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Locating the Remaining Oil in Mature Fields

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Abstract

Identification of by-passed oil is the key to unlock the remaining potential of mature fields. Locating and quantifying the size of oil pools is necessary to justify a range of in-well activates and plan in-fill drilling. This paper presents a new algorithm for reservoir engineers to generate seamlessly and regularly (at desired frequency) up-to-date remaining and moveable oil maps, within days of receiving the latest production and surveillance data.

The algorithm consists of three parts:

I. A material balance engine that ensures at the flow unit level that conservation of mass is computed over the entire map.

II. A mapping algorithm which ensures a realistic saturation change or movement of OWC and GOC, by integrating a 2D flow velocity solver with a gradual deformation algorithm to account for assumed geological trends and fractional flow values at each producer and injector.

III. A coupled search algorithm which allows the computation of a 'best' solution that honors both material balance and the fractional flow behavior of the wells at each time-step.

The results of new algorithm were extensively validated with one pour synthetic case and two fields located in Asia Pacific and the Middle East to ensure its all-round robustness in different geological and reservoir dynamics settings. The results consistently show a remarkable fidelity against a full physics 3D approach. When these two alternative methods are compared quantitatively, oil volume distribution generated by the new algorithm shows over 85% compliance with results of 3D simulation. This new approch, therefore, provides a breakthrough in reservoir management. It is not only a significant step-up from the conventional 'classical engineering methods' of using bubble maps, diagnostics plots and material balance, but provides results that closely mimic those achieved through a detailed history-matching process – which, though theoretically ideal, is often not a practical approach in mature fields with numerous wells and complex history given its highly resource- and time-intensive nature.

Introduction

Mature fields already account for 70% of the hydrocarbon liquids produced globally. Since the average recovery factor for oil fields is 30 to 35%, there is substantial quantities of remaining oil at stake (Höök et al., 2009; Litvak et al., 2007). Moreover, with the chance of discovering giant oil fields ever diminishing

(Blaskovich, 2000), mature fields will contribute significantly to the energy supply of the world in the future (Lantz and Ali, 1991; Wang et al., 2002; Wen-Rui, 2008). The identification of by-passed oil, therefore, is the focus activity in mature fields for reservoir engineers for improved decision making and planning future development (Babadagli, 2007). To achieve a quantified understanding of remaining oil targets, two main approaches are traditionally employed by the subsurface teams, diametrically opposed to one another in terms of their degree of sophistication (Ahmed, 2006; Dake, 1983; Egbogah, 1994):

- On the one end of the spectrum are the classical reservoir engineering approaches, which are usually labor-intensive, require manual integration of multiple software processes (bubble maps, material balance, spreadsheets, etc.) and have inherent ambiguity (Ahmed, 2006; Craft et al., 1959; Dake, 1983).
- On the other end are the fully integrated static and dynamic modelling workflows. These are theoretically the ideal solutions, since complex 3D models are able to incorporate localized geological characteristics and the full physics of simulation. However, 3D numerical history matching is a challenging, non-unique solution exercise, with a delivery time that can become impractically long in the context of "locate the remaining oil" (LTRO) studies (Ahmed, 2006; Aziz and Settari, 1979; Ertekin et al., 2001).

This study developed a robust algorithm that allows to generate remaining oil maps that honor both the 'known' estimated localized phase distributions around the wells together with material balance for each reservoir unit. It is expected that this approach will become increasingly reliable with reservoir maturity and with greater production constraints (number of wells), but unlike the reservoir simulation history-matching, this process remains practical, resource-light and time-effective regardless of complexity.

Methodology

Overall process description

The remaining oil compliant mapping (ROCM) process consists of an integration of a number of steps and calculations as shown in **Fig. 1**. Broadly speaking, the ROCM process is reverse to how a traditional numerical simulator carries out calculations. At each timestep, the following process is carried out:
The first step in the ROCM process is to conduct a fractional flow inversion: converting watercut (WCT) and gas-oil-ratio (GOR) for each well penetration to an equivalent target saturation triplet (Sg, So, Sw); these will be the local constraints to achieve in the optimization process.

The second step is to compute stream flow velocities and coupled with the geological trends (permeability). The resulting velocities and time-of-flight are used as a 2D canvass to distribute the phase saturations with the adequate boundary conditions, at injectors, aquifers, and flow barriers.

The ROCM mapping engine distributes phase saturations constrained to flow velocities and the geological trends, but very importantly retains elements of flexibility with a number of tuning parameters; these parameters allow to deform the 2D phase saturation distribution from the initial deterministic solution, so that both global (overall material balance) and local (well-block) saturation objectives can be achieved.

Now enters the in-board optimization of the ROCM process: a search engine is introduced to couple the ROCM mapping engine with the material balance calculator, and a combined objective function is defined to include both remaining in-place targets (remaining oil = initial – produced oil), and the local objectives of well WCTs and GORs. The material balance engine ensures at the flow unit level that conservation of mass is computed, over the entire map. With pressure history and in-place volumes as given, aquifer influx time series are computed.

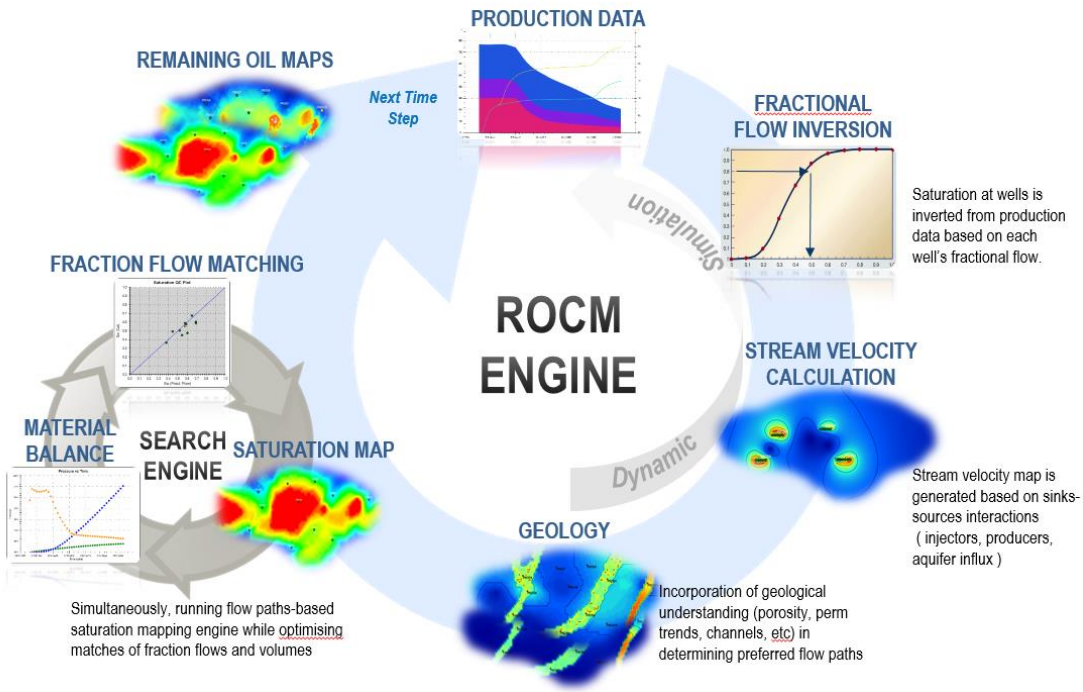


Fig. 1. The remaining oil compliant mapping algorithm broken down in its essential steps.

