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# Reserves Estimation from 3D CSEM Inversion for Prospect Risk Analysis

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## SUMMARY

Net rock volume is the main uncertainty affecting the evaluation of recoverable reserves for prospect risk analysis. We present a Monte Carlo method for estimating a net rock volume probability distribution from an anisotropic 3D CSEM inversion result. Given a CSEM favourable exploration setting, the method can significantly reduce the uncertainty in net rock volume, especially for stratigraphic traps. The method relies on the sensitivity of CSEM to the volume of resistive rock and on the transverse resistance equivalence principle for relating the low resolution inversion result to possible reservoir scenarios at the well log scale. We demonstrate the performance of the method using unconstrained inversion results from a full-azimuth 3D CSEM survey over a known oil field. No prior information in terms of well data or field geometry was assumed to simulate an exploration case. The uncertainty associated with the resulting net rock volume probability distribution as measured by the P10/P90 ratio is less than 6, which is considered low by common industry practice. The actual net rock volume defined by the reservoir top and the oil-water contact coincides with the 60th percentile of the distribution, i.e. the predicted range of possible net rock volumes is very reasonable.

## Introduction

Estimating reserves is fundamental to the risk evaluation of exploration prospects. The probability of economic success $P_e$ assigned to a prospect is given by the product of the probability $P_g$ of discovering a flowable hydrocarbon (HC) accumulation and the probability $P_{MEFS}$ of the discovered accumulation being greater than the minimum economic field size (MEFS) quantified in recoverable reserves (RR):

$$P_e = P_g * P_{MEFS} = P_g * P(RR > MEFS) \quad (1)$$

(Rose 2001). It is standard industry practice to calculate $P_g$ by evaluating a number of independent geologic chance factors associated with the components of a petroleum system that are required for a HC accumulation to exist, i.e. source, reservoir, etc. The calculation of $P_{MEFS}$ requires generation of a prospect reserves distribution to which the economic threshold can be applied. The reserves distribution is obtained from a statistical evaluation of the reserves equation:

$$RR=NRV * \Phi * (1\text{-}Sw) * Rf/Boi . \quad (2)$$

Here NRV is the net rock volume, Φ is the porosity, Sw is the water saturation, Rf is the recovery factor and Boi is the formation volume factor.
CSEM has the capability to influence both the probability of geologic success $P_g$ and the probability of an economic discovery $P_{MEFS}$, leading to better informed exploration decision making. Due to the strong sensitivity of formation resistivity to HC saturation, CSEM is a very good direct hydrocarbon indicator (DHI) and thus can be used to update $P_g$, e.g. using Bayesian risk modification (Buland et al. 2011), based on CSEM anomaly and data quality characteristics in analogy to seismic amplitude risk analysis (Roden et al. 2005). The impact of CSEM on the prospect reserves distribution results from its sensitivity to the net rock volume; the CSEM response of a HC accumulation is not a local scattering phenomena, but a partially guided wave response whose strength depends on the volume of resistive reservoir rock (area x thickness). Given a CSEM favourable exploration setting, the volume sensitivity can result in a significant reduction in uncertainty since prospect area and net pay are associated with the highest uncertainties (P10/P90 ratios) in the reserves estimation, especially in frontier exploration and for stratigraphic traps.

We present a statistical interpretation method for estimating net rock volume based on anisotropic 3D CSEM inversion data. The method makes use of the transverse resistance equivalence principle and applies a Monte Carlo simulation constrained by the CSEM inversion model. The result is a net rock volume probability distribution that can be used in the reserves equation (2). The method has been applied to real commercial exploration projects, but for reasons of commercial confidentiality, we simulate an exploration case using the widely published CSEM data set from the Troll West Oil Field (TWOP) in the Norwegian North Sea to illustrate the capability to achieve a low P10/P90 ratio for the net rock volume and compare the resulting probability distribution to the actual net rock volume.

