir interval presents a seismic bright spot with two associated flat spots, (Figure 2a and c) interpreted as gas-oil and oil-water contacts. This expected model is supported by the seismic amplitude analysis indicating the presence of a likely hydrocarbon-bearing reservoir. The main uncertainty is the hydrocarbon saturation; given the shallow depth to the reservoir, it is possible that low gas saturation is producing the bright amplitudes.

In the 3D CSEM inversion data, an Rv anomaly can be seen at the top of the structure and the resistivity anomaly is consistent with the uppermost part of the seismic anomaly and the first flat spot in the structure seen in Figure 2b.

After incorporating the 3D CSEM results, the integrated interpretation determined the accumulation consists of a good reservoir with high gas saturation down to the first flat spot and low hydrocarbon saturation further down dip. This observation provided an increase in the probability of success and a reduction in the reserve estimation for the prospect.

The interpretation was later confirmed by the drilling results from two wells. One well was inside the first flat spot encountering 40 m of net pay with high gas saturation and the second well, focused on a deeper target which has low CSEM sensitivity, encountered a similar reservoir interval in the down dip section but with low hydrocarbon saturation.

Case A illustrates the integration of 3D seismic and 3D CSEM data provides more interpretation certainty than using either dataset independently. Used separately, CSEM would have difficulty determining if the anomaly was hydrocarbon and seismic would have a high degree of uncertainty regarding the hydrocarbon saturation.
This integrated interpretation was confirmed by a well that only encountered gas shows with good quality reservoir sands at the target level. Furthermore, the CSEM resistivity estimation showed an excellent fit with the well log resistivity trends (see Figure 4).

**Case C**

The prospect is located approximately 1800 m below mudline and consists of an anticlinal structure situated within a compressional belt where a variety of compressional structures...
occurs at various scales. The prospect is riddled by faults displacing various stratigraphic levels including the interval where the target is located. Overlying the main structure, a seismic sequence is present which is almost devoid of faults, providing just enough sealing capacity for the entire structural closure.

The main target is a regional reservoir interval and it presents quite reasonable conformance with the structural closure and is associated with anomalous seismic amplitudes (Figure 5a). The initial interpretation relies purely on seismic data and geological knowledge and favours the presence of a hydrocarbon accumulation. The main risk is the hydrocarbon saturation/seal, as the column height is quite large.

In the 3D CSEM inversion data, an Rv anomaly is present that has a good fit with the seismic amplitudes within the structural closure (Figure 4b). This reduces the risk of low saturation being the origin of the seismic amplitudes, and confirms the large areal extent of the accumulation. With this interpretation, both the probability of success and reserves of this prospect were updated. The degree of uncertainty is higher in this case than the previous two cases as the seismic is affected by a shadow from shallow high amplitudes and the CSEM is affected by the presence of salt and a complicated overburden. There are other highly resistive features in the dataset, but they were interpreted as non-hydrocarbon related when integrated with the seismic data.

The target was drilled encountering two hydrocarbon-filled reservoir intervals and confirming the interpretation derived from the integration of regional geology, 3D seismic, and 3D CSEM data.

Case D
This prospect consists of a large anticline riddled with faults displacing various stratigraphic tiers and two known regional reservoir intervals 500 m and 1100 m below mudline. The shallow interval is characterized by strong seismic amplitudes with a large areal extent that indicate a high likelihood of a reservoir with risks in reservoir quality and hydrocarbon saturation. The deeper reservoir is shadowed by the high seismic amplitudes above, thus making a complete interpretation of the seismic amplitudes at the reservoir level challenging. Some bright amplitudes can be mapped inside and outside the shadowed area but the higher risk for this deeper target is reservoir distribution and hydrocarbon saturation.

The 3D CSEM data in the area are of very good quality and considered to have excellent sensitivity to both target levels. There is no resistivity associated to the first target implying an increased risk of low hydrocarbon saturation (lower probability of success) and a decrease in the expected reserves associated with this target. The second target has an Rv anomaly associated with it, and when mapped as TR, the resistivity anomaly is clearly limited by the main fault set that runs along the structural axis (Figure 6). Other smaller faults in the structure seem to act as TR boundaries, thus providing some insight into the hydrocarbon distribution inside the reservoir. These results allowed for a change in the evaluation of both targets: first target was deemed as low value, while the value of the second target can be increased significantly, mainly through a significant reduction in the reserve estimation uncertainty. The lack of supporting seismic amplitudes for the second objective reduces our ability to reduce its uncertainties further. The low seismic data quality makes the resistivity data more valuable as it provides an insight on the hydrocarbon-filled reservoir distribution that the seismic could not produce.
Four case histories were used to illustrate the positive impact of using CSEM resistivity data in an integrated interpretation to improve prospect evaluation at a portfolio scale in accordance to probability of success and reserve estimation.

References


A well was drilled encountering a low saturation reservoir in the shallow target and a hydrocarbon charged reservoir (approx. 60 m of net pay) at 1100 m below mudline. The well has been announced as a discovery, and the integration of both seismic-structural interpretations and the Rv anomaly distribution is used to enhance the understanding of hydrocarbon accumulation and distribution within this discovery.

Conclusions

- The addition of a new data set measuring an independent earth property, such as resistivity, should reduce interpretation uncertainty. By adding 3D CSEM to the workflow, we can reduce uncertainties associated with an incomplete geological model. Utilizing an improved geologic model during prospect evaluation results in a more accurate assessment of the probability of success, and reserve estimation.
- When a common interpretation is derived from independent datasets, interpretation uncertainty can be very low (Case A). When the quality, sensitivity or meaning of the data, seismic or CSEM, is compromised, e.g., due to complexity or limited sensitivity, uncertainty will be higher (Cases B, C, and D).
- The quality and assertiveness of each dataset must be carefully evaluated. It is extremely important that interpreters are capable of understanding the strengths and limitations of each dataset to produce a sensible joint interpretation of all the data.

Figure 6 Co-visualization of transverse resistance (TR) overlain on a structural map at the target objective and seismic variance attribute. Note the fault layout with faults striking mainly N-S to NE-SW. There is good spatial correlation between the TR magnitudes and the fault layout in particular along the structural trend defined by fault A. Furthermore, there is spatial correlation between individual fault blocks and TR magnitudes suggesting compartmentalization.