The Remaining Oil Compliant Mapping (ROCM) engine description

Whilst it is not possible to describe in full details the ROCM engine, due to Intellectual Property restriction on the invention, this section provides an overview of the key elements of the algorithm behind ROCM.

A mapping algorithm which ensures a realistic saturation or contact movement of water and gas, by integrating a 2D flow velocity solver with a gradual deformation algorithm to account for assumed geological trends and fractional flow values at each producer.

There are two fundamental elements within the ROCM engine:

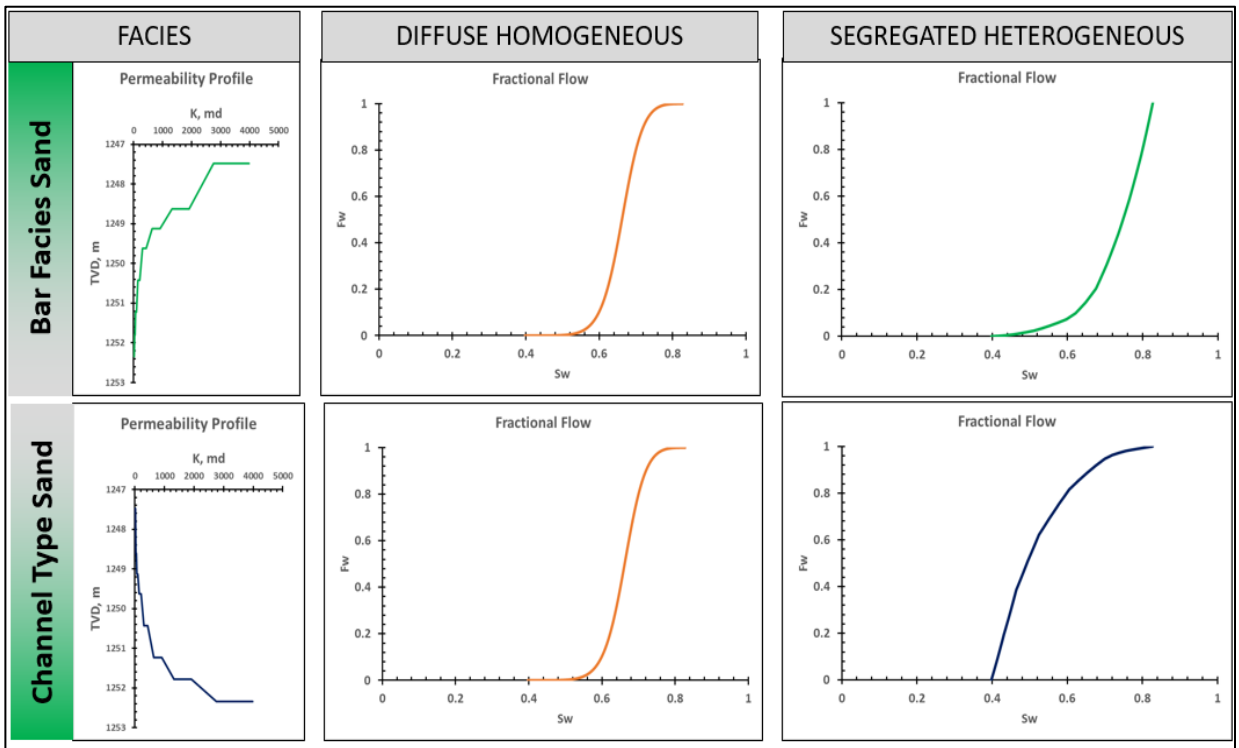
1. Fractional Flow Function
2. Saturation transport function: explicit proxy

Fractional Flow Function

First the fractional flow function, which operates the necessary conversion of phase ratios (watercut, gas-oil-ratio) to an equivalent average saturation in the grid-block where the well penetration resides. Whilst it is not the intent of this paper to enter a detailed mathematical discussion, it should be noted that at the level of a perforation, the fractional flow functions GOR vs. Sg (total cell) and WCT vs. Sw (within liquid) must be bijective in parts for the inversion process to be performed.

Two main flow formulations can be used: diffuse or segregated flow conditions. The diffuse flow condition may be suitable in a near-homogeneous thin flow unit, where gravity forces are negligible compared to viscous forces. The segregated flow condition are typically more suitable if the vertical dimension of the flow unit is of importance: for instance presence of vertical heterogeneity and/or the expectation that gravity forces cannot be neglected compared to viscous forces. One advantage of the segregated flow assumption is the possibility to readily convert phase saturations into gas-oil and water-oil contacts (or gas-water if a gas-water system was considered).

The impact of the vertical permeability profile and the choice of the flow conditions are illustrated in **Fig. 2**. Note that the approach allows to cater for partial perforations of the flow units; a grid-block to well block sweep efficiency can also be introduced to represent localized coning of water or gas.



Swc	Sor	Krw*	Kro*	No	Nw
0.4	0.17	0.5	1	4.5	3

Fig. 2. Illustration of fractional flow functions for two log motifs: coarsening upward (bar-like, top) and fining upwards (channel type, bottom). Diffuse and segregated functions are generated, demonstrating the impact of the log profile on the Fractional Flow function.

Saturation transport function: explicit proxy

At the heart of the method resides the saturation transport method. Whilst providing a detailed formulation is outside the scope of this paper, it is important to highlight the main innovation of the ROCM algorithm, which is to have obtained an explicit transport function for the phase saturations.

The **Fig. 3** shows the general formulation of the explicit 2D saturation transport function, incorporating all terms of the full physics solution of the diffusivity equation (described here for one dimension 'x') which is solved iteratively via a numerical scheme in a traditional reservoir simulator. The explicit proxy functions Sw(x,y,t) and Sg(x,y,t) are parametric in nature, and include a coupling of permeability, porosity, gravity, velocity terms; an inertial term is also included. This transport function was developed empirically, through years of controlled experiments with a large number of reservoir simulation cases covering the full range of displacement conditions.

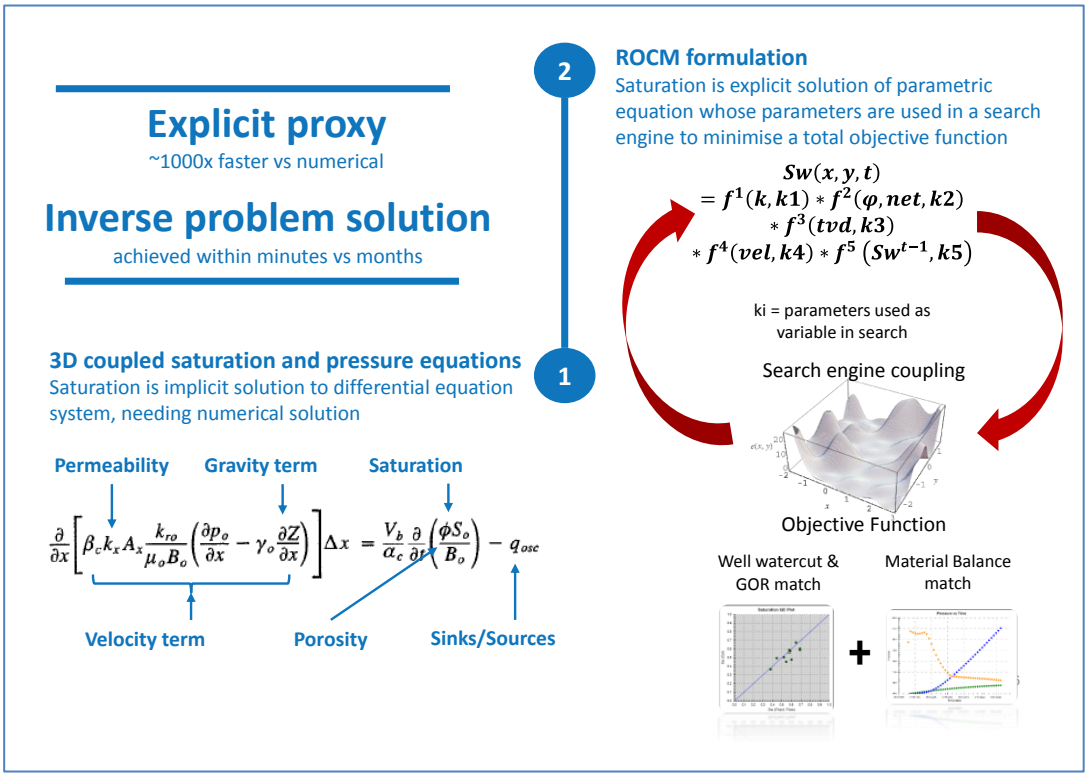


Fig. 3. The ROCM explicit saturation transport function as a cornerstone of the remaining oil mapping method