## CSEM anomaly interpretation using the transverse resistance equivalence principle

Marine CSEM is a low-frequency technique. Unconstrained CSEM inversion therefore has a resolution that is typically above the reservoir thickness (Figure 1). A hydrocarbon related resistivity anomaly in a CSEM inversion result is an upscaled ("averaged") version of the resistivity anomaly at the well log scale.
In case the only piece of available data is the CSEM inversion result, there are an infinite number of net pay and HC saturated formation resistivity scenarios on the well log scale that would be consistent with the inversion result. These scenarios can be calculated from the transverse resistance equivalence principle, as will be derived below. All resistivities considered in the derivation are vertical resistivities.
Given a 1D resistivity trace extracted from a 3D CSEM inversion model, the transverse resistance equivalence principle states that

$$\int_{\text{CSEM anomaly}} \Delta R_{csem}(z)dz = \int_{\text{pay zone}} \Delta R_{well}(z)dz , \quad (3)$$

where $\Delta R_{csem}$ refers to the resistivity anomaly due to hydrocarbons in the CSEM resistivity trace and $\Delta R_{well}$ is the resistivity anomaly due to hydrocarbons at the well log scale. Equation 3 can be rewritten in terms of average resistivities as

$$Z_{csem} * \langle \Delta R_{csem}(z) \rangle_{\text{CSEM anomaly}} = Z_{res} * \langle \Delta R_{well}(z) \rangle_{\text{pay zone}} . \quad (4)$$

Here $\langle\ \rangle$ denotes the averaging operator, $Z_{csem}$ is the thickness of the CSEM anomaly in the CSEM resistivity trace and $Z_{res}$ is the actual thickness of the hydrocarbon charged reservoir interval, i.e. the net pay. Given a relatively uniform background resistivity variation over the depth interval of interest defined by the CSEM anomaly, equation 4 can be simplified to

$$Z_{csem} * (R_{csem} - R_{bg}) = Z_{res} * (R_{res} - R_{bg}), \quad (5)$$

where $R_{csem}$ is the average value of the CSEM resistivity trace over the CSEM anomaly interval associated with the thickness $Z_{csem}$, $R_{res}$ is the average hydrocarbon charged reservoir resistivity over the pay zone associated with the thickness $Z_{res}$, and $R_{bg}$ is the average background resistivity.
Equation 5 can be rearranged to yield an expression for the "electromagnetic" net-to-gross ratio defined as $NTG_{em} = Z_{res}/Z_{csem}$:

$$NTG_{em} = (R_{csem} - R_{bg})/(R_{res} - R_{bg}) \quad (6)$$

Assuming the background resistivity $R_{bg}$ is known, equation 6 allows for calculating $R_{res}$-$Z_{res}$ pairs that are consistent with the CSEM resistivity trace, i.e. the average CSEM resistivity $R_{csem}$. If the resistivity $R_{res}$ of the hydrocarbon interval was known, the net pay $Z_{res}$ could be calculated from the relationship. This however is not the case in exploration. As we will show in the next section, a good way to deal with lacking information and uncertainties is to run a Monte Carlo simulation on the CSEM inversion result.
So far we have only considered a single resistivity trace, i.e. the 1D case. It is straightforward to extend the analysis to the full 3D CSEM inversion model. In this case, the averaging over the CSEM anomaly results in an average resistivity map (Figure 3), which may then be interpreted in terms of equation 6, i.e. we iterate over each cell in an area of interest to achieve a full net rock volume calculation.

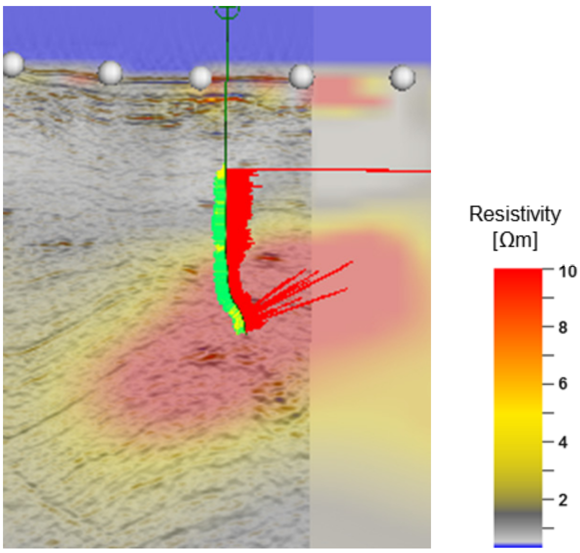


***Figure 1*** *A hydrocarbon related resistivity anomaly in a CSEM inversion result is an upscaled version of the resistivity anomaly at the well log scale. The transverse resistance equivalence can be used to interpret the CSEM anomaly at the well log scale. Example from Yuan et al. (2009).*

## CSEM anomaly interpretation under uncertainty

We use a Monte Carlo method to handle the uncertainties in the interpretation. To do this, we must associate a random variable with a probability distribution to each source of uncertainty in the calculation. For net rock volume calculations from an average resistivity map obtained from a 3D CSEM inversion model, the main uncertainties and corresponding random variables are the following:

- What is the background resistivity value? Variable: $R_{bg}$
- What resistivity values must be considered anomalous? Variable: $R_{cutoff}$
- What is the hydrocarbon charged reservoir resistivity? Variable: $R_{res}$

Suitable distributions for $R_{bg}$ and $R_{cutoff}$ should be defined based on the average resistivity map itself. The $R_{res}$ distribution must be obtained from nearby wells, analogues or other a priori information.
The Monte Carlo algorithm (Figure 2) draws a random value for each of the above variables. The algorithm then iterates over all cells of the map with average resistivity value $R_{csem}$ above $R_{cutoff}$ and calculates their contributions to the total net rock volume for the given combination of $R_{bg}$ and $R_{res}$. The steps are repeated many times and a cumulative probability distribution for the net rock volume is generated.

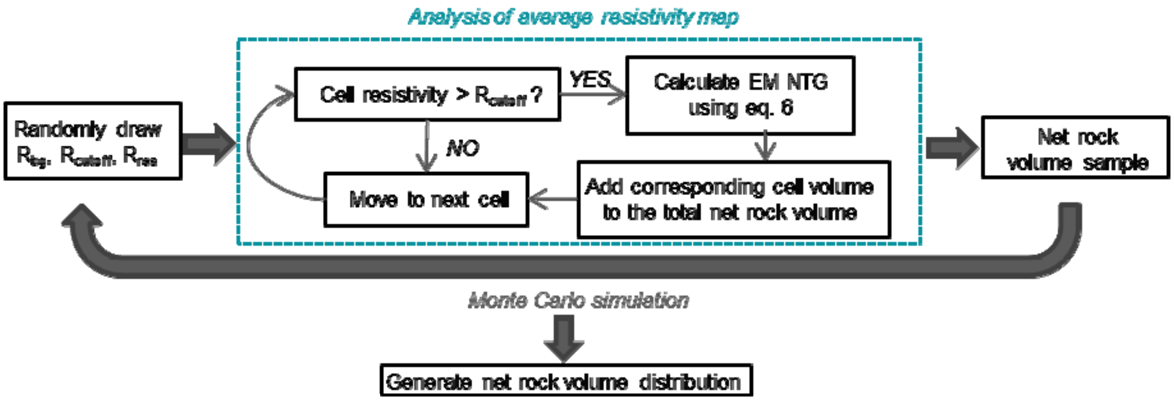


***Figure 2*** *Monte Carlo algorithm for calculating net rock volume from an average resistivity map.*

**Application to the Troll West Oil Province (TWOP)**

We demonstrate the performance of our net rock volume estimation workflow on the Troll West Oil Province (TWOP) over which a full-azimuth 3D CSEM survey was acquired in 2008 (Gabrielsen et al. 2009). Anisotropic 3D inversion of the survey data has been reported by Morten et al. (2009).
No prior information about the hydrocarbon charged reservoir resistivity, the net pay and the reservoir area was assumed in order to simulate an exploration setting. We only used the reservoir top horizon from seismic and the results from an unconstrained anisotropic 3D inversion. An average vertical resistivity ($R_v$) map was generated (Figure 3) using the top reservoir horizon as a depth reference. The averaging window started 400 m above the horizon and ended 300 m below it. The CSEM anomaly is completely inside this window.