Due to its explicit nature, the parametric proxy is extremely computationally effective. It is therefore very practical to couple it with a search engine, in order to minimize the error of an objective function, namely the combination of global and local saturation targets for each time-step.

Validation

Validation is necessary to ensure that the mathematical formulation, solution techniques and software implementation are correct. The validity of the new procedure is examined against results generated by a commercial numerical reservoir simulator for a pure 'synthetic' case, and thereafter for two different fields located in Asia Pacific and the Middle East. These two actual fields were selected for offering very distinct characteristics, and because a matched reservoir model was available for both of them, offering therefore adequate conditions for a controlled experiment.

The Case Study 1 field is a sandstone stacked oil and gas reservoir developed primarily by vertical and deviated wells, with over 300 wells present in the structure. The reservoir recovery mechanism is moderate aquifer, with gas cap expansion and gas re-injection. One of the major reservoirs had been the subject of an extensive reservoir study effort and reservoir simulation was available.

The Case Study 2 field is a carbonate reservoir with one major 100-150m thick reservoir, under active water injection. The field is developed with ~30 horizontal producers and injectors, is subject to the complexity of compartmentalizing faults and open fractures enhancing the movement of water through the reservoir.

Synthetic 2-phase 2D validation

As a first demonstration of the accuracy of the ROCM engine, a simple 2D model was setup, representing a channelized system establishing preferential flow paths within a lower permeability background facies. The purpose of such a model is to illustrate how reliable the mapping algorithm can be under like-for-like

conditions (2D simulation vs. 2D ROCM).

The model setup is shown below in **Fig. 4.** The bubble map analysis shows that the majority of the flow happens through the channel facies, with the strong aquifer influx directed into the high permeability facies.

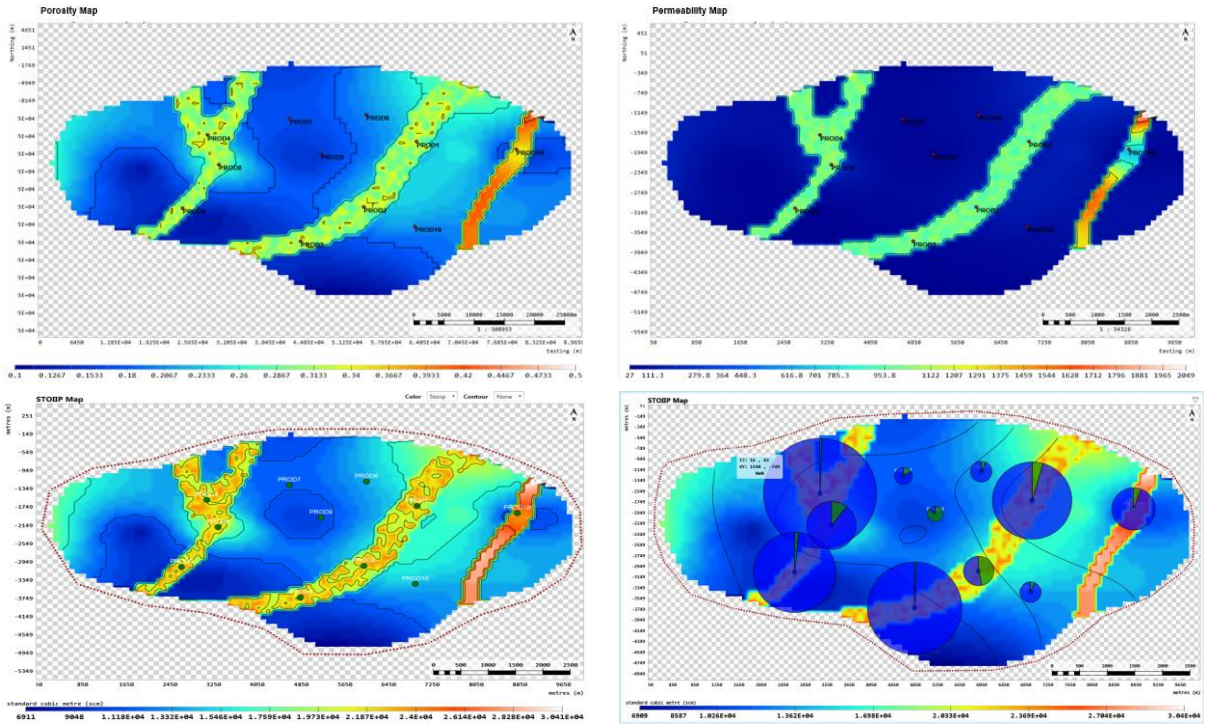


Fig. 4. Synthetic case setup Porosity (top left), Permeability (top right), initial oil-in-place (bottom left), and bubble map outcome at the end of production (bottom right)

The quality of the match in terms of final saturations is shown on **Fig. 5**. The performance of the ROCM algorithm is evident at reproducing the saturation distributions under a displacement mechanism with a very heterogeneous case.

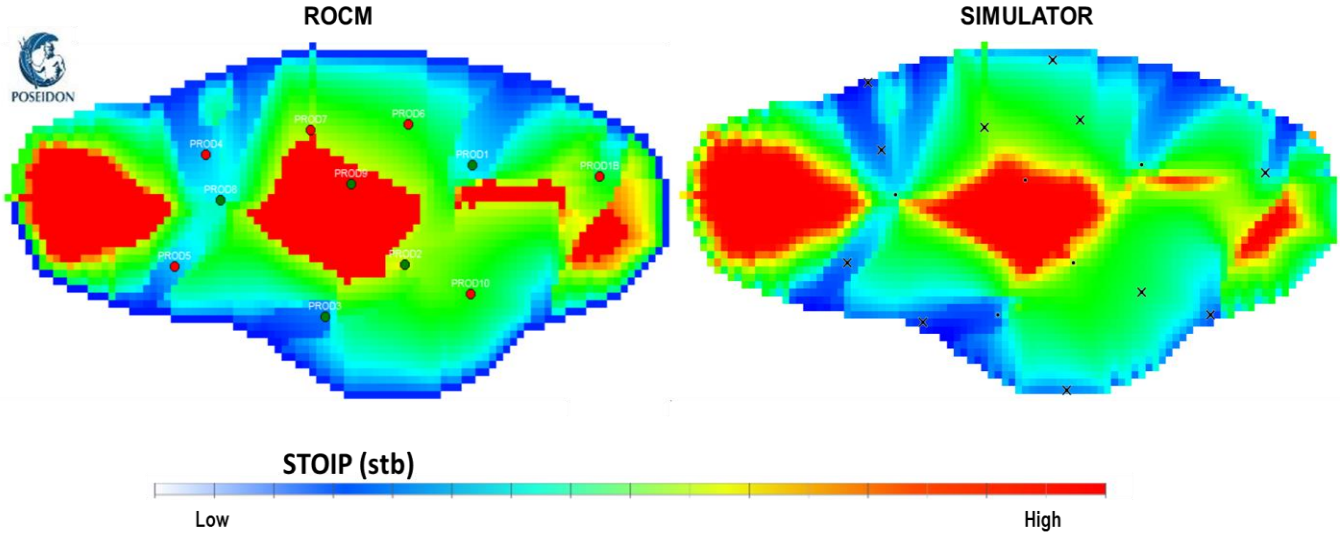


Fig. 5. STOIP maps generated by ROCM (left) and commercial numerical reservoir simulator (right).