The Monte Carlo simulation tested possible reservoir scenarios using the following resistivity ranges: $10\ \Omega m < R_{res} < 100\ \Omega m$, $2.6\ \Omega m < R_{bg} < 3.2\ \Omega m$, $3.3\ \Omega m < R_{cutoff} < 4.7\ \Omega m$. To keep things simple, uniform probability distributions were chosen. Note that the range for the reservoir resistivity $R_{res}$ is very large since no well data were used to constrain this variable. The limits for the $R_{bg}$ and $R_{cutoff}$ variables were chosen based on histograms derived from the average vertical resistivity map.
50,000 Monte Carlo realizations were produced. The resulting cumulative probability distribution for the net rock volume is shown in Figure 3 together with the actual volume defined by the top reservoir horizon and the known oil-water contact (OWC). The distribution is relatively narrow with a P10/P90 ratio of less than 6; the actual volume coincides with the 60th percentile. Other information such as analogues or seismic interpretation could be used to limit or condition the distribution, e.g. the higher end of the rock volume distribution could probably be ruled out using seismic interpretation. By cross-plotting the Monte Carlo input variables against the resulting net rock volume samples, we found the main controlling factor in the rock volume estimation to be the reservoir resistivity $R_{res}$.

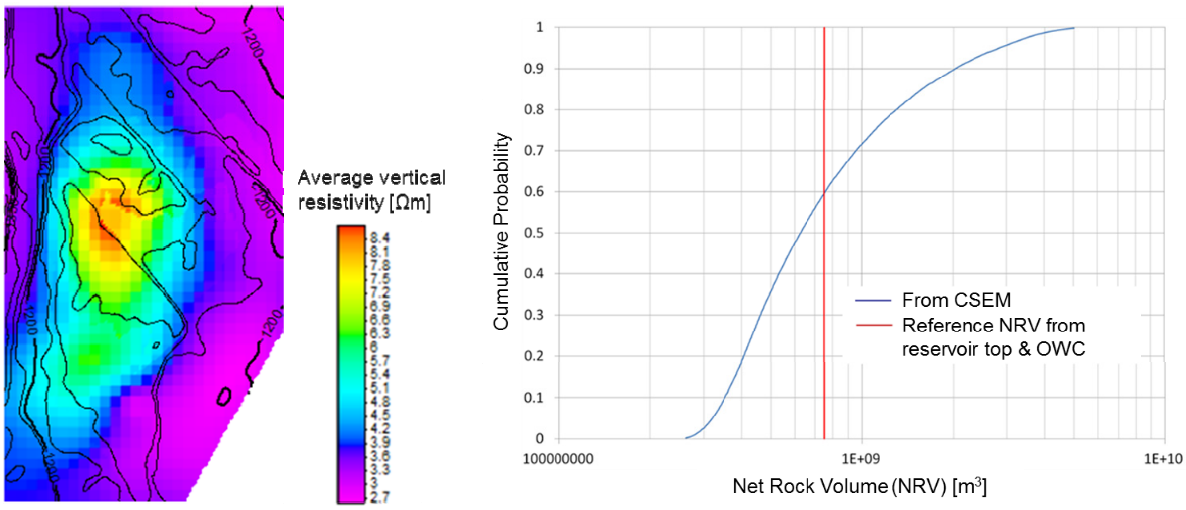


***Figure 3*** *Troll West Oil Province (TWOP) example. Left: Average vertical resistivity (Rv) map. The contours mark the top of the averaging window, which starts 400 m above the top reservoir horizon and ends 300 m below it. Right: Estimated cumulative probability distribution for the net rock volume. The reference volume calculated from the reservoir top and OWC coincides with the 60th percentile.*

## Conclusions

Unconstrained 3D CSEM inversion can provide a reasonable statistical estimate of net rock volume. The uncertainty in the estimated volume will generally be lower than for volume interpretation from seismic, especially for stratigraphic traps. For the chosen example, the P10/P90 ratio for the net rock volume is less than 6, which is low by common industry practice. The main uncertainty in the estimation is the hydrocarbon charged reservoir resistivity. The presented method is easily integrated into statistical reserves estimation tools and hence facilitates the use of CSEM data in exploration decision making. Given well data from a discovery well, the same method can be used to refine the reserves estimation. In addition, the availability of well data allows for reservoir characterization by joint quantitative interpretation of CSEM and seismic data (Morten et al. 2011).

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