Case Study 1

To validate the new algorithm, a large offshore mature clastics oil reservoir with five (5) distinct gas caps with more than 30 years of production history. The engineers observed the expansion of gas caps as the field depleted. There are more than 300 wells (both producers and injectors) and currently around 150 active strings. The field is highly heterogonous with permeability ranging over four orders of magnitude: from 1s-1000s of mD as shown in **Fig. 6**.

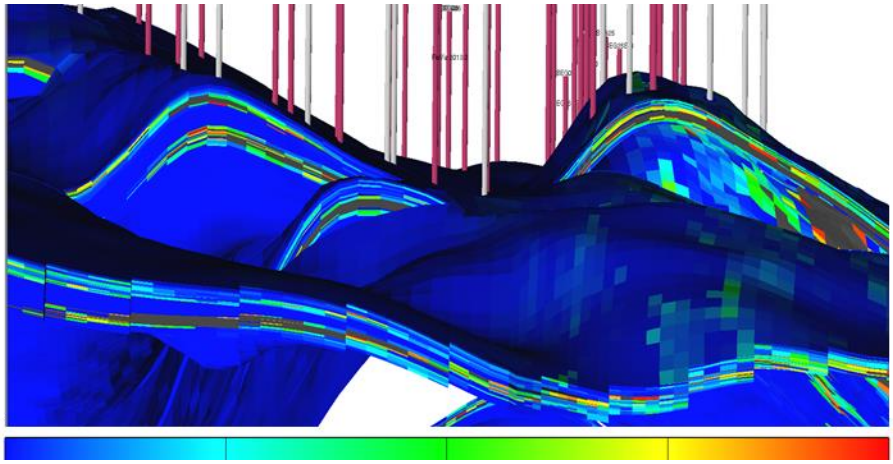


Fig. 6. Permeability distribution.

The STOIP and gas saturation map generated by a commercial numerical simulator and the new ROCM engine have been presented in **Fig. 7** and **Fig. 8,** respectively. The results show a remarkable fidelity between ROCM and the full physics 3D simulation. Five areas have been picked up to compare STOIP and gas saturation results generated by both the commercial numerical reservoir simulator and ROCM as shown in **Fig. 9** and **Fig. 10,**Fig. 8 respectively. When these two alternative methods are compared quantitatively, the ROCM oil volume distribution accuracy is greater than 85% compared to simulation outcomes as shown in **Fig. 11**. The accuracy of match is more than 90 % for the gas saturation maps as presented in **Fig. 12.**

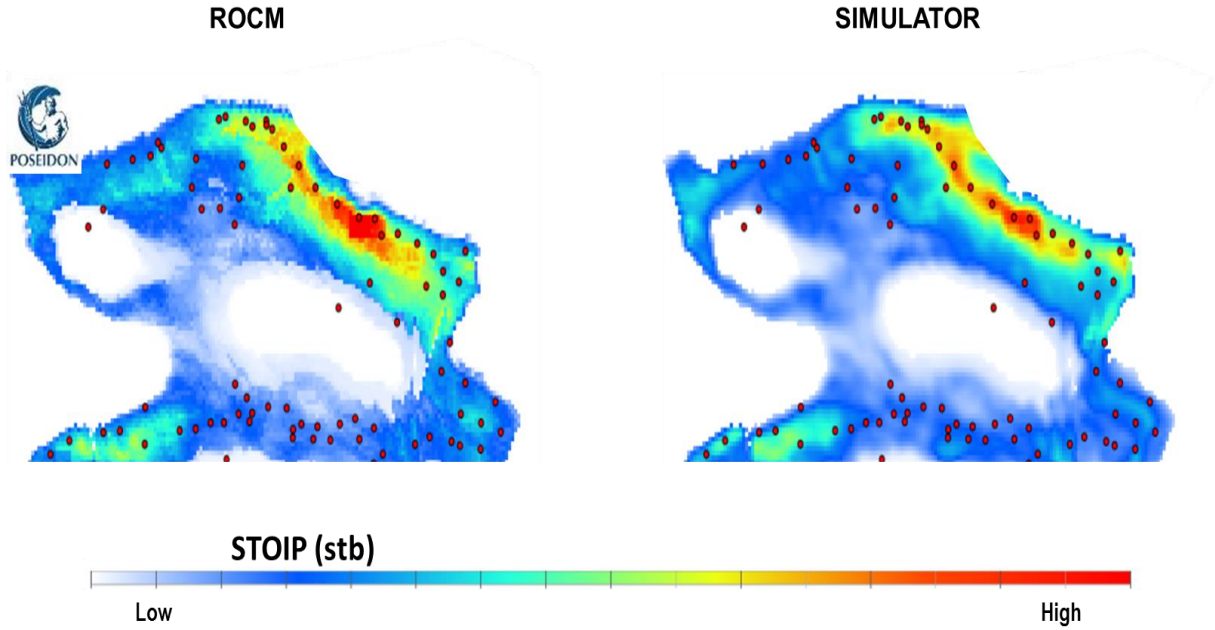


Fig. 7. STOIP maps generated by ROCM (left) and commercial numerical reservoir simulator (right). Results shown for a sector of the field only, and the hydrocarbon distribution has been altered to protect confidentiality.

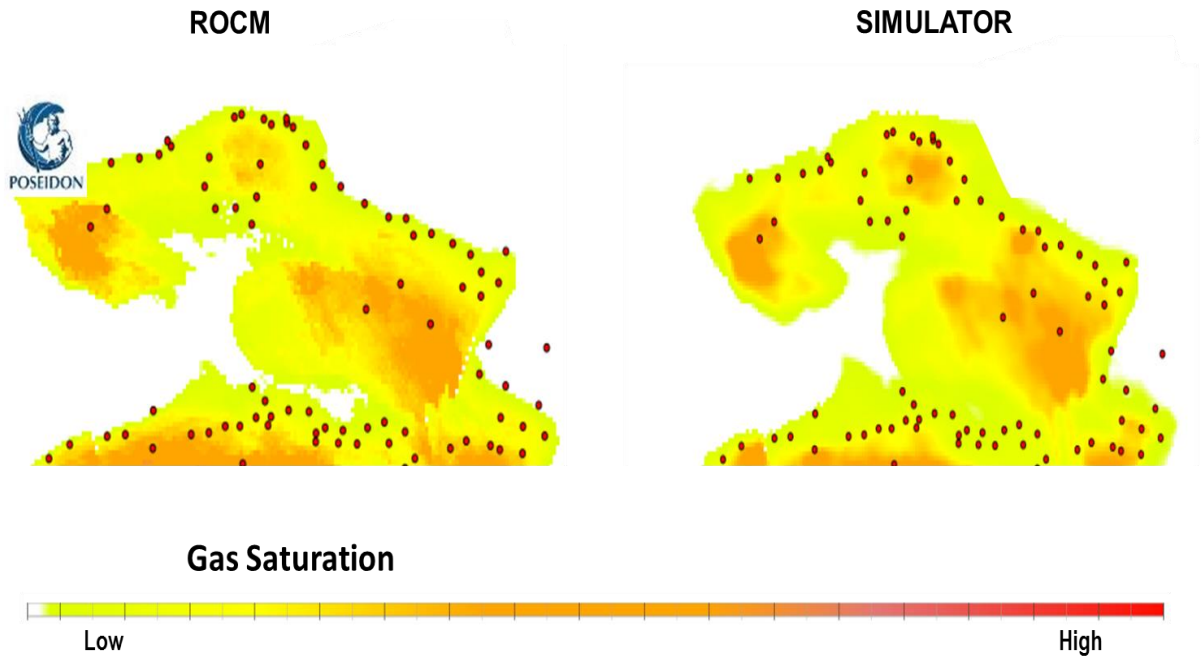


Fig. 8. Gas saturation maps generated by ROCM (left) and commercial numerical reservoir simulator (right). Results shown for a sector of the field only, and the hydrocarbon distribution has been altered to protect confidentiality.

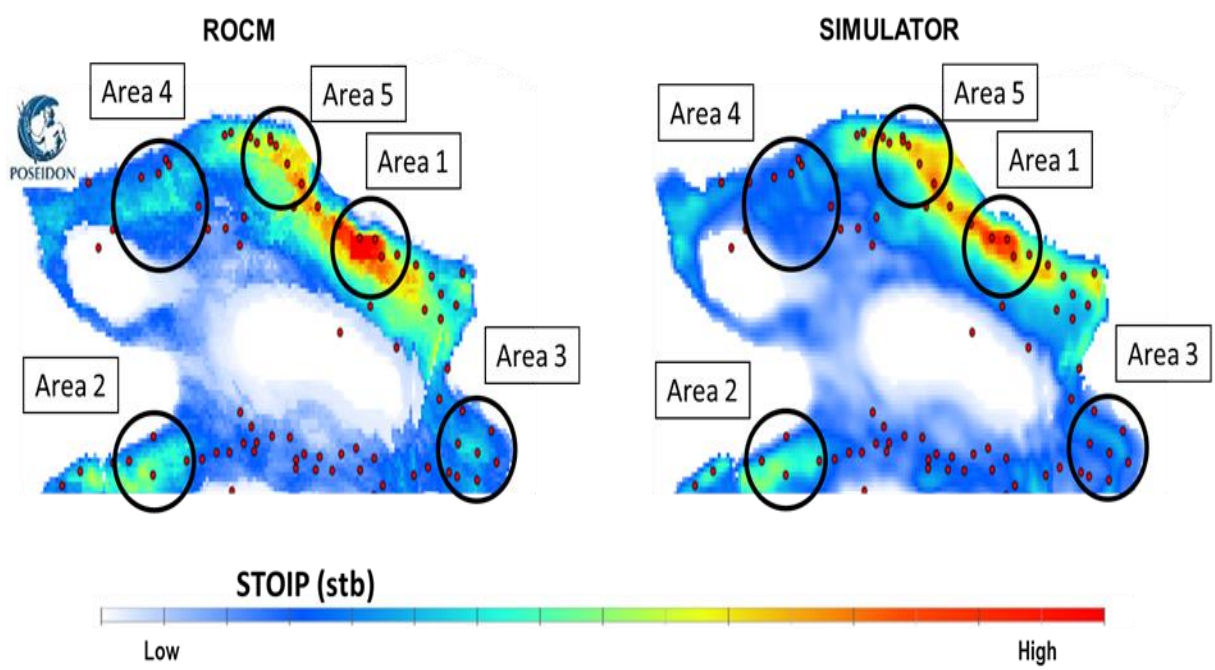


Fig. 9. Selection of five areas to compare STOIP maps generated by ROCM (left) and commercial numerical reservoir simulator (right). Results shown for a sector of the field only, and the hydrocarbon distribution has been altered to protect confidentiality.

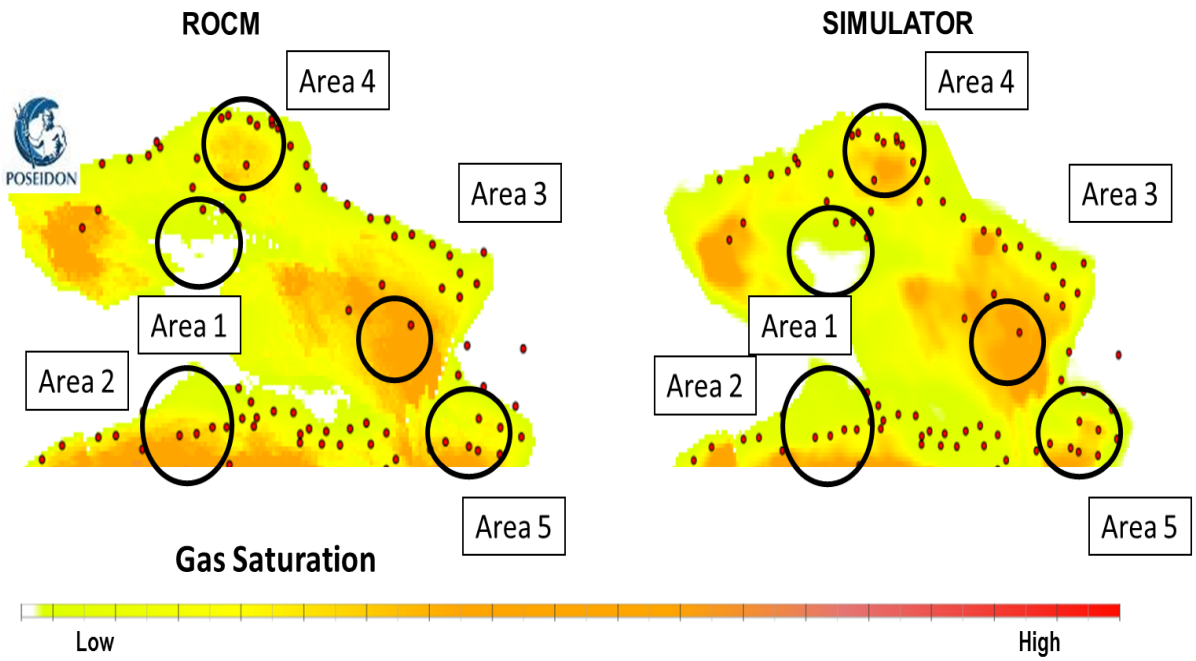


Fig. 10. Selection of five areas to compare gas saturation maps generated by ROCM (left) and commercial numerical reservoir simulator (right). Results shown for a sector of the field only, and the hydrocarbon distribution has been altered to protect confidentiality.

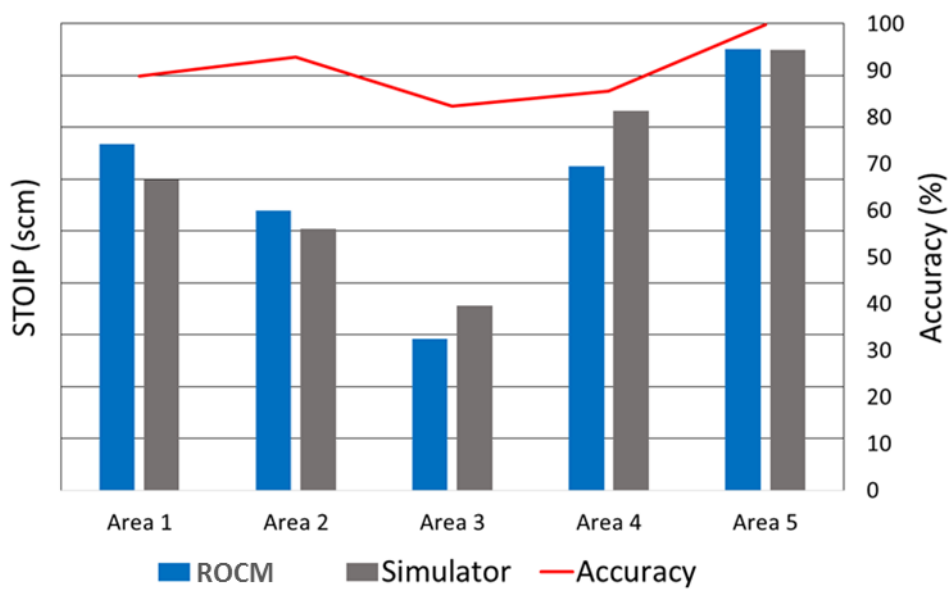


Fig. 11. Comparison of STOIP results generated by ROCM and commercial numerical reservoir simulator.

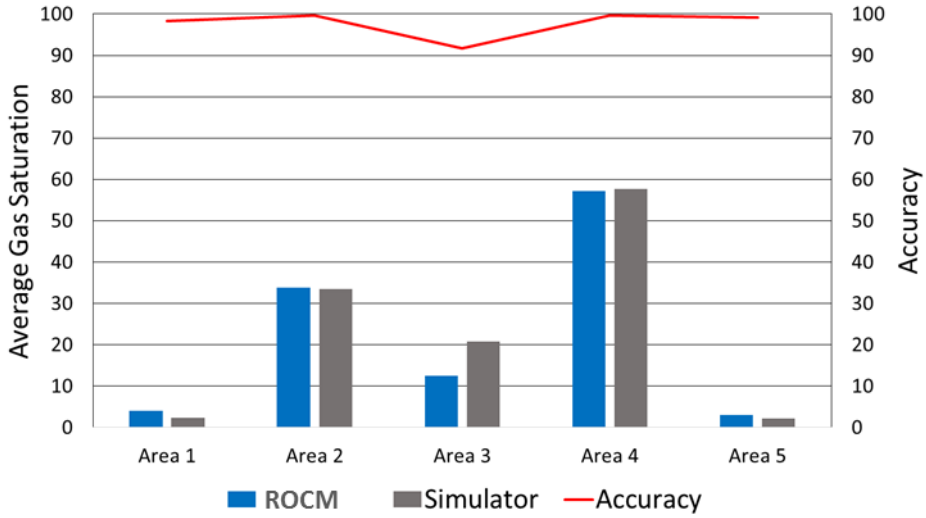


Fig. 12. Comparison of gas saturation results generated by ROCM and commercial numerical reservoir simulator.

Case Study 2

The second field to validate the new approach is located in the Middle East, a major carbonate field with more than 30 horizontal wells. The reservoir pressure is still above the bubble point pressure and the main recovery mechanism is the water flooding (both injected water and aquifer). Comparison of results reveal that the results of the numerical simulator and ROCM closely match (**Fig. 13**).

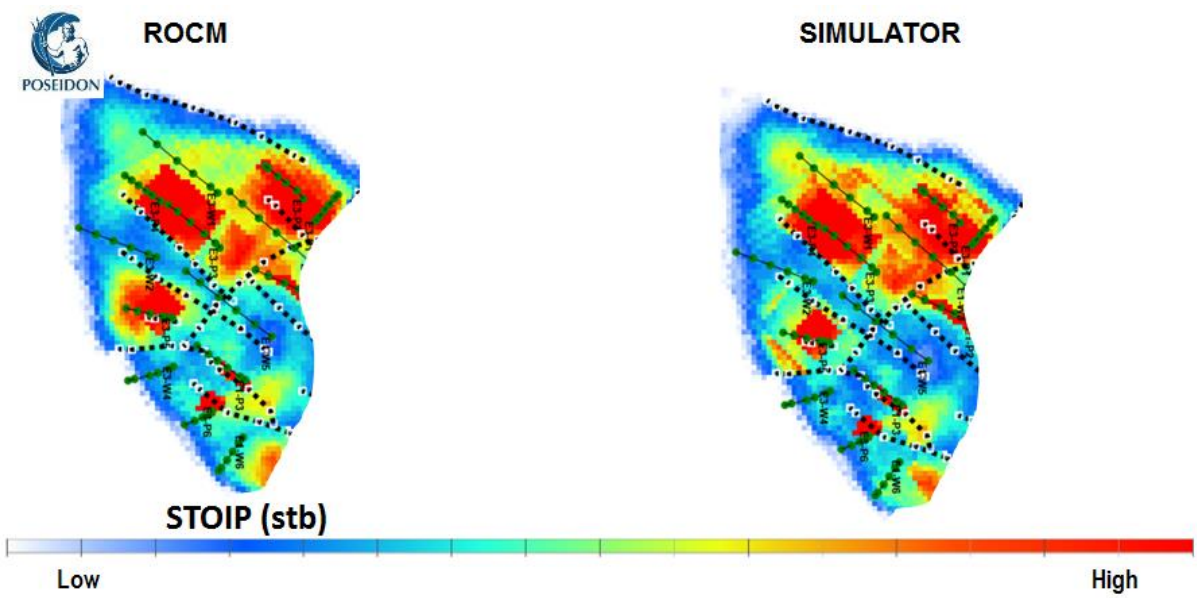


Fig. 13. STOIP maps generated by ROCM (left) and commercial numerical reservoir simulator (right). Results shown for a sector of the field only, and the hydrocarbon distribution has been altered to protect confidentiality.

Discussion and Application

The main application of this method is in obtaining reliable remaining oil maps to identify future development targets; the method is designed to embrace uncertainty in geological trends and production allocation, as the faster turnaround time of the method allows to test these uncertainties through a scenario approach.

This process naturally lends itself to a reservoir management and LTRO context, where the objective is to delineate and quantify opportunities for in-fill drilling. In the example shown in **Fig. 14**, Infill and Behind Casing Opportunities (BCO) can readily be identified with ROCM approach as they stand out in the map generated by ROCM. But are very difficult to pick on the bubble map display. Note how infill and BCO locations can readily be identified on ROCM maps, but aren't clear with bubble maps.

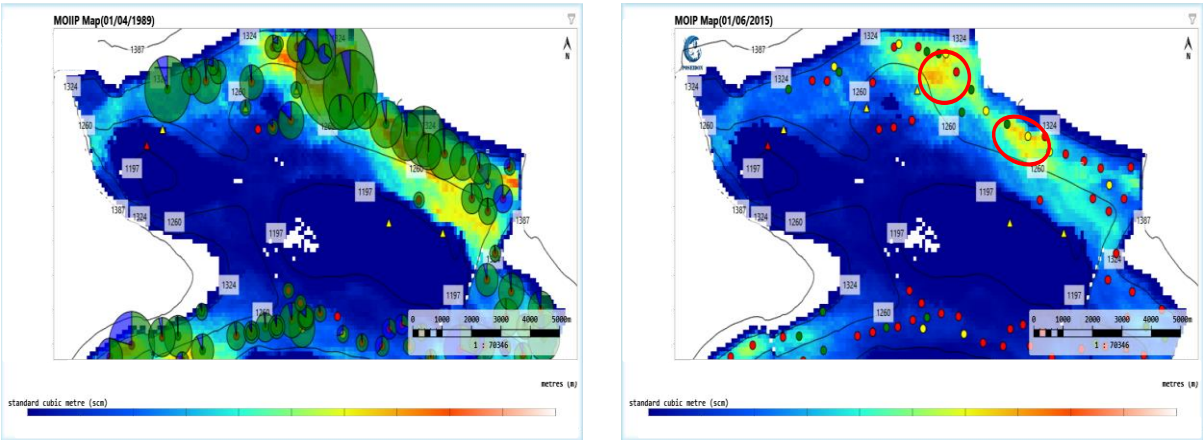


Fig. 14. Comparison of traditional bubble maps overlaying initial STOIIP (left) vs remaining oil maps generated using the ROCM algorithm (right).

Furthermore, ROCM can be used to study opportunities of re-perforation in active wells and restoration of idle wells. Saturation maps are converted to fluid contacts and displayed on a synthetic log (C-Track). Extensive validation was conducted using reservoir simulation vs. ROCM C-Track predictions and an excellent level of accuracy has been observed as shown in **Fig. 15**. By combining the area-wise saturation predictive power of ROCM with the vertical resolution, it is now possible to obtain effectively a 3D distribution of saturation. Compliant with each well's fractional flow behavior, flow-unit material balance, with an overall remarkable fidelity to full-physics numerical simulation. Combined with the significant matching process acceleration, uncertainty analysis can be performed, to understand better the risks associated with incremental activities. The implications for accelerated, quantitative and reliable idle well rejuvenation, infill location identification and surveillance planning are very obvious.

Fig. 17 reveals how ROCM can help engineers to control gas production by shutting off a part of the perforation. The process doesn't rely on history-matched models, and unlike them can be readily updated as new data comes in, allowing to produce monthly well & reservoir saturation distribution maps and the next generation of stick plots (**Fig. 18**).

Conclusions

ROCM is an excellent reservoir management tool for mature fields, designed to drive practically and effectively the continuous identification of in-well (perforation, shutoffs) activities and infill & injection opportunities. Whilst remaining oil compliant mapping is not anticipated to remove the requirement and value from full physics simulation, it offers a distinct speed advantage over the full static-dynamic history matching workflow, whilst retaining a demonstrable fidelity. The remarkable insights and quantification capability of compliant mapping will establish this method as a far superior methodology to the classical engineering approaches utilized in LTRO workflows, where engineers must make sense of various maps, cross-plots and diagnostics such as bubble maps, material balance calculations etc. The ROCM approach offers a seamless integration of the these approaches via a time-effective and high fidelity reduced physics approach, providing the engineers with the desired deliverables of 2D remaining oil maps and quantified incremental activity benefits for in-well and infill opportunities.

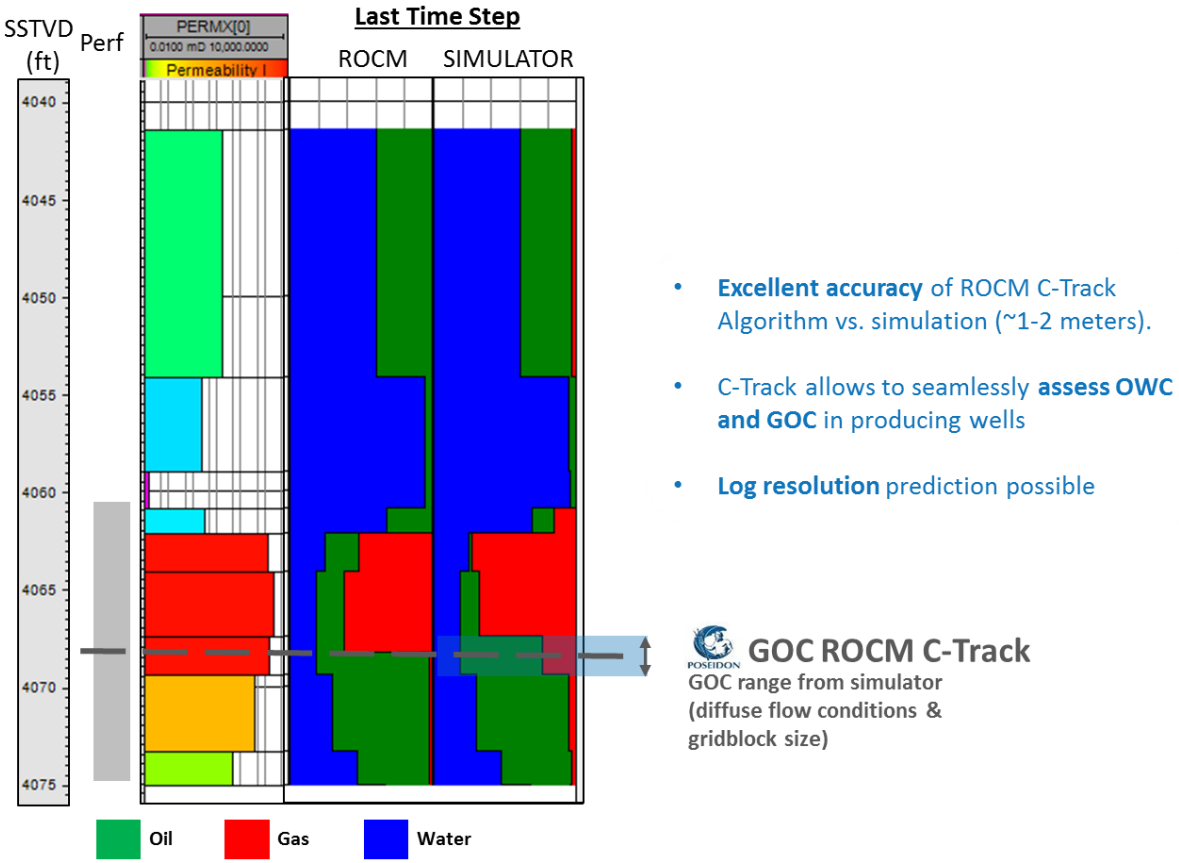


Fig. 15. Validation of in-well saturation prediction.

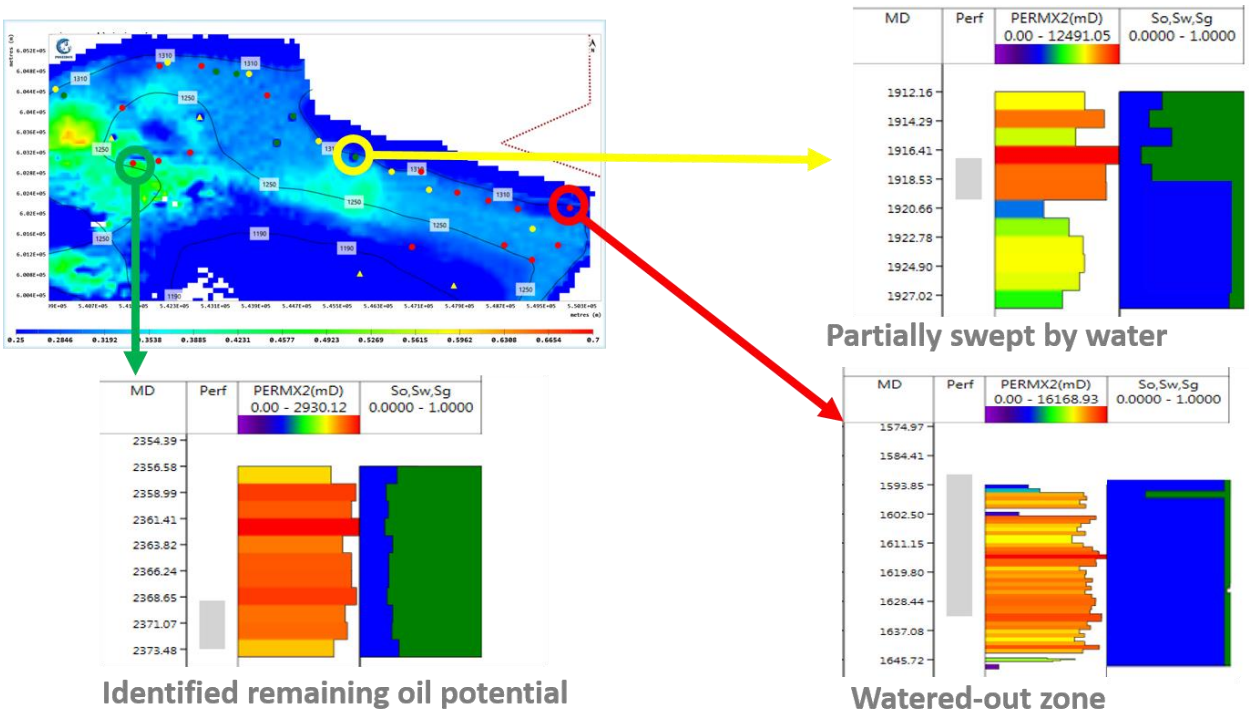


Fig. 16. Identification of remaining oil potential and watered-out zones.

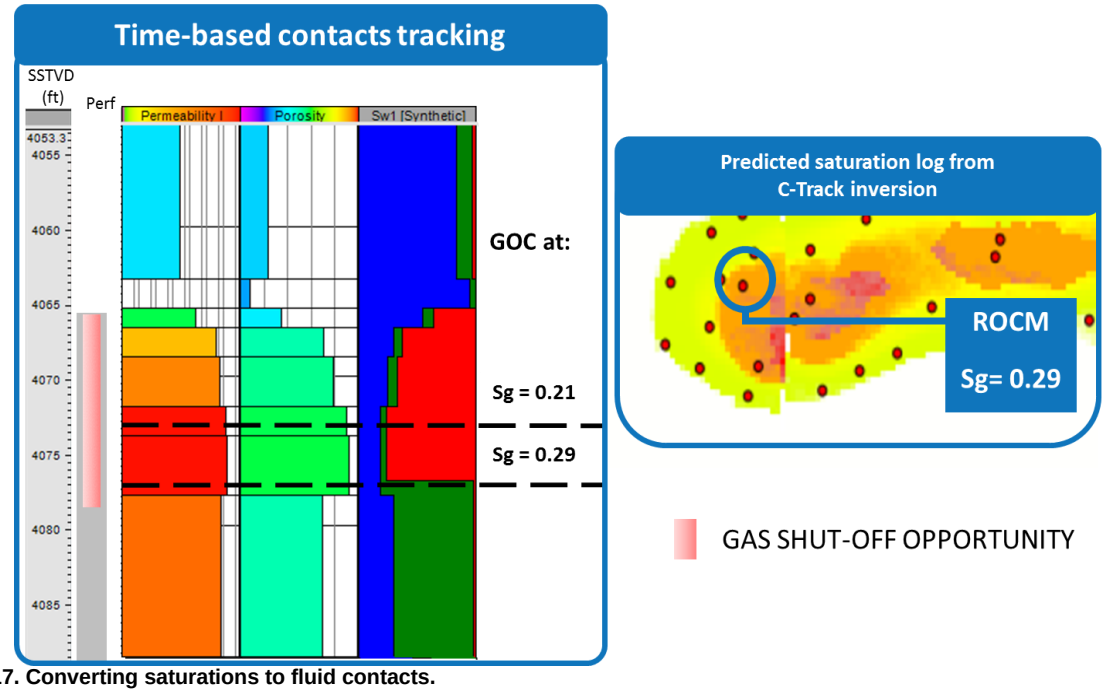


Fig. 17. Converting saturations to fluid contacts.

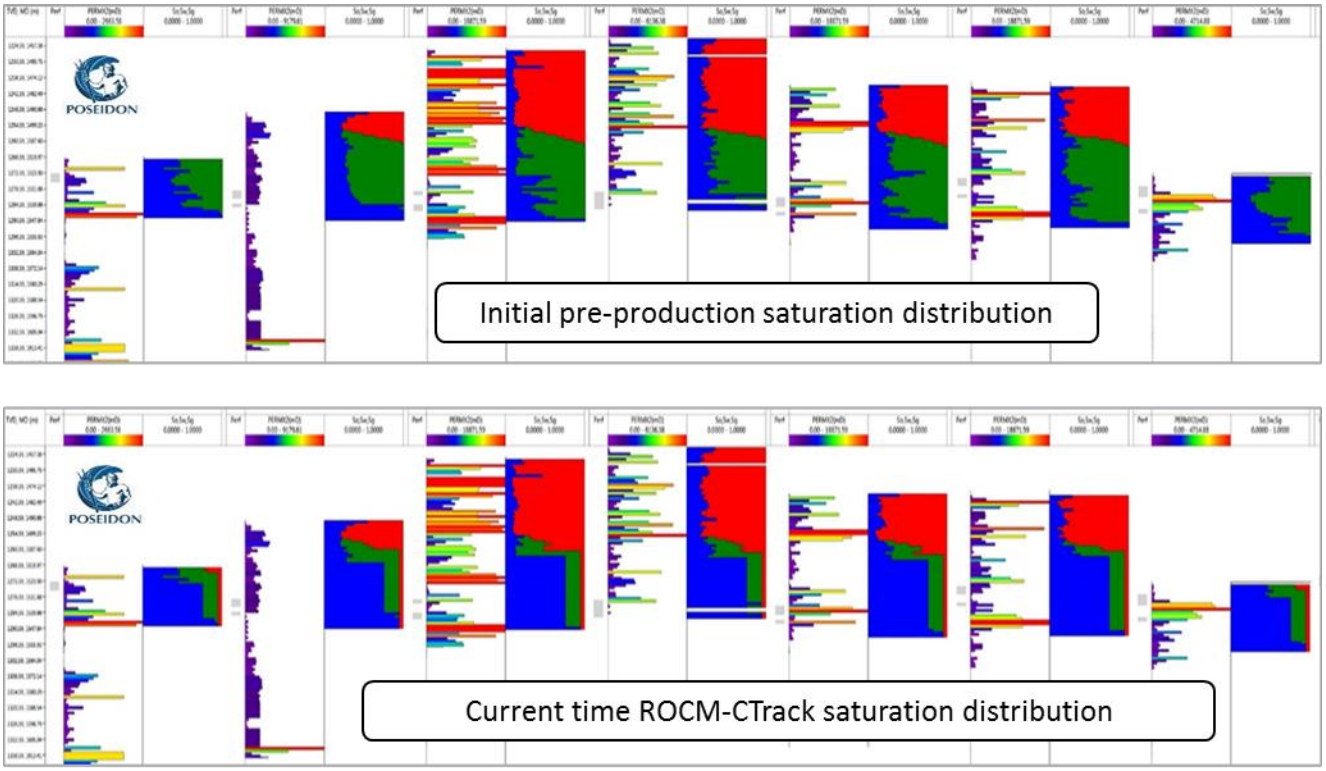


Fig. 18. Saturation distribution in-well level.

Achnowlegements